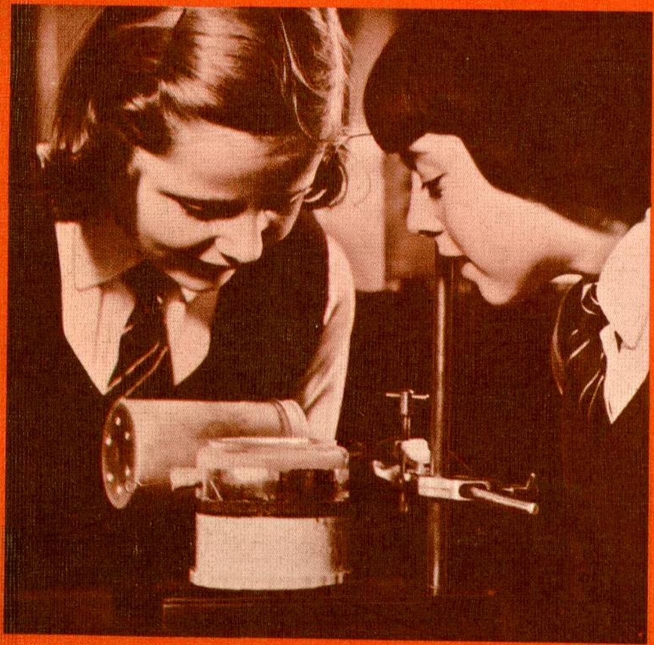
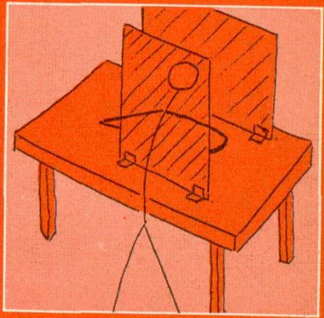
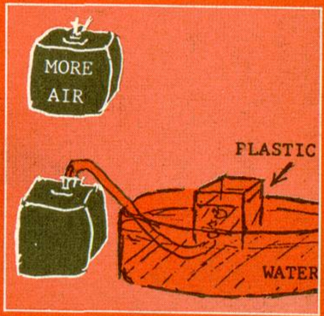
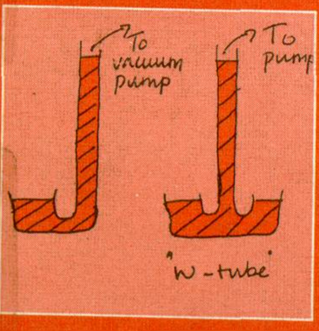
PHYSICS

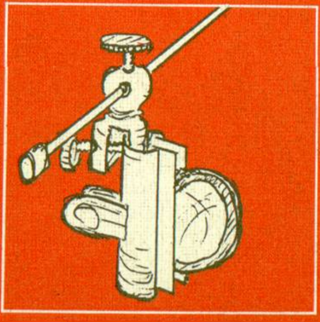
Teachers' guide I

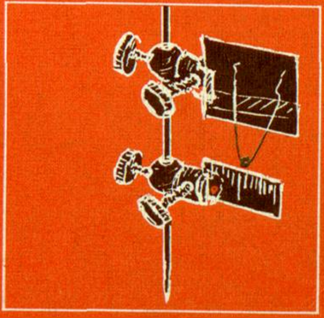












NUFFIELD PHYSICS TEACHERS' GUIDE I

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FOREWORD

This volume is one of the first to be produced by the Nuffield Science Teaching Project, whose work began early in 1962. At that time many individual schoolteachers and a number of organizations in Britain (among whom the Scottish Education Department and the Association for Science Education, as it now is, were conspicuous) had drawn attention to the need for a renewal of the science curriculum and for a wider study of imaginative ways of teaching scientific subjects. The Trustees of the Nuffield Foundation considered that there were great opportunities here. They therefore set up a science teaching project and allocated large resources to its work.

The first problems to be tackled were concerned with the teaching of O-Level physics, chemistry, and biology in secondary schools. The programme has since been extended to the teaching of science in sixth forms, in primary schools, and in secondary school classes which are not studying for O-Level examinations. In all these programmes the principal aim is to develop materials that will help teachers to present science in a lively, exciting, and intelligible way. Since the work has been done by teachers, this volume and its companions belong to the teaching profession as a whole.

The production of the materials would not have been possible without the wholehearted and unstinting collaboration of the team members (mostly teachers on secondment from schools); the consultative committees who helped to give the work direction and purpose; the teachers in the 170 schools who participated in the trials of these and other materials; the headmasters, local authorities, and boards of governors who agreed that their schools should accept extra burdens in order to further the work of the project; and the many other people and organizations that have contributed good advice, practical assistance, or generous gifts of material and money.

To the extent that this initiative in curriculum development is already the common property of the science teaching profession, it is important that the current volumes should be thought of as contributions to a continuing process. The revision and renewal that will be necessary in the future, will be greatly helped by the interest and the comments of those who use the full Nuffield programme and of those who follow only some of its suggestions. By their interest in the project, the trustees of the Nuffield Foundation have sought to demonstrate that the continuing renewal of the curriculum – in all subjects – should be a major educational objective.

Brian Young
Director of the Nuffield Foundation

CONTENTS

Note

This General Introduction is included in the volumes of the Teachers' Guide for both Year I and Year III, since it is those two Years which offer possible starting-points for the course. But it will also be a source of reference for teachers concerned with other Years.

The General Introduction is meant to serve two purposes: first, to set the scene for the course as a whole, by providing a brief historical background to its development, and a discussion of its main aims; and second, to assemble the notes to teachers on those themes which are relevant to more than one Year of the course (and which cannot therefore conveniently be included among the notes which appear under individual Years).

It is suggested that the text should be read through by every teacher before first embarking on a trial of the course; but it is hoped that teachers who are already familiar with the material will refer to it again from time to time as a useful anthology of ideas on both general and particular themes.

The Appendices reproduce the texts of two papers read to conferences of science teachers by the Organizer during the development of the physics programme. Although they were not intended as official statements of policy, the topics they discuss – teaching science for understanding, and examining – are likely to be of such general interest that they have been included here in full, to supplement the inevitably briefer comments in the main body of the text.

ESTIMATED ALLOCATION OF TIME

YEAR I

If it is assumed that a school year includes 30 weeks and that each week includes 2 physics periods, each of which lasts for 40 minutes, then a very rough estimate of the number of periods suggested for each section of this Year would be:

Chapter 1	14
Chapter 2	4
Chapter 3	6
Chapter 4	4
Chapter 5	8
Chapter 6	10
Chapter 7	6
Chapter 8	8
	60

Although these estimates are rough they will, nevertheless, provide some guidance as to weight to be placed on the various parts of the programme. It should be noted that the relative amounts of printing are not proportional to the teaching time required. Where subject matter is new and unfamiliar, it has been dealt with at length in order to help any teacher who may wish to experiment with it. On the other hand, more familiar subject matter has often been dealt with briefly.

KEY TO MARGIN REFERENCES

C = Class experiment
D = Demonstration experiment
H = Suggestions for optional experiments at home
F = Film
T = Teaching of material (lectures, discussions with pupils, etc.)
P = Problem
* * * = Commentary (notes on methods, aims, etc., offered to teachers)
‡ = Reference to footnote
§ = Reference to a comment made by a teacher during trials.

(The experiments are numbered serially through the Year, irrespective of the classification C, D, F or H. The same numbers will be found for each experiment in the *Teachers' Guide to Experiments and Apparatus*. Where (a), (b) ... are added to the number these refer in some cases to separate parts of the same group of experiments, in other cases to alternative versions of an experiment.)

GENERAL INTRODUCTION

BACKGROUND INFORMATION

THE PHYSICS PROGRAMME: GENERAL INTRODUCTION

'Physics for All' in Grammar Schools: Five-Year Course

The course has been designed as a five-year course from 11 + to O-level. It is intended for all who do physics in grammar schools. It is to be a General Certificate of Education O-level course; and it must be suitable for use in all streams in grammar schools and perhaps in the top streams of secondary modern schools where such O-level examinations are taken. Thus the range of ability involved is a wide one. That does not seem to present great difficulties where the emphasis is on experimenting and discussion for understanding, because such teaching can be modified by the teacher who knows his pupils. In constructing the course and writing detailed suggestions, we have aimed specifically at the standard of the 'B' stream of a three-stream grammar school as the centre of our target; but we believe our programme is suitable both for the fastest grammar school streams and for the fastest in secondary modern schools.

(In certain schools, it is customary for some pupils to complete the O-level course in four years. And in some independent schools, pupils start science at a later stage and have in the past condensed the traditional O-level course into a much shorter time. If the Nuffield Physics programme is to achieve its aims of teaching physics as a modern science and give pupils a lasting sense of understanding physics as a structure of knowledge, it is very unlikely that compression of our five-year course into a shorter time will succeed.

In our trials we assumed pupils would have the full five years.

Physics for Non-Scientists

Many of the pupils who take O-level physics never go any farther with physics. For this reason, the Nuffield course is designed as a programme of 'Physics for All', a course suitable for the general educated man or woman. The emphasis is on teaching for understanding and not on collecting information or memorizing formal statements by rote or solving mechanical problems by formulae or carrying out routine measurements by following detailed instructions. We believe that the latter activities, however useful they may seem in training future scientists, fail to give the educated non-scientist an understanding of science, or even that liking for science which might make him preserve his knowledge.

Physics for future Scientists

In discussing our plans, we have come to believe that the future scientist, too, needs such teaching for understanding. We doubt whether a course devoted to training in techniques and complete coverage of material can do as much as our course can for future physicists and engineers and other scientists. They too need to understand their physics if they are to make great use of it.

Physics for All

However, at the moment we are thinking of pupils in general. And we think of them, not just when learning physics at school, but a dozen years later when they are out in the world: a young man working in a bank, presently to be manager; a lawyer, who must deal with scientists and even with science; a nurse; the manager of a shop; a history teacher in school or university; and the mother or father of young children who in turn will approach science with an attitude – of delight or boredom – that starts at home.

We have chosen the content of the course to give pupils opportunities for experimenting on their own to provide for thorough discussion, to include some atomic physics, and above all to form a connected programme of physics. Physics must be shown as a connected fabric of knowledge, in which something learnt in one place proves useful somewhere else, and something discovered later throws light back on something worked with earlier. We want pupils to think things out for themselves, learning physics as they do so. We do not believe that much gain in understanding comes from formal learning of definitions or the working of examples by substituting numerical values in a formula. Thus, some of the careful teaching and training of present physics courses can, we suggest, give place to less formal teaching, with both teacher and pupils aiming at understanding. On that basis, it is more important to know the meaning of a formula, and where it comes from, than to learn the formula by heart. It is more important to do an experiment oneself than to practise carrying out routine instructions. It is more important to discuss several rival answers to a question, and learn that there may be more than one 'right answer', than to follow a training in procedure without really understanding it.

Practical Work: Class Experiments

A very strong influence in young people's understanding of science and scientific work is their own experimental work. Professional scientists devise their own experiments, meeting difficulties as well as successes, trying things out with a watchful eye and a critical mind, more often making short notes than writing a long formal report. Our pupils can do the same, with both understanding and delight, if we give them opportunity and plenty of time. They need this personal experience of science. For that, they need time and encouragement; but not too much detailed instruction, because they need to feel that it is their own experiment and to learn by their mistakes as well as their successes. Then they can acquire the feeling of doing science, of being a scientist – 'a scientist for the day'. They feel the thrill of being a detective – not only finding the clues, but doing their own reasoning from them and even assessing their reliability.

Physics of Today

Young people today hear a lot of scientific talk about satellites, of atoms and electrons, of radioactivity, etc., and we have a duty to meet this interest in our physics. We can accept their awareness of these things and build upon them.

Theory

Towards the end of the course, when reasoning and the beginning of informed philosophical thinking come naturally into play, there should be examples of theory taking its place in science. Curiously enough, it is often in doing his own experiment that a young scientist first finds for himself the importance of theory. We should encourage pupils to look *at* their evidence as well as looking *for* it; and to ask whether it is reliable and how they know how reliable. Finally they should ask themselves how they are interpreting their own evidence. They should see science building knowledge by 'models', with imaginative thinking taking part. In general, they should learn to question and not to take for granted so much that claims to be scientific.

The Five Years

In the early stages, Years I and II, children will be making acquaintance with phenomena in the physical world; a stage of seeing and doing, without formal note-taking and without expressing the results in formal statements. Then, in Years III and IV, there should be a stage of more organized investigation and learning, with intriguing questions to provoke thinking. Towards the end of the course, in Year V, the part played by theory in making a grand scheme of knowledge can be explored overtly and shown to be a proper part of scientific work. Thus science will appear to be much more than just the acquisition of facts, or a scheme for giving a set of right answers; but rather something for the intellect, making demands on every boy and girl at the best level for his or her abilities.

Extensions

Our course does not branch out into options, which might lead to difficulties both in administration and in examination arrangements; but we do wish to encourage special studies and extensions of teaching where there are special interests. We hope that every good teacher will develop ideas of his own, and sometimes follow some particular limb which interests him or his pupils, even though it diverges from the main branch of our tree. Such excursions along small branches often find scope for stimulating teaching at its very best. From time to time in this *Guide* there will be suggestions of possible extensions.

The main tree – the general framework of the course – is suggested for all, because it is designed to build connected knowledge.

However, the course is not intended to be stereotyped or an invariable scheme for teaching, offered insistently as a whole. We do not insist that our course has a unique structure that makes it best of all; and yet it does have a structure – the result of much careful thought and planning – which will play an essential part in achieving our aims. For that reason, we hope that teachers who wish to derive full benefit from our programme will, in the main, let the suggested structure be their guide – at least until they have seen the full interplay of concepts and attitudes through successive years. On a later round a wise teacher who has tried our scheme and seen its strong points and weaknesses will branch out with his own choices.

Teaching for Understanding: Use of this Guide

Since we hope to teach for understanding, success will depend not on the exact choice of content in the course so much as on the spirit engendered. Pupils themselves must find that physics is an interesting business of genuine finding out, of doing one's own experiments and one's own thinking, and arguing as well as learning what the teacher tells them. This spirit may need a complete change in our method and attitude to teaching; and for this reason we offer a *Teachers' Guide* that gives a profusion of commentary and suggestions. We hope that each teacher will select from it those things that he finds useful in planning and running the course. This *Guide* is offered, therefore, not as something to be followed rigidly in detail, but as something that offers help in giving pupils a good sense of science as creative knowledge.

A more detailed discussion of the aim of teaching for understanding is offered in Appendix I to the General Introduction (page 64).

Examinations

It would be useless to teach for understanding and then give examinations that ask for memorized definitions and formal calculations. Both pupils and teachers would encounter disaster. For example, the following question would show pupils that our intentions had not changed:

1. *a.* State an expression for the distance, s, travelled from rest in time t by an object moving with constant acceleration a. *b.* How far will an electric light bulb fall from rest in 10 seconds?

Whatever the teacher told them, intelligent pupils would revise the formulae the night before the examination. Instead of that we can move a little closer to the kind of examination questions typified by:

'PLEASE ANSWER THE QUESTIONS BELOW ON THE EXAMINATION PAPER ITSELF.

1. *a.* In the expression $s=ut+\frac{1}{2}at^2$,
   (i) What does u stand for?
   [... 2 lines for answer ...]
   (ii) What does ut tell us?
   [... 2 lines for answer ...]
   (iii) Explain why the $\frac{1}{2}$ is there.
   [... Three lines for answer ...]
   b. If you used this expression for the free fall of an electric light bulb dropped from rest, you could expect it to predict quite well the distance fallen in 1 or 2 seconds. But if you used the expression for a 10-second fall, the prediction would disagree seriously with a test by experiment. Suggest why.
   [... Five lines for answer ...]
   c. What kind of motion would you expect for the bulb after 10 or 20 seconds of fall? Why?'
   [... Six lines for answer ...]

This set of questions asks about physics, and the answers will enable the examiner to find out whether the pupil understands the physics of the 'formula': its origin, meaning and use. Further specimen questions, together with a consideration of some of the problems of examining a course of this kind, are to be found in Appendix II (page 79).

External Examinations

We are fully aware of the importance of external examinations at the end of our five-year course. In addition they play a very important part in pupils' careers. Whether we like it or not, they have a strong influence on pupils' attitude to any teaching programme and they necessarily modify our teaching. In fact, even the most wonderful teaching programme that we could imagine would be largely spoiled within a few years if it had to be tied to examinations that did not fit its methods or spirit.

So we were very glad to be able to announce in Spring 1964 that, as a result of our discussions with the Secretaries of the Examining Boards and the Secondary Schools Examination Council, a special set of alternative papers for pupils involved in our trial programme would be set by all the Boards cooperating in examining our pupils. The Foundation was able to circulate the following announcement:

> The nine University Examining Boards have asked us to make it known that they have unanimously agreed to cooperate in setting special alternative papers for the pupils involved in the trial programme who would normally be taking O-level in the summer of 1965 or 1966, and have indicated to us their determination to insure that the interests of these candidates will not be jeopardized in any way. These special examination arrangements in the three science subjects also have the full approval and backing of the Secondary Schools Examination Council.

Following this agreement, examining in physics was placed in the hands of the Oxford and Cambridge Schools Examination Board, in cooperation with other Boards. The first examination papers were set by that Board and distributed to all other Boards who sent them to schools so that candidates could take the examination under their usual Board.

The Examination Board and the S.S.E.C. accepted the full Nuffield *Teachers' Guide* (Years I, II, III, IV, and V) *in lieu of a syllabus* and agreed that the Examiners should endeavour to frame the examination in conformity with the suggestions in the *Guide*. This arrangement is necessarily experimental, but we have every confidence that Boards will continue to provide good examinations for our project.

Examinations and their Relation to the Style of Teaching

We hope that the external examinations in future years will continue to do justice to our programme, to both its syllabus selection and its style of teaching.

In that case, a pupil's chance of success in 'Nuffield' type physics examinations will depend on the way he has done experiments in the laboratory and learned his physics by working on constructive problems – rather than on his memory of formal material revised just before the examination. A school which tries our programme along the lines suggested and carries its pupils through Years I, II, III, IV and V (or at least through III, IV, V) in the spirit of these *Guides*, should consider its candidates have as good a chance as they would have had after a traditional course in a traditional examination. However, schools sometimes find a special need to shorten their programme or let pupils enter a special programme like ours for a shorter time, and in such cases we must give a strong warning that such pupils may be at a disadvantage when they come to sit external examinations based on the full five-year course. We do not boast that pupils cannot be coached with some success for 'Nuffield' type exams; but we are sure that the value of coaching is far smaller for such examinations – or rather for the kind of results they expect – than for traditional examinations.

We are seeking in our teaching to give pupils an understanding of science of lasting value; and examinations that do justice to that aim will ask more informal, but more penetrating questions. Furthermore some of the marking of such examinations needs to be done in a rather different way. For example if examiners constructed a model answer beforehand they might find it necessary to broaden it. If a certain formal statement is required for some part of the marks, pupils who have worked hard at our programme may well fail to give it in proper words. If, on the other hand, an informal description is asked for, with the aim of finding out whether pupils understand what has been done, examiners will find themselves reading the answers with flexible judgement and imagination – although they must still exercise the discipline of firmly requiring good knowledge.

This discussion of the examinations ahead of our pupils offers both the necessary assurance which teachers need if they are to take on this different kind of teaching, and a warning to schools that it is not wise to take on only a fractional version of our programme.

Homework Problems

Questions for homework or for discussion in class can play a very important part in a course that aims at understanding. Instead of setting a question after everything has been done and explained, we can encourage thinking and active learning by setting a suitable question *before* or during the development of a topic. Then the question becomes part of our teaching – or rather of the pupils' learning. That is why some questions are printed in the *Teachers' Guide*. These are offered as suggestions and samples. We hope teachers will try using those questions, or similar ones that they construct, as introductions, stimulants, and sometimes continuations in the teaching of a topic. These specimens are not necessarily placed at the right point in the *Guides*: in many cases a question should be given considerably earlier, as a preface to teaching.

A large collection of questions is provided in separate booklets. We hope that teachers will enjoy devising more questions of this kind. In marking answers to such questions, one should remember their objectives: to encourage thinking and to test general understanding. One needs to be very flexible in accepting unusual answers and ready with praise for sensible thinking even if the result is not technically correct.

Vague Questions and Rough Estimates

Although of course we shall ask for some of the calculations characteristic of good physics, we should also encourage pupils to write general accounts of experiments, to make critical comments on experiments, and sometimes to make rough guesses. Many a pupil grows up through school years and arrives at the university or outside life with the conviction that physics only deals with very precise measurements. A professional physicist has to make many rough guesses. It is the essence of his scientific skill to make those guesses as well as he possibly can and to know something about their roughness. Therefore teachers will find suggestions from time to time of rough experiments or rough guesses; and we hope they will put them before pupils as good science, and not as sloppy thinking. To encourage teachers who feel doubtful about such rough guesses, we quote from a letter written by Professor Philip Morrison of Cornell University concerning 'Fermi Questions':‡

> ... It is by no means possible to specify the training and readiness of a prospective graduate student by a mere list of topics. There is a kind of power over the theoretical and experimental studies in which he has engaged which is difficult to define, but whose presence is perhaps more important than much knowledge which

‡ From a letter from Professor Philip Morrison, in *American Journal of Physics*.

is more formal and complete. There is one test for such power which is at the same time a remarkably apt method for its development. That is the estimation of rough but quantitative answers to unexpected questions about many aspects of the natural world. The method was the common and frequently amusing practice of Enrico Fermi, perhaps the most widely creative physicist of our times. Fermi delighted to think up and at once to discuss and to answer questions which drew upon deep understanding of the world, upon everyday experience, and upon the ability to make rough approximations, inspired guesses, and statistical estimates from very little data. A few samples are indispensable:

How much does a *watch* gain or lose when carried up a mountain?

How many piano tuners are there in the city of Chicago? (These are authentic Fermi questions from the source.)

A few more of Fermi type:

What is the photon flux at the eye from a faint visible star?

How far can a crow fly?

How many atoms could be reasonably claimed to belong to the jurisdiction of the United States?

What is the output power of a firefly, a French horn, an earthquake?

Such questions can of course be found for nearly any level of education. It should go without saying that no such question fulfils its purpose unless it is being heard for the first time. The accumulation of confidence and skill which such answers bring is a very good apprenticeship to research. Indeed, the conception of experiments and the formation of theoretical hypotheses are activities which are well simulated by asking and answering good Fermi questions.

Class Experiments

If the young pupil does his own experiment, and really considers it his own, pride and interest will help him to learn much from it. It is difficult for an experienced physicist to restrain his natural impulse to teach clearly, to show pupils what to do, to put a mistake right or to hasten on some pupil who has paused to think. We are used to getting pupils through the experiment by the end of the period. Yet in this course, doing one experiment on his own is worth more – in understanding science – than five done quickly under efficient guidance.

And a pupil's own notes, written informally like the notebooks of most research men, will keep him nearer to real science than formal writing up of each experiment. The pupil himself gains little from a 'list of apparatus used' – an artificial formality that must seem as strange to a child as it does to a research scientist – or from meticulous drawings that take a disproportionate amount of time and interest for their ruling and colouring. We hope that teachers will encourage pupils to keep notebooks of short (but fairly neat) notes of their own work. Then, as a real diary of their work as a scientist, the book will be one to be kept and treasured.

In the early years, some experiments can well be done without making notes: they are things to do and see, and we should no more ask for notes after the experiment than we do after a visit to the circus. Certainly the circus visit if it is 'written-up' cannot lead to a formal conclusion, except perhaps that 'we enjoyed it'; and in some experiments a formal conclusion would be equally out of place.

Our main hope is that teachers will encourage children to work on their own, to meet their own difficulties, to enjoy making the apparatus work and finding things out for themselves. Discussion *after* the experiment should look for outcomes, perhaps general rules, and suggestions for new experiments; but treatment of errors, and arguments about accuracy, should not burden the earlier years. Given a good start, pupils will enjoy small doses of those discussions in later years.

And we hope teachers will avoid giving away the answer that is being looked for. Far from that they may need to praise an unexpected answer which, though not wholly true, is the result of serious work.

So we hope that teachers will somehow remain as silent as possible in class experiments, and resist temptations to prepare or to explain. One should reflect: 'Whose experiment is this, mine or the children's? What kind of success will do lasting good? Their success in doing a few things on their own, or their success in following through many directions?' Two difficulties will arise:

a. Faster pupils may run far ahead of slower ones. We must have good questions or suggestions ready that will lead them on to further experiments – usually new ones rather than a more accurate repetition of the one they have done. Such 'buffer experiments' will play an important part.

For a slow pupil, however, repetition by his own request may be very valuable since it is done with a newly gained understanding as backing. We may even encourage that occasionally: 'Knowing what you now know, how long would it take you to do that again really well?'

b. Lazy pupils will get little done. This is a difficulty feared more by critics beforehand than by teachers in trials. In practice, teachers find this happens more rarely than they expected – perhaps that is because an open laboratory without much direction offers a wide range of opportunity. And, in theory, we ask: 'Does it matter? What is the lasting gain for a pupil driven through an experiment efficiently?' Most of our experiments are intended to give pupils experience as scientists rather than technical training. To gain such experience, a pupil needs some drive from within – which an open laboratory can encourage. A teacher's skilful drive from without may carry the lazy fellow through an experiment, but it may well fail to contribute to his understanding of science.

Logical Order

Children are not logical in their learning. They will not thank us for strict logic in building our teaching order and in providing experimental checks before each new step. That is what we should perhaps do in the sixth form and must do in university physics; but here we want to build some understanding rather than puzzle our pupils with formal requirements.

We are concerned with what the pupil actually learns and knows and understands rather than fulfilling our own needs of proper logic in building sound science. We must of course build sound science as far as we can, but we should accept the limitations of pupils' viewpoint and skills and make the best of them.

So in early years we shall let pupils learn by gaining increasing acquaintance with concepts and instruments, rather than insist on waiting for full preparation in knowledge or skill. Then in later years we can reinforce the informal knowledge the child has built by further experimental tests and a more reasoned discussion.

For example we shall treat atoms as familiar things from the beginning and encourage children to learn more about them; but we shall maintain a warning flag by asking again and again in the early years: 'How do you know there are atoms? How do you know how small they are? ... Did that experiment tell you for certain, or did you have to make a risky guess (assumption) in it?'

Good scientists know a lot about their own limits of knowledge. We should talk to children as one scientist to another: not often with logical formal discussion, but always the lively talk of one expert sharing his interest with a neighbour.

The Work of Teaching in this Programme

All this takes extra time, practising experiments as well as teaching classes, and reading the descriptions that pupils write. This is the burden of a programme of teaching for understanding. It is an extra burden on teachers carrying out a first trial in a school.

We hope this burden can be eased by enabling teachers who are interested in our programme to attend special in-service courses. Such courses could help to familiarize them in advance with the new material and the teaching approach which is recommended. During the development of the Project, the Foundation provided in-service courses of this kind for teachers in the trial schools in association with the Department of Education and Science: the experience so gained will, it is hoped, help to set the pattern for the future. The agencies normally concerned with in-service training, and notably the Schools Council, have shown great willingness to meet the continuing demand, and there is good reason to believe that any teacher wishing to attend a special course will have little difficulty in doing so.

Following the Programme

Teachers will ask whether it is intended that the programme given in these *Guides* should be followed exactly. 'Of course not. This is a suggested programme, and we hope that teachers will make choices and modifications as they think best. We do not claim our programme is ideal though we have tried to make a connected scheme – and on the latter count, we hope teachers will consider trying out our scheme in our suggested form, before making modifications which might break up the connections unexpectedly.'

From our experience in preliminary trials it is clear that teachers view the nature of a Year of this course quite differently in retrospect at the end of the year from their plans and pictures at earlier stages. Many insist that on a second round they wish to follow the programme again in essentially the same form, using their experience to modify the amounts of emphasis and proportions of time, to teach for still greater benefits and fuller coverage. Judging from their report, we think that a teacher embarking on our programme would be very wise to try it first in the form we suggest; then again in our form for a second round modified by experience; and then in a third round he should start to make modifications to his heart's content, with the full knowledge of possibilities.

In suggesting that, we are not boasting that our programme is ideal or unique but only reminding teachers that it is the outcome of considerable work in building a connected scheme whose structure becomes more fully apparent as one teaches one's way through it.

We hope that teachers who know our programme well will make their own modifications. But we do plead with newcomers to examine the structure of the programme carefully first. We believe that it is an organism rather than a collection of separate items. As one commentator puts it: 'If you chop pieces out of it, it bleeds.' As an organism, a connected scheme of living teaching, we hand it on to teachers with great hopes. But its vitality and promise must then rest in their hands.

GENERAL TEACHING NOTES

NOTE ON PREPARATION OF EXPERIMENTS BY TEACHERS

Physics is an art as well as a science: an art of understanding nature and conveying that understanding to fellow men. We share with other arts the activities of mind and spirit concerned with creative understanding – extending knowledge beyond the storing-up of factual material. Like artists in many other fields, we not only practise our art but teach its practice to others. A physicist has to conduct an 'art' school for the next generation. He provides information and gives some training in techniques, but above all he encourages young students to practise art themselves, at the same time freely and subject to his critical eye. By his interaction with what they do, he hands on his own heritage to their generation.

No teacher in an art school would show a new technique or set students to work on a new problem without first trying the work through himself. It is not that he does not already know enough to imagine what will happen; nor is it that he must carry out the work for his students and let them learn either vicariously or by copying him. It is that in his close interaction with students, when they are learning by their own efforts, his comments must be guided by his firsthand experience of their medium.

For example: imagine an artist about to give his class a new kind of oil paint that has just been delivered to his art school. He will try some painting alone the night before, so that, when he works with his students, he can deal with troubles of techniques and know when he can maintain a safe silence. Yet we as physicists, with our wide and varied experience both of experimenting and of teaching, often take a risk over new apparatus, and trust that young pupils working with it will either succeed or bring us troubles that we can solve immediately. There we may fall below the level of the wise art teacher, who practises each technique, not for the sake of issuing detailed instructions but rather for the opposite purpose of being able to leave students alone while yet encouraging progress.

In the Nuffield Physics programme there are a number of experiments and kits of apparatus that are similar to ones now in use – after all Physics is Physics – but they come in unfamiliar form and may be put to a different use. For the sake of good teaching and a fair trial of our apparatus, we urge every teacher to try out the experiments privately beforehand, treating things as a pupil would. The simpler the apparatus the more important that is. Here are some examples:

Example A: Oil Molecule Estimate (Year I). The class experiment of estimating the size of an oil molecule sounds fairly simple, and a quick, rough trial may confirm that impression. Yet a cautious teacher who tries that experiment through several times in succession will discover interesting troubles – as well as finding how easy it is to misjudge the size of a small drop and obtain widely varying estimates. No amount of printed warnings to see that the tray is cleaned or suggestions of what to say if a child finds leakage round his boom can ensure a proud, successful class experiment as those previous trials will.

Example B: Electric Circuit Board Kit and Electromagnetic Kit (Years II, III, IV). Teachers will find that these kits provide for simple familiar experiments; and yet, if one tries them oneself, one discovers the answer to small unexpected difficulties – it is often more important to know those for the sake of silence than for the sake of a quick putting things right, since we want children to solve their own problems.

Example C: Fine Beam Tube (Years II, IV, V). The fine beam tube deserves some apprenticeship. One rehearsal will enable a teacher to operate it properly; and yet a further playing with it will yield a skilful familiarity that enables the teacher to bend the electrons confidently to his will and give a very valuable demonstration. The pupils should share the teacher's delight in this wonderful experiment, rather than sense the anxious feeling that any of us have when demonstrating a tricky and unfamiliar piece of apparatus in a half-dark room.

Example D: Rays and Images (Year III). Where the apparatus carries with it the suggestion of a new approach, trying it out beforehand is even more important; to clear the ground for the teacher to proceed happily along the new line.

It might seem safe enough to ask the pupils to get out lamp boxes, slits and cylindrical lenses, and then to play with them on a white sheet of paper in a half-dark room. True, pupils will learn some things about lenses but they will only accumulate an undirected collection of information, some of it difficult to interpret. If, before teaching the first class with this apparatus, the teacher spends some time trying it out, both with his own expert knowledge of optics as a background and with the attitude (if he can manufacture it) of a young beginner, he will discover a great deal more than just helpful hints. He will find how to guide the experimenting through to valuable results that will build a knowledge of optics. Reading printed commentary or instructions will not do that; nor will memory of one's own past experiences provide the close contact and special knowledge that are needed here. This particular group of experiments needs even more extensive trial beforehand. A first quick look at a pinhole camera or at cylindrical lenses and rays will give an impression that the whole group of experiments is easy but vague and unproductive. Only if one follows through the instructions in the detailed way that we ask of pupils can one discover their potentialities as well as their minor difficulties. For example: The change from the traditional three slits to a comb of many slits will alone make a major change in pupils' learning.

D (i) Pinhole Camera. For example, trying out the pinhole camera in the actual room to be used with the object lamps placed as they will be for pupils, enables one to find where to stand and how to slide the lens across to achieve the full delight of collecting all the little images into one bright image. (That does not mean that one should then drill the pupils into standing in the right place and using the lens in the right way at the first trial; but it does mean that one is ready to arrange things to go well.)

D (ii) Fan of Ray Streaks. Again, with the first experiment of a fan of rays hitting a strong cylindrical lens, if one has tried the experiment one is ready to guide a pupil into treating the aberration of the outer rays as a minor 'disease' – and to say casually, 'Is it the same if you turn the (plano-convex) lens the other way round?' And one is ready to tell another pupil that he will see a clearer story if he twists his lens until it is 'perpendicular to the rays'.

D (iii) Telescope Ray Model. And again, when a teacher has set up a three-ray model with two lamps as objects to show a simple telescope he knows how to get students to try it fairly quickly, as a side issue from using the real telescope; and when the model shows the obvious 'eye-ring' he is ready to say: 'Yes. Now go back to your real telescope and see it happening there.'

Laboratory Organization

Cafeteria Tables. In managing many of our experiments provision has to be made for pupils to draw upon extra apparatus when necessary. Experience has shown that this is best done by placing that apparatus ready on a side bench. Pupils can then help themselves to the items, use them and then return them.

This method is of great help in, e.g., work with the Worcester Circuit Boards (Year II), ripple tanks (Year III), the ray streaks (Year III).

Safety Screens. Whenever the teacher has to give a demonstration with something made of glass which might shatter and hurt him or the class, we recommend a pair of large 'safety sheets' of Perspex. The sheet between the teacher and the apparatus should be 36 inches high by 24 inches wide. This is not so wide that he cannot reach his arms round from behind and manipulate the apparatus; and this is high enough to shield his face. The sheet between the apparatus and the class should be 30 inches square.

These sheets (of $\frac{3}{16}$ inch Perspex) should on no account be framed for that would spoil the feeling of full transparency: they could well be supported by pairs of slotted bases.

NUFFIELD CHEMISTRY AND NUFFIELD PHYSICS PROGRAMMES

Coordination between the Programmes

We want our Physics programme to fit closely with the Nuffield Chemistry programme, so that the two play complementary parts in the teaching of pupils. Needless to say our colleagues share that wish. We have held extensive discussions with them and are in gratifying agreement on general principles and approaches to our science teaching. We hope that the two courses will be taught together with great profit. However, in their present form the two courses show some overlaps and some differences in order of attack which will need recognition.

Energy

Physics and chemistry both place great importance on early teaching of the concept of energy and subsequent use of it as a binding thread throughout later stages. But the chief aspect of energy chosen for emphasis in the introductory stages differs in the two courses.

In chemistry, the first form of energy to be discussed and measured is thermal energy; and this is so important in modern chemistry teaching that heat will be the primary form of energy in that approach with mechanical forms appearing subsequently. In later stages, of course, mechanical and electrical forms of energy and their interchanges take on full importance; but the teaching will lead into these from heat. After the general discussion of Conservation of Energy in Year IV of the physics programme, it is taken for granted that mechanical and electrical energy are forms of the same thing as heat: i.e., conservation of energy is assumed as a commonplace fact.

In physics, we introduce energy very early as something which has to be exchanged – brought in from some fuel – when a 'useful' job is done. That brings us to mechanical forms, the energy stored in a stretched spring and energy-of-motion. The idea of potential energy is extended from the stretched spring to storing energy in the gravitational field – 'like stretching a giant spring attached to the Earth'. Interchanges between these (mechanical) forms of energy each involve a force moving through a distance and we choose (force) × (distance) as a measure of the transfer of energy from one form to another. We call that product 'work', but we do not use 'work' as a name for a form of energy. Instead we say it is a useful measurement that shows the transfer of energy FROM one form TO another form – rather like a cheque showing transfer of money FROM one account TO another. (See General Note on 'Work'.)

Keeping track of energy changes by amounts of work, we find by experiment that simple machines such as levers and pulley systems do not manufacture energy but only transmit the input-energy to the output (minus a tax for friction, etc.). Thus mechanical forms of energy appear as the primary ones, measured in work units, such as foot.pounds-weight or newton.metres. At a much later stage, when we have shown that $\frac{1}{2}mv^2$ is a measure of kinetic energy, and the idea of conservation laws has been introduced, we discuss Conservation of Energy in its broad form by reviewing experimental measurements of exchanges between heat and other forms. From a great *variety* of measurements – different forms of apparatus, different types of interchange – we see the evidence piling up to point cogently towards universal conservation. We then adopt conservation as valid and use it from then on. We even suggest that it is such a useful principle that we shall maintain it by installing still more forms of energy if necessary.

Since, in our Nuffield Physics Course, we do not take energy conservation for granted until we present general experimental support, we cannot take heat as our primary form of energy in the early stages. We certainly should not measure heat in joules to begin with – that would be like calling the defendant 'the murderer' before the case is proved. Instead, we measure heat in the traditional way, by giving it to water and multiplying mass of water by temperature rise. (In practice, of course, we, as modern physicists, use electrical heating in calorimetry. We do one experiment with water to calibrate our heater and then avoid messy methods with water.) That provides a system of thermal measurements for our review in Year IV.

However, in our early teaching we again and again meet energy changes that lead to some heat and leave the balance-sheet unbalanced unless we call heat a form of energy. So we mention heat as something that appears sometimes in the place of mechanical energy: but we try to keep a warning flag flying in the minds of both teacher and pupils, to say that treating heat as a form of energy, with the total as always constant, is something still to be proved. In practice this leads to little difficulty, since our main concern is with mechanical energy in the early Years.

The Philosophical Question

Behind the difference between these two approaches lies a philosophical question: should we take conservation of energy completely for granted – as both teachers and children assume conservation of mass – or should we develop it as a great generalization backed up by experiment?

The former view enables the teaching to speed ahead to new studies, and it is a very tempting one in teaching many fields outside physics – fields where there are great new developments to be covered and attempts to justify energy conservation look like delving into old history.

The latter view is held by many a physicist who feels that young people should see the experimental basis of his science, of laws that range from a simple law of levers (which only the Greeks thought could be proved by geometry) to conservation of momentum and conservation of energy and on to rules of quantum mechanics.

Perhaps each view has a proper place in science teaching; the complete assumption in studies outside physics, and the full enquiry inside physics. We find on analysis many examples of similar differences of treatment. A physicist, busy teaching some part of his field, is more than willing to compress the chemical aspect of his story into a compact statement that a wise chemist would wish to expand and justify in his teaching. And thus these differences may lead to a useful division of labour in which each teacher expands and discusses things that are quite wisely taken for granted by colleagues in a neighbouring field.

Nevertheless this difference of approach to energy is not trivial. On one view, experiments like those of Joule or Callendar and Barnes are simply attempts to measure the specific heat of water (in joules per kg.C°). Then a single good method should suffice in teaching, as typical. On the other view the whole gamut of 'Joule' experiments is to be described in our teaching as the foundation for a powerful generalization.

Summary: The Present Position

To sum up, the present position is this: in Year IV our 'Court of Enquiry' effects a synthesis of the energy-teaching in our chemistry and physics programmes. Until then, in chemistry, attention is focused largely on heat as the primary, measured, form of energy;

whereas in physics mechanical forms are introduced as primary – with interchanges measured by work – and heat starts as a subsidiary form, whose full membership in the energy family remains in question for some time. Before Year IV, heat is measured in kilocalories and mechanical energy is measured in work units, such as joules.

But after Year IV's discussion, *all* forms of energy, as we now know them, are regarded as forms of the same thing, and all are to be measured in the same units, joules.‡

‡ In chemistry units of 4·180 joules are sometimes used. This is the 'defined' kilocalorie.

NOTE TO TEACHERS
ON THE ROLE OF THE WORD CONSTANT IN SCIENCE

Young pupils think of science as consisting of doing exciting things and finding out knowledge. Older scientists are also concerned with extracting rules or laws to codify the things that have been found out. That activity of generalizing, arriving at some law after a variety of experiments or observations, seems to be a very important thing in human intellectual growth; and yet it seems strange and difficult to young pupils if we put it to them too early as an essential characteristic of science. (Of course there are other essential characteristics which carry science beyond any catalogue of laws or principles, into a structure of theory in which both experimental knowledge and imaginative thinking are woven together.)

Yet young children *do* have to generalize: they do that when they are first learning language, acquiring names for general classes, such as 'dog' over and above all individual dogs. They carry that farther and when they name abstract qualities, and thus proceed to the abstract thinking which plays such an important part in man's intellectual activities. Children *do* generalize: from noticing many lawns they say 'grass is always green', and then they just say 'green grass'.

The constancies among natural events are a protection against hopeless insecurity. If all nature behaved differently from day to day, our complex rational life would be impossible. So a child's seeking, and remembering, of what is 'natural' and 'constant' is a necessary part of sane mental development. It is also a beginning of science. Adult scientists are more formal still. They do not say '$p.V$ is always constant'; or 'constant $p.V$'; but they state Boyle's Law in a much fuller way. Nevertheless, the word 'constant' is the key to the nature of the law.

If we ourselves reflect on the laws of physics we find that many of them contain the word 'constant' or its equivalent; and most of the others can be reworded to contain that word. In fact one could almost claim that every law, in physics, chemistry, biology, and perhaps even in other fields, can be stated with the word 'constant' as the essential word. That is one of our great activities in science, to look for constancy, to look for events, or characteristics of events, that repeat, always giving the same answer in the same circumstances. (We should not claim that such repeatability is a characteristic of all scientific knowledge. The island of Krakatoa has only blown up once. It is unlikely to blow up again like that, and the events would not be the same if it did. Yet we have a great deal of scientific knowledge concerned with that eruption.)

We should not try to give young pupils every law with an insistent word 'constant' in it. But we should remember to give importance to that word and to the idea it represents. We can say that [stress/strain] is constant; [force/acceleration] is constant; then we can expand into [total momentum] is constant and [total energy] is constant. In those latter 'conservation laws' the idea of *constancy* is just as important as the concept of *momentum* or *energy* – in fact it is chiefly because we find constancy that we bother to find a name for the concept.

Once we know that the total of something that we can measure or calculate remains constant throughout all vicissitudes, we have a very powerful tool for predicting, for keeping track and account-keeping, for increasing our understanding of nature. No wonder the conservation laws are very important, and when we change our science very fruitful. (For example in developing Special Relativity, the conservation of momentum is assumed as an axiomatic starting point to enable the concept of mass to be modified to a new form.)

With young pupils we should not surround the conservation laws with heavy mysterious insistence, but we should praise them, saying: 'The total stays the same through thick and thin; and that will help you to keep track of things in experiments, in engineering, and in understanding things in the world.'

Essentially, our seeking of constancy in our study of the natural world is the same as a young child's seeking of security by cataloguing the things in his environment that stay the same or repeat in the same way.

NOTE TO TEACHERS ON 'WORK': YEARS I, II, IV

In this programme, we propose to return to an old-fashioned use of the name 'work' in physics: work calculated by multiplying [force] by [distance] as a statement of the *amount of energy transferred* from one form or place to another. We shall not use 'work' as a name for a type of energy itself. We shall *not* use it as a rough name for mechanical energy.

If we think of energy as analogous to money, then work is not analogous to some cash but to a bank cheque which measures a transfer of money from one account to another.

In ordinary talk, most scientists today use the word 'work' loosely for mechanical energy and more precisely for the gain or loss in potential energy or kinetic energy, particularly in those cases where the change can be measured by [force] multiplied by [distance]. Then, finding plus and minus signs rather dangerous, they distinguish between opposite changes by talking about 'work done by' and 'work done on, or against'. Though we may feel sure *we* shall never make a mistake between those two opposites, quite good pupils often get confused. (Try asking a capable young physicist whether the 'work' involved in a certain part of a hysteresis cycle is work done *by* the magnetic field or work done *on* it. Try asking about a particle in water in a centrifuge tube, as it moves out. Is work being done *by* or *against* centrifugal force? When the current in a coil of wire is increasing, is work being done *by* or *against* the induced e.m.f.?) So long as work means a definite chunk of energy, any question between work done *by* and work done *on* is a very serious one – we are asking which side of the balance-sheet the item should go to.

We are anxious to avoid distortions. Some pupils look upon a calculated piece of work as a specially respectable chunk of energy, while energy changes that cannot be measured as work (or are too inaccessible for easy measurement) seem inferior. And some pupils concentrate so strongly on the output form of energy in a transfer that they forget to mention the energy form in the original supply; and then they almost say by mistake that energy is being manufactured. (Example: We lift 10 pounds to a shelf 5 feet higher and say, the work is 50 foot.pounds. That is true, but we then say, 'That means there is a gain of potential energy of 50 foot.pounds.' That also is true, but it is only half the story. We should add: 'And there is a loss of chemical energy in our muscles of 50 foot.pounds.') These troubles can be avoided by careful teaching, but since we are making a new programme, we wish to suggest a treatment that applies generally and easily and is much more fully proof against mistakes. If we say, 'Work *is* a force multiplied by distance (in the direction of force) – that is our definition' then we can say, after illustrating and describing the various types of energy change, that we are going to use work as our way of stating *how much energy has been shifted* FROM one form TO another.

Calculating work by [force] × [distance] arises naturally at the very beginning when we raise loads and measure what it has cost us in foot.pounds. Then whenever we calculate [force] multiplied by [distance], we call it 'work', we say 'This work is the amount of energy changed FROM such and such form TO such and such other form.'

For example, a 10 kilogram lump of lead, pulled by the Earth with a force of 98 newtons, falls freely 3 metres downward. The work, [force] × [distance], involved in this is 294 newton-metres or 294 joules. That is the transfer of energy FROM gravitational potential energy TO kinetic energy. With beginners, we should *not* use such formal wording; but we should use FROM and TO in this way.

If this emphasis on transfer from one form to another makes us seem to deal only with *changes* of energy, we ought not to be sorry – since that gives a strong reminder of conservation. And our colleagues in the Nuffield Chemistry Project will be glad.

Example

As an example of the treatment we suggest, consider the following questions and answers:

Question (1). A boy throws a cricket ball up into the air and it finally lands on the ground. Describe the energy changes.

Answer. *As he throws the ball*: FROM chemical energy (in his muscles) TO kinetic energy of the moving ball (+ some waste heat in his body).

As the ball moves slower and slower upward: FROM kinetic energy TO gravitational potential energy.

As the ball falls again: FROM gravitational potential energy TO kinetic energy.

When the ball arrives: FROM kinetic energy TO heat.

Question (2). In throwing the ball, the boy exerts a force of 40 newtons while he shoves the ball $\frac{1}{2}$ metre. How fast is the ball moving? How far will it travel in ....?

Answer. We can say: The work involved is 20 joules – never mind about *on* or *by* – and the energy transfer is 20 joules FROM chemical energy TO kinetic energy thus. Then we can calculate how fast or how far, for the ball.

(Quite apart from a 10 per cent error because we forgot that the boy was also lifting the ball, this is a poor examination question because it asks for formula-using calculations from invented, inaccessible, data; yet we should discuss some changes like this in class.)

Electrical Changes of Energy

Much later when we come to potential differences in electric circuits, we can say the p.d. is the energy transfer, per coulomb charge, FROM electrical form TO mechanical or thermal form. We can clarify e.m.f., at least in our own minds, by saying e.m.f. is the energy transfer, per coulomb, FROM mechanical or chemical form TO electrical form. We can always say clearly which way the energy goes without bothering about *work done by* or *work done on*.‡

Change to a New View

To pupils or teachers who say they have already learnt that work is energy and complain about the new view, we say: 'Think of a cheque that is used to pay a bill. The cheque is not money. It is an instruction to the bank that they shall pay the money *from my account to your account* so the cheque itself is neither plus nor minus. The cheque shows a transfer of money. In the same way "work" shows a measurable transfer of energy.'

Units

If work shows transfer of energy from one form to another, the units used for work must also serve for energy. We shall presently use 'newton-metres', which we name for short 'joules'. We should have some spring balances marked in newtons so that we can then proceed empirically to joules. In our earliest teaching we shall measure work in foot-pounds – just as we must measure pressure in pounds per square inch, because those are familiar units. We would like to be more careful and say, from the start, foot.pounds-

‡ To make the essential idea clear, we have carelessly linked the descriptions above to coulombs without stating the other units. If we use MKS units, the p.d. in volts is the energy transfer, in joules, per coulomb.

weight; but most of us find that that seems pedantically fussy to pupils who see no need for it.

We may be wise to move on to kilogram.metres if only to make the metric system match our start with foot.pounds.

Fuel

In our earliest discussion of energy we should refer to fuel from the beginning, rather than by just describing the mechanical energy got out of machines or by discussing the input and output energies for things like pulleys or levers. When we lift a lump of lead up vertically *it gains* gravitational potential energy (or the gravitational field gains that) but *we lose* some chemical energy. That chemical energy was provided by our food, not directly but in the sense that if we go on doing manual work we need extra food.

If we raise a load by using a petrol engine or a steam engine, or an electric supply driven by a steam engine, fuel is being converted somewhere into less useful stuff. The fuel does not manufacture energy, nor can we say that fuel is energy; but its change into less useful stuff is accompanied by a change of energy from some stored up form to another form. Sometimes that other form is the thing that we desire and say we get from fuel, for example the heat that we put into bath water. More often we value the process of energy transfer rather than the final form of energy. For example, when we drive 50 miles the chemical energy of petrol ends up as low temperature heat which is of no value to motorists.

We should include food with fuel. And we must add sunshine itself as 'free fuel from the Sun'.

NOTE TO TEACHERS
ON CONSERVATION OF ENERGY: YEARS I, II, III, IV

Conservation Laws

Both scientists and young children look for cases of conservation: scientists in order to formulate useful laws to guide their thinking, children to gain a sense of security, to mark something that remains constant in their growing knowledge of nature. (See the Note on Constant.)

Both scientists and young children are apt to take conservation for granted, until they find they have made a mistaken choice. Physicists, chemists and children assume the conservation of electric charge – as Coulomb himself did. Faraday is said to have assumed the conservation of electric current and arrived at his First Law of Electrolysis without ammeters. Some young physicists accept the conservation of $\frac{1}{2}mv^2$ in *any* collision – until they obtain a silly answer for an inelastic event.

In a way, conservation laws for mass, momentum, energy, and electric charge give physics its backbone. They are not entirely statements of experimental knowledge – but contain implicit assumptions and definitions. They are tied to the natural world and do contain experimental knowledge but their *form* is the result of our choice.

Therefore we should feel uncomfortable about letting our pupils take all conservation laws as axioms, or as 'obviously true' premises for deduction, and thus lose some understanding of the quantity that is conserved. And yet we should not crawl through a long series of experimental explorations or tests. Experiments to demonstrate mass-conservation usually look like bungling attempts to verify the obvious. Experiments to show charge-conservation – which scientists still believe in without modification – lose much of their point when we have to apologize for leakage.

Conservation of Momentum

Conservation of momentum, we feel, must be given some experimental demonstration even though our apparatus, not being a completely isolated system, loses some momentum to the rest of the world.

Conservation of Energy

But, above all, conservation of energy has, we feel, a double claim to experimental discussion. *First*, because it is not obvious. It was not obvious to the capable physicists of the eighteenth century. If we now say it is obvious to every schoolboy, we only mean 'obvious' by dogmatic indoctrination.

'. . . Something for Nothing'

If we use the justification 'you cannot get something for nothing' we are only encouraging very cheap, mistaken, logic: we are trying to prove conservation by quoting a catch phrase which states conservation! The phrase is *not* true of other things: you can get any amount of force, pain and quite a lot of other measurable quantities for almost nothing, certainly for payments which do not go in proportion to the amount received. If you calculate the quantity $m\sqrt{v}$ (mass) multiplied by (the square root of velocity), you will find that its sum increases in many inelastic collisions.

General Importance of Conservation: Modern View

Second, the conservation of energy has grown to be so powerful and useful that we now support it at any cost. If necessary, we invent a new form of energy to supplement the balance-sheet and keep it true. We subsidize our conservation principle (perhaps rather like a national egg subsidy to maintain an essential product). Yet we remember the new form is hypothetical and we are prepared to 'pay' for our assumption.

That was the position for a long time of the neutrino, a particle imagined to maintain conservation. In contrast with Greek philosophers, good physicists did not happily incorporate this imagined particle in their sure knowledge but constantly reminded themselves and others that it was a 'necessary invention'. They were the more ready to invent and use this particle because it could be made to carry away not only unaccounted-for energy but also unaccounted-for momentum and spin-momentum. In other words, it fitted consistently into an otherwise incomplete picture. But physicists adopting the neutrino did not wait desperately for experimental confirmation of its existence (which we now have) but proceeded more on the lines of saying: 'Let us *assume* it does exist and then take the consequences. If the picture of nature that this assumption forces us to adopt continues to be easy to work with and fruitful, we shall continue to use it, even if it contains a mysterious particle whose existence is doubtful. Our "mistake", if we are making one, will appear in the properties we find ourselves forced to ascribe to the particle.' Although many a physicist would not admit such an attitude explicitly, it is characteristic of modern physics.

So the conservation of energy has grown far beyond the experimental building of Joule and others, both because it is supported by such a broad spectrum of converging evidence and because we are prepared to maintain it by our own invention and definition if necessary – and take the consequences in the picture of the world that it then enables us to draw.

Of course this philosophical comment is nothing that any of us should teach, in dealing with young pupils. Nor need we all of us agree with it. But it gives the background for our concern over the teaching of energy.

Early Teaching of Energy

We should introduce energy as something very important that we 'get from fuel', that does useful jobs of work for us in raising loads, etc., that can be changed into the form of heat, and so on. In early discussions we shall probably take conservation for granted without pupils (or even teachers) noticing the assumption; but we should not continue to do that all through. If we did, we could not honestly say that the conservation of energy is a great principle in our knowledge of nature. In other sciences, energy conservation will probably be assumed from the beginning to the end; and that places a somewhat stronger moral burden on us to talk about the experimental basis. We should be careful to keep a warning flag flying from the very beginning.

If we want to discuss, or show, experimental evidence, we have three lines of attack:

a. Ideal machines have equal input and output of mechanical energy. (We can 'examine' a lever or a set of perfect pulleys.) The result may be summed up in the form: 'perpetual motion machines always fail'. (See the Note on Perpetual Motion.) When we carry out investigations with a real machine and find that the mechanical energy output is always less than the input, we are led towards the idea that heat may be a form of energy.

b. The total of [calculated potential energy] + [calculated kinetic energy] is constant in conservative (!) systems.

c. We have sound experimental basis for regarding heat as a form of energy.

a. We should certainly deal with simple machines; and, for our introduction of conservation, we might well treat them in ideal form, or nearly so.

b. Conservation of [P.E.+K.E.] should be mentioned (and could be *illustrated* experimentally) but we must not exult over that as a great illustration of the Principle of Conservation of Energy, because we devised $\frac{1}{2}mv^2$ to make that form of conservation true. The expression $\frac{1}{2}mv^2$, which we must use in calculating out any test, is itself derived from [force]$\times$[distance] in a way that necessarily makes it the complement of potential energy in any conservative system.

(Without a definition of 'conservative', the last remark may be meaningless. We mean a system in which K.E. depends on velocity alone, not on position, and P.E. depends on position alone. For most purposes, we can say more simply, 'it is a system where the force is the same on *the way out* as on *the way in*'. That holds for a good spring being compressed and then allowed to expand. Suppose such a spring is inside a cylinder pushing against a frictionless piston which is used to compress the spring. The spring pushes with the same (outward) force, when it has been compressed to some chosen length, whether the piston is moving outward or moving inward.

However that does not hold when there is friction. If the piston moves in the cylinder with appreciable friction, the dragging force exerted by that friction changes its direction so that it always opposes motion. Then, although the spring itself may be perfectly elastic and store up P.E. reversibly, the combination of piston and spring is no longer a 'conservative system'. When the piston is moving inward, the friction-drag on it is outward, added to the push of the spring. And when the piston is moving outward, the friction-drag is inward, opposing the push of the spring, so subtracted from it. So the resultant outward force on the piston differs according to the direction of its motion – it is bigger 'on the way in' than 'on the way out'. In such a case, we see heat being developed during the motion; and, with our knowledge of energy, we do not expect to find P.E. and K.E. maintaining a constant total.)

Another example: we may regard a body sliding on a frictionless hill as a conservative system; but a body sliding on a rough hill is not. We pull the body by a thread parallel to the hill. We make it move *steadily* uphill, or let it move steadily downhill – using gravity and the upward pull of the thread. On a rough hill the thread's pull is greater on the upward journey than on the downward one. Again, an easy test is whether heat is developed.

c. We are left with the great series of nineteenth-century experiments done by Joule and others in which interchanges of electrical energy, chemical energy, thermal energy and mechanical 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. We shall ask pupils to survey that evidence, *not* as an arbitrarily chosen chapter in the history of science, but to show the building of a very important part of science. The many and varied experiments need some description, and then the converging values of 'J' exhibit the evidence. If pupils know beforehand that these are pieces of testimony from difficult experiments, pointing to the guilty victim – a universal constant for 'J', as a symbol for conservation – they will not find this great story confusing.

We must, of course have a different unit for the thermal measurements (most of them done with water) from that used for the mechanical measurements – until 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 will be a series of statements such as '10,000 joules of mechanical energy went in, 8,000 joules of thermal energy appeared and 2,000 must have been lost somewhere, probably as escaping heat'. That description would make the story look lame as well as confusing.

Therefore we shall not get rid of the Calorie as a unit until after we have discussed the evidence for general conservation of energy. In early experiments we shall make some thermal measurements with thermometers and water and express them in kilocalories. Then, without proceeding to specific heats, latent heats, etc., we shall hand much of the usual work in calorimetry over to chemistry teaching. It finds a very important place in a modern chemistry programme which deals with thermal measurements of reaction energies and treats, such as atomic heats, at an early stage. (Once he has given away specific heats, etc., to his chemist colleagues, it is surprising how comfortable a physicist can feel about that division of labour. Specific heats have been a routine measurement in physics; but only when we meet the variation with temperature of specific heats of solid elements and of gases do they become vitally interesting to a modern physicist by pointing to quantum effects – but unfortunately that seems too difficult for young pupils. There are a few thermal things whose loss or lending we regret, such as cooling by evaporation, and the mechanism of boiling; but we trust physicists will tuck in their commentary at the appropriate place – perhaps by raising questions about that in homework.)

NOTE TO TEACHERS ON 'PERPETUAL MOTION': YEARS I, II, IV

The idea of perpetual motion is a fascinating one to children, as well as to grown-up inventors and even some gullible educated non-scientists. Physics teachers should discuss perpetual motion with their pupils at various stages, perhaps even as early as Year I, perhaps much later; and we hope this can be an enjoyable and very profitable discussion.

It is not wise to say harshly 'Perpetual motion is nonsense. It cannot happen. You must learn that' – that will only cause disappointment and make science seem more dogmatic than reasonable.

On the other hand, we certainly should not encourage pupils, even young ones, to speculate for long on ingenious schemes to achieve perpetual motion. We should compromise, by showing pictures of some schemes of perpetual motion and asking pupils what the 'catch' is. We should discuss hopes and difficulties; and explain that over the past 300 years there have been many ingenious schemes, some of them real models (which failed to work) and some just sketches on paper or ideas in people's heads.

We should admit frankly that it would be worth a fortune beyond all fortunes if one could produce a perpetual motion machine. And we should insist clearly that we have no hope of ever producing such a thing. That is because we have applied clear knowledge of science, such as the 'Lever Law', to every design of machine that has been offered and we have been able to show that, unless our experimental knowledge is quite wrong, the machine will put out no more energy than it takes in. Furthermore all the machines that have been built have failed in practical trials. We do have some general scientific knowledge which we trust completely (such as the sun rising in the east day after day) and if some scheme of a great invention is clearly impossible unless it can be an exception to our general scientific rules, we are likely to say it is hopeless.

In saying that all models have failed, and that physicists have found a 'catch' in every promising suggestion, we are merely recording history – albeit impressive history with a vast and varied range. In claiming we are *sure* that perpetual motion is impossible, we are trusting the principle of conservation of energy – and there we can only state our strong belief. We *cannot* prove that the principle is universally true throughout our world; and we should not try to do so by verbal tricks. 'You cannot get something for nothing' is often quoted in support or even in proof. Yet it is really only a catch-phrase description applied to energy *after* we are convinced of conservation (therefore that phrase is much better avoided in our teaching).

Even after that, children will bring suggestions for perpetual motion machines, and we should be sympathetic and comment on them gently.

'Perpetual Motion' v. 'Perpetual Movement'

Some of the arguments or plans that children bring us will arise from a misconception of the phrase 'perpetual motion'. It is a most unfortunate term, because both children and adults think that it refers to a machine that will just go on running. In physical science, it does not mean that: it means a machine that will go on putting out more energy than it takes in. If there were such a machine it could have its output energy divided between two uses, one lot channelled round to the input to provide the input energy for the machine itself, and the rest for our use – a surplus of energy brought out to drive a car or run a power station or anything else we like. That is the form of 'perpetual motion' which we think impossible.

'Perpetual movement', in the sense of things just going on moving without gaining energy, is possible and quite common. Examples: the Moon; gas molecules; and, with close approximation, many mechanical devices, such as a bicycle wheel spinning on good bearings (or a brick coasting on a glass table with a jet of air under it to provide an almost frictionless bearing). It is the latter examples that children quote, asking anxiously if perpetual motion is not, perhaps, almost possible after all. It is an enormous help if we start any discussion of perpetual motion by explaining that, unfortunately, scientists have adopted that name for a special, quite impossible, but very tempting, thing: a device that perpetually produces *extra* energy. If we give the name 'perpetual movement' to the other case, of merely continuing motion, that helps to avoid this confusion. *Perpetual movement* is possible: it does occur. But it will not make anyone richer (except the ball-bearing manufacturers) because, when we try to take energy out of it – hoping for 'perpetual motion' – the perpetual movement slows down to a stop.

The idea of a dynamo providing current to supply a motor which drives the original dynamo by means of a belt is a very tempting one for young people; and they offer that as a perpetual motion: it is perpetual movement. In real life, a pair of machines, coupled electrically and mechanically like that, and given a start will run to a stop because of waste heating in the wires and friction in the bearings. Yet those waste effects are small compared with the power transfer back and forth between the two machines if they are well designed. In fact very big generators and motors are tried out against each other on a test bench like that by the manufacturers, with only a small extra supply from an auxiliary generator to make up for the defect below perpetual movement.

NOTE TO TEACHERS ON GETTING TIRED WHEN HOLDING A LOAD AT REST

When we think of food providing energy for a useful job, we all of us wonder about getting tired when we simply hold a heavy load still in our hands. That certainly fatigues us and it certainly draws upon some food energy – which ultimately appears as waste heat. And yet we are not obviously storing up any potential energy. Pupils may ask about this. 'If I carry a heavy suitcase from the bottom to the top of a building 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 at rest in my hands, 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) $\times$(distance)?' The answer is this: There are two quite separate things to be explained here: the feeling of fatigue when we maintain muscles in tension to hold a load at rest, and the continuing demand for food energy.

The feeling of fatigue is chiefly produced as follows: When we use muscles to maintain a tense posture, they squeeze the blood vessels and diminish the blood flow. As a result, the chemical products of muscular activity accumulate and are not washed away so quickly by blood flow. This accumulation of chemical products stimulates the nerves to 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 and each fibre relaxes and renews the tension in turn, again drawing on chemical energy. When a fibre relaxes the energy that is returned is not returned to chemical energy but only to heat.

So the steady pull of the muscle is really the sum of many brief tugs. We might call this a 'dynamic' force, like the force made by air molecules bombarding the wall 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 statistical sum of innumerable pulses of tension if we went into atomic detail.

Thus a muscle supporting a load is not like a shelf exerting a static force but more like a jet of water supporting a ball with a dynamic force. As with the jet, there is a continual conversion of energy into heat; but as with the jet the muscle can respond amazingly quickly to commands.

Because their fibres cannot reverse the chemical changes of contraction when they relax, there is a continual output of heat from a tensed muscle. This output increases surprisingly little when the muscle is made to do external work as well.

The pounding molecules of gas never experience fatigue because at each impact they bring in heat energy and carry it out again as heat.

(The sum total of these pulses of force, the 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 produce heat. The shelf does not need any fuel to do that job. That is a very useful criterion; can we replace the man or horse or electric motor by some inanimate prop which does not need fuel?

As another example, consider two stories, each of a man pushing a wagon on a railway line. One man stands behind the wagon and pushes it so that it moves along the rails at constant speed against friction. The man must run to keep up with the wagon and maintain his push. He is drawing on chemical energy in his leg muscles, to provide for waste heat in himself; and, for the wagon, he is providing for the heat developed by friction on the rails and in the air. If we calculate the 'work' that shows the transfer of energy from the man to the wagon, it will give us the energy transferred in the man's muscles *to* friction heat for the wagon – but that 'work' will not include the heat developed in the man or his shoes.

The second man is also pushing the wagon, but sideways. He runs along beside the wagon and pushes on it, trying to push it over. The wagon being on rails does not fall over. Does the second man make any useful transfer to the wagon? Work, as we know, is not just (force) × (distance) but (force) × (distance-moved-along-the-line-of-the-force). In this case, the force is perpendicular to the motion of the wagon. So, for the second man, there is no work showing transfer from him to the wagon.

Applying our criterion, we see that the second man could be replaced by a marble statue on roller skates, leaning against the wagon and coasting along beside it. If the statue's roller skates were frictionless, we should not have to give it any fuel to maintain its uniform motion. A real man would draw upon his food energy only because of the inelastic trembling of his arms and shoulders with which he pushes.

On the other hand, the first man will continue to draw upon his food energy as he pushes the wagon along. A marble statue would fail in his place; it would fall down flat on its face.

If the wagon is accelerating, similar stories apply; the work for the first man gives the transfer *from* his food energy *to* the wagon's increase of kinetic energy and the heat that produced by friction. A marble statue could not replace him successfully. For the second man (leaning sideways against the accelerating wagon), there is no transfer of energy from man to wagon. However, the man must draw upon his food energy not only for his friction-heat and for his muscle-maintaining-waste-heat but also to provide his own increase of kinetic energy. And an accelerating marble statue to take his place would need some kind of engine to provide its increase in kinetic energy.

NOTE TO TEACHERS ON UNITS

At an early stage, the Nuffield Physics Group made a decision to use MKS units. Where we have an open choice, we propose to use metres for lengths and kilograms for masses; but we do not intend to carry that consistency to statements that fly in the face of common sense. It looks silly to measure the width of a finger in metres: it is obviously one centimetre wide. We shall keep millimetres and centimetres as subsidiary units (and inches and feet as well for beginners). Kilometres and miles will remain familiar on maps and speedometers. Grams will go on appearing in weight boxes whether the Nuffield Physics programme succeeds in reforming the apparatus manufacturers or not. We have to use common sense and admit common units, but we shall avoid proliferation into things like hectograms.

For measurement of heat we shall use 'large Calories', or kilocalories. Despite the modern move to use joules for energy in any form, we must not measure heat in joules until after the great nineteenth-century experiments have been discussed – until 'the case is proved', in Year IV.

Our reason for choosing MKS units is not a fanatical belief that a change of units can make the teaching different; or a still more extreme belief that it could change the facts of physics. We have chosen this system of units for two reasons: (1) because we think it is likely to come into use in more and more textbooks; and (2) because it makes common electrical measurements fit more easily with our development of mechanics – amps, volts, watts, joules, newtons, all fit together.

Currents and potential differences are measured in amps and volts both in scientific laboratories and in commerce. We measure power in watts and kilowatts as well as horsepower – and the latter unit is likely to be used less rather than more in future. If we measure masses in kilograms and distances in metres, we shall have newtons for forces, and newton.metres or joules for energy. That will fit with our use of 'volt' for a 'joule/coulomb', instead of a CGS definition that would bring in a big factor like 100,000,000. Even for that advantage alone, giving a clear simple meaning to volts and watts, the MKS system is very valuable.

Fortunately we do not need to take sides in the controversies over rationalized units or the meaning of the constant in Coulomb's Law. In this programme we are concerned with volts and amps; and the most advanced concept involving MKS units will be electric field strength in volts/metre, which are the same as newtons/coulomb.

It will be helpful if teachers encourage pupils to use metres and kilograms wherever that seems reasonable. In all cases of very large quantities and very small quantities – such as the distance of the Moon, the number of molecules in a room, e/m for electrons, the size of a molecule – we might just as well use MKS units, since the power of 10 will make the statement 'unreal' in any case.

In the case of power, we suggest that it is important for educated people to have a feeling for a watt, a kilowatt and perhaps a megawatt.

NOTE TO TEACHERS ON INTERACTION

We assume that masses are additive – that one mass does not interact with a neighbouring mass in a way that changes the response of one or both to a field of force. We assume that energies are additive, that these are no interaction terms. This assumption of no-interaction seems obvious to us because we so often select cases where it holds.

There are many other cases where it does not; and the 'interaction terms' form some of the most interesting developments in science. A current of 2 amps pushed through a resistor produces a certain output of heat. Two currents of 2 amps, pushed together through the resistor as a current of 4 amps, do not produce just twice the output of heat.

The importance of interaction is easier to see in a fictitious example like the following: Suppose we are irritated by two lots of stray noise in an office where we are working: the noise of a group of people whispering, of intensity N_w, also the noise of a trombone player practising quietly in the opposite corner, of intensity N_t. If we *could* measure our irritation, I, we might find that the irritation due to the whispering goes up in proportion to the intensity, $I_w = K_w N_w$ where K_w is the 'irritation-constant' for whispering. And we might possibly find that $I_t = K_t N_t$ where K_t is a different constant applying to trombone noise. Even if we could take measurements and discover such simple relationships, we should not be wise to assume that the total irritation, I, is given by the sum of the two components, $I = I_w + I_t = K_w N_w + K_t N_t$; because one kind of noise is quite likely to change our sensitivity to the other kind of noise – a little trombone noise, hardly irritating in itself, may completely obscure some very irritating whispering. There is interaction between the effects of two kinds of noise in producing irritation; and we must either declare that the K's are not constant or be lucky enough to express it by an extra interaction-term such as $KN_w N_t$. In the latter case, with $I = K_w N_w + K_t N_t + KN_w N_t$, we see that the irritations are no longer additive.

We take it for granted that velocities along a straight line are additive – that seems natural – and yet Relativity will make us change our mind. Fortunately, in ordinary mechanics velocities are additive, masses *are* additive, and changes of energy *are* additive.

NOTE TO TEACHERS ON VECTORS

In Year IV, pupils should see illustrations and uses of vectors. If in their mathematics they are studying vectors, we may need to explain that this is a much more informal approach – our vectors are simple and 'ugly but very useful', like the elephant child's trunk. We need not even use the name 'vector', but may just talk of 'trips' or 'journeys'. Then we show how such things are added, pointing out at once that this is a new kind of adding in which 2 and 3 no longer make 5: the sum may be anywhere between 1 and 5 – and it has a direction that is just as important as its number. We introduce the name 'resultant' for the vector sum.

For class experiments, a pupil should drag a pencil across a sheet of paper while his partner drags the paper in another direction, not necessarily at right angles. This is too rough to succeed except in the hands of skilful children who practise it. Of course we do not call this vectors, but say 'problems in navigation'. For better results, give pupils a frame with some arrangement for winching it along at a more or less constant speed. Under the moving frame and its cross-moving pencil as passenger, a piece of paper strapped to the table will enable pupils to log the resultant course.

We suggest that the following are 'vectors', that is, they add in this way: trips or distances travelled; velocities (because these are distances travelled in one hour), and probably forces. Strictly speaking, it is risky to assert that forces are vectors without an experiment to demonstrate or test that statement. (And it is wrong to say that forces must be vectors because they have magnitude and direction – there are certainly things that have magnitude and direction but do not add up by vector addition.)

Vectors as things to be added by the geometrical (parallelogram) construction seem clear, simple, useful things to older students. The pupil in school who first meets vectors at an early stage in physics finds them queer and difficult; and almost impossible to understand when it comes to subtraction. Since this sense of difficulty disappears almost completely as time goes on, we urge teachers not to press any discussion on vectors beyond what seems sensible to their pupils at each age. In professional physics, vectors have assumed paramount importance, with special mathematical methods and terminology to enable them to be dealt with quickly on a very grand scale. That is no reason why we should insist on bringing in vectors too early to catch a pupil's fancy.

There will be no need to touch on vectors in Years I, II and III. Even the simple discussions of projectiles which we offer can be treated without overt teaching of vector constructions. In Year IV we should try to offer a demonstration of a collision in two dimensions, to be analysed by means of multiflash photographs. That will bring in vectors, probably at the right moment. In Year V a knowledge of vectors and an understanding of their subtraction becomes essential for faster pupils in their treatment of motion in a circle. Even then, however, most of the work of the year will not need vectors. We look forward to great uses of vectors – in A-level work.

NOTE TO TEACHERS ON TEACHING ELECTROSTATICS WITH ELECTRONS

Here is an account of an experiment to demonstrate electrostatic induction, told as a romantic story with mobile electrons.

'This metal ball has a negative charge, because we have put some extra electrons on to it. Those electrons run about freely on the surface of the ball and they make an electric field with their charge, all round the ball. When I bring this uncharged, metal sausage near the ball, extra electrons on the ball, with their electric field, repel the loose electrons in the surface metal of the sausage and drive them away towards the far end.

'So there is a collection of extra, negative, electrons at the far end; and that leaves some positive charges always there: they are embedded in atoms which are part of the crystal structure of this metal surface. But their effect was neutralized by the effect of the negative charges of the loose electrons swimming around among them in the surface region, until those electrons, or rather only some of them, ran away to the far end.

'So now we have the metal ball covered with negative electrons all over its surface and the long metal sausage with a covering of extra electrons at the far end and anchored positive charge left at the near end.

'What happens when I break the sausage in half? I then have two half-sausages, one with a negative charge of extra electrons, one with a positive charge because it is short of some electrons, and I can hold those quite separate, having gained two separate charges without in any way hurting the original negative charge of extra electrons on the round ball. We call those induced charges, because they are charges which have been persuaded to separate by the electric field of the extra negative electrons on the ball.

'Now go back to the stage before I broke the sausage in half. Here is the sausage again, originally uncharged, placed near the negatively charged ball. I have positive charges left here, near the ball, by lack of electrons; and negative charges, electrons, have run away to the other end. Now I connect this long sausage to the ground either with a wire or with my body, by touching the sausage with one finger and the ground with my damp feet. Those negative electrons at the far end of the sausage are driven away by the electric field of the charged ball and (although they have to move a little in the wrong direction to get to my finger in the middle and then down through my body and away) they are driven that way because of the driving forces of the field.

'So, in the end, those negative electrons – the excess ones, that is – run away to the great Earth, sharing the charge between the sausage and the Earth in a proportion which leaves practically no extra electrons on the sausage. Yet the positive charges are left there in the sausage unaccompanied by neutralizing electrons, at the end near the ball. Now take the sausage far away from the ball and we have a metal sausage which has lost some of its electrons, so it is positively charged.

'Of course, electrons will run over the surface until the unbalanced charge is more evenly distributed, making a positive charge all over the metal sausage, though more of it at the curved ends than in the middle. Then we have acquired a positive charge from a negative one originally on the metal ball, without losing any of those extra electrons on the ball. So we can do this again and again and get any number of positive charges "by induction" from the negative charge on the ball.'

The events described in that romantic story are true, so far as distribution of positive and negative charges is concerned. But to many wise critics, the story of hordes of electrons tearing along the surface like troops of scouts on a field day is an unjustified embellishment of the proper scientific story – at this stage. There is no evidence whatever, in the simple experiments that pupils are doing, of the only movable things being particles of negative electricity.

Electric charge might well come in the form of two continuous forms of juice, one positive, one negative, able to separate in an electric field, and able to neutralize each other's effects when left alone. We are, therefore, embroidering the story with details which seem to make it easier for young pupils to remember and have apparently the virtue of being scientifically *true*. But is that really good science? Was it good science when the followers of Niels Bohr took his early description of electron orbits in atoms so literally as a *true* picture that they inscribed all those ellipses on many a textbook? We now know that there is no way of locating electrons in a sharp orbit like that. We know that those early descriptions contained romantic embellishments that were actually misleading.

In the case of electrons in metals, we are well assured that electrons *are* free to move and the positive charges *are* anchored, but yet some of us are uneasy about using that knowledge when we can give our pupils no hint of its coming from experiment. On the other hand, our young pupils know about electrons as, to them, quite familiar things. They know they are negative, they have heard that they move freely in metals, and if we do not admit this someone else will certainly continue the story for us and tell our pupils that we are just being old-fashioned.

We should not be intimidated by that, but we should not be unreasonable; so we are probably wise to talk about electrostatic events in terms of mobile electrons; but we should from time to time warn our pupils clearly that they are using a picture that is, at the moment, unsupported so far as they know.

NOTE TO TEACHERS ON LOGIC AND VOLTMETERS

Perhaps this is the moment to confer privately with teachers about the general logic of using moving-coil voltmeters. The logical difficulty about using such voltmeters in an experiment to 'discover' or to 'test' Ohm's Law is not of such great importance here as in many teaching programmes, because we do not intend to stress Ohm's Law very strongly. We shall treat it in Year IV, but we shall include materials and things which do not have Ohm's-Law-behaviour.

If one designs a voltmeter by putting inside it a high resistance that obeys Ohm's Law and measuring the current through that resistance with a milliammeter, whose dial is then labelled volts, one must realize that there is a threat of serious illogic if one then uses that instrument to test Ohm's Law! Many a young 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 comforted himself by expounding the logical difficulty to both pupils and colleagues.

In fact, however, this 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 time by executing simple harmonic motion) to time a pendulum or even a loaded spring. We use the watch and make perfectly good discoveries concerning simple harmonic motion. A full and careful logical examination of the statement that 'light travels in straight lines' or of Newton's First Law of Motion and the meaning of Force, 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 the voltmeter question. We can present a voltmeter as a ready-made closed instrument and assure ourselves of its behaviour by tests from outside. 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 wire, and none of these things matter; because we satisfy ourselves by experimental tests that this 'black box' does in practice measure energy transfer between electrical form and other forms, in joules for every coulomb.

We do that first by making a crude overall test, connecting the voltmeter across 1, 2, 3 cells in series, acting on the basis of a belief in the conservation of energy. (If we are not sure of that basis, we shall probably have troubles in discussing any form of meter. 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. In fact, the basic experiment there is 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 then involve us in a difficult transformation of units.)

Then we test our voltmeter by a calorimetric method, at one or more points on its scale. 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 does serve as 'an experiment of principle' to show that one *could* substantiate the behaviour of a voltmeter without opening it, and therefore without illogic.

On account of the difficulties, we suggest that the calorimetric test should not be shown; but, instead, teachers should be ready to describe it to any pupil who wants to know the full story. It would be wise not to raise this hare with a whole class of pupils; but just to be ready to answer questions when any are asked.

Of course we must be careful not to use voltmeter, ammeter, stopwatch and calorimeter to measure 'J' in a class or demonstration experiment if we are already using, in practice or in imagination, a calorimetric experiment to give validity to our voltmeter's scale.

Thus, there are several levels of knowledge at which we can put a moving coil voltmeter into 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 enthusiast, but no sense of understanding. As part of physics teaching, it is bad.

b. The black box with description of use and purpose by assertion: This is an early level which we may have to use in physics 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, measured in coulombs. We state clearly that 5 amps means 5 coulombs per second. (Thereby we are operating at 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 the voltmeter in Year III.

c. The black box turned grey by systematic external demonstration or tests: This is the treatment of voltmeters in which we give the overall test with several cells and the calorimetric calibration mentioned above. It is proof against any complaint of illogic on account of the resistor inside.

d. The 'secondary standard treatment': This changes from a black box to a completely transparent box through which we can see the primary standard behind it. We simply say 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 current balance, that weighs the forces between measured coils against known gravity-pulls, combined with a Lorenz disc which measures a standard ohm in terms of dimensions of some coils and the speed of rotation. This is satisfying to a much more advanced student but to describe it to young pupils is probably to produce a sense of insecurity, and impression that physicists let one of the passengers in the back seat hold the steering wheel.

e. Complete revelation: We open up the voltmeter, see 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. The 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 voltmeters is an interesting experiment and very important practical engineering.

This discussion is not intended to suggest any discussion of these matters with pupils in Year III or in Year IV or even V.

NOTE TO TEACHERS ON PROPORTIONALITY

Much of our knowledge of physics is expressed in the form of proportionalities. (See also the General Note on Constant.) 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 embark on curative measures of blame, exhortation and explanation, but we have only moderate success – the stumbling blocks often remain.

It is suggested by some wise 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 the following comments:

Start with simple examples of proportionality as a relationship, in which A doubles, triples, etc., when B does: for example, cost of a basket of eggs *v.* number of eggs, weight of potatoes eaten per week *v.* number of men in an army camp, weight of copper wire *v.* length of wire; area of a square *v.* $(\text{side})^2$. In each case, we should emphasize the essential characteristic that one thing increases just as the other does, the two keeping step. Illustrate that by a graph with a straight line through the origin.

Then with the help of the graph point out another view, that if A varies directly as B the fraction A/B keeps the same value – it is the slope of the graph line. In many uses in science it is the *constancy* of A/B rather than the particular value of that constant fraction that is important. It is the constancy that tells us an important law of nature, while the value only gives us information relating to a particular example – Ohm's Law is true for a great variety of wires but the value of the resistance applies to a particular wire.

Since we are aiming at using proportion in science, we should avoid trick methods that may serve as temporary props when it is taught prematurely in arithmetic – such as reducing a problem about men digging ditches to a unit form that tells us how many weeks it would take one man working one hour a day and one day a week to dig a ditch one yard long, one foot deep and one inch wide – that result to be built up by mystical multiplication into the required answer for the time needed by many men to dig some huge ditch. That method, which often failed to equal clear-headed skill, carries pupils far away from a simple feeling for proportion. Instead of that, we might move to more informal versions of our first descriptions and say, as physicists do, 'A goes as B'. Then we can say that the stretch of a spring goes as the load; the area of a circle goes as its radius squared; the volume of a cube (or sphere) goes as the cube of the linear dimension.

Then we should take a look at inverse proportionality, expressing it in two forms: PV is constant, and P varies directly as 1/V. Pupils who word that as 'P goes as 1/V' are likely to have a clear feeling for this relationship.

Note that in our first discussions we have not emphasized the value of the proportionality constant, the value of A/B or of PV. Sometimes pupils are taught to start by working out the value of the constant from one set of data, then to use that value of the constant to calculate another value of B for some given value of A. That will yield the right answer without any doubt, but it diverts attention from the structure of the relationship and it probably does not help a clear understanding – so we should avoid it as far as possible.

Returning to problems about men digging ditches, we suggest that pupils should attack them with a common-sense feeling for proportion, such as: 'The time needed *goes as* the length of ditch, so 200 feet instead of 50 feet multiplies the time by 200/50; ... the time needed *goes inversely as* the number of men, goes as 1/number of men, so 4 men instead of 12 men makes a factor of 12/4, ...'

Non-proportional examples. Simple proportionality is common in elementary physics teaching partly because we choose those easy relationships for our pupils, partly because they are the important beginnings of physical science, chosen or sought out by man in an attempt to find the simple relationships first. There is, therefore, a danger of pupils' thinking that every physical relationship is likely to be, or worse still ought to be, one of simple proportionality. We should give them some examples, even flippant ones, to the contrary. For example:

a. A spiral spring of steel wire is hung up and loaded. Its length with no load is 10 inches, with a 1 pound load its length is 12 inches, with 2 pounds 14 inches, with 10 pounds 30 inches. Is length directly proportional to load?

b. An army camp (unlike the simple one mentioned earlier) needs:
2,200 lb potatoes per week for 100 men
4,200 lb potatoes per week for 200 men
6,200 lb potatoes per week for 300 men
Why is the potato supply not directly proportional to the number of men?

(The answer is not spoilage, which is likely to be a constant fraction, but the silly story, 'We have forgotten the cooks, who need 200 lb per week themselves'.)

c. A spiral spring of heavy steel wire is placed in a vertical tube (like a gas jar) and a piston of negligible weight is placed on top, so that experiments can be carried out on the compression of the spring. The spring is 20 inches high with no load. With 5 pounds on the piston the spring length is 15 inches, with 10 pounds the spring length is 10 inches. Having learned from an earlier problem not to use the whole length of the spring in looking for proportionality, we ask: 'Is the change of length proportional to the force?' (Yes.)

Now the spring is removed and the piston is made airtight (but remains frictionless and of negligible weight). The air enclosed in the tall jar is now the 'spring' to be experimented on. With no load the piston is 20 inches above the bottom, with load 5 pounds 15 inches above and with 10 pounds 12 inches above the bottom. We ask the same question.

(This is, of course, a Boyle's Law story for a tube of cross-section about 1 square inch so that atmospheric pressure provides the equivalent of 15 lb extra load all through. This should not be used to divert a discussion of proportionality into Boyle's Law – unless it happens to crop up at the right time. If Boyle's Law is discussed, this problem could take an interesting form by asking for the height with load 15 lb, both for steel spring and for air.)

d. If 1 barking dog can keep 5 people awake all night, how many people can be kept awake by 2 barking dogs?

e. Henry VIII had 6 wives. How many wives did Henry IV have?

f. A fence consists of light wire netting with a thick wooden post every 10 feet. The fence along the side of a field has 10 posts. How many posts would a fence twice as long have?

g. A bank notifies the police that banknotes numbered 1262 to 1272 inclusive have been stolen. They then ring up again and say that twice as many notes have been stolen, beginning with 1262. What should the end number be?

h. A current of 5 amps driven through a certain resistor immersed in water delivers 3 kilocalories in 1 minute. How much would a current of 10 amps deliver in the same time?

CONDENSING THE GUIDE TO A SYLLABUS?

In planning the material to be offered to teachers, the Foundation felt that the course or programme should be presented in the form of an extensive *Teachers' Guide* and not as a compact syllabus.

Since our emphasis is on changes of attitude and treatment rather than on a new choice of topics, we believe that many teachers would like to have a guide that will give an account of aims, reasons for choices of experiments and detailed descriptions of the treatment we suggest – altogether, a volume of commentary instead of a compact syllabus.

Teachers who find the commentary covers familiar ground can always omit it – the actual topics are marked by subtitles and the suggested experiments by C or D in the margin with a number.

In thus departing from custom and providing a long guide, we hope that teachers will appreciate our reason for it and will bear with its length and the reading that it involves.

Many teachers, both 'old hands' and new ones, will wish for a compact syllabus as well. And yet, while sympathizing with that wish we hesitate to print a syllabus, because a syllabus can be interpreted in many different ways. It would be easy for a critic, unintentionally, to interpret ours quite differently from our actual plan. So we would prefer to give a critic our full *Guide*. Moreover, teachers who have already embarked on a trial of our programme (with the full knowledge they will soon have) would hardly be satisfied with an editor's choice of summary. They would consider it far too short to serve as a substitute guide and they would find it missing many a point that they wish to have in their own summary. So, instead, we hope each teacher will extract his own summary from the *Teachers' Guide*.

The course is planned as a connected scheme, so teachers are strongly advised to read all five Years of the *Guide* – Year I in particular sets the stage with some general commentary that affects all later Years. Nevertheless teachers will feel the need for some kind of outline of the course outside the Year they are teaching, so we give below outlines of the five Years for that purpose. They are only skeleton outlines and should *not* be taken as a syllabus.

OUTLINE YEAR I

(Note that this is not a syllabus. It would be misleading if taken as one. It is only a skeleton outline offered to teachers of other Years for reference.)

Materials and Measurements. Instruments

Exhibit of materials. Testing a vacuum.
Discussion of crystals; idea of atoms.
Magnifying glass and microscope in class experiments.
Weighing and measuring samples of solids, liquids, gases. (Idea of density.) (Problem to discuss number of atoms.)
Making a microbalance as class experiment.
Measuring sheet of paper, penny, paper thickness, aluminium leaf.
Practice with metric measurements.
Rough guesses in measurement of lengths, masses, times.
Timing.
Simple introduction to statistics.

Open Class Experiments

Empirical investigation of simple seesaw.
Empirical investigation of springs
copper wire springs; steel springs – open experimenting, stretching copper wire (demonstration and class) (discussion of laws and limits).

Pressure Gauges and the Atmosphere

Demonstrations to introduce pressure and simple pressure gauges.
Class experiments with U-tubes to measure gas pressure, lung pressure.
Atmospheric pressure: demonstration measurements; barometer effects of pressure; (guess at height of atmosphere).

Molecules

Model of a gas.
Brownian motion – seen with smoke in class experiment.
(Diffusion of gases.)
Estimate of oil-molecule length:
simple surface tension experiments; spreading of oil;
class experiment with measured drop of oil.

Energy

(Note that discussion of energy and work is resumed in Year II. We may well postpone till then a good deal of the discussion of energy forms, illustrations of energy changes, discussion of work, and foreshadowing of conservation. However, the final experiments, cloud chamber and spark counter, should not be postponed.)

Introduction of energy as something needed for 'useful jobs' and provided by fuel.
Idea of work, measuring transfer of energy, introduced but not used.
Description of some forms of energy:
energy in fuel and food,
potential energy stored by springs, or by gravity,
energy-of-motion (K.E.).
Experimental illustrations of energy changes.
Energy and machines: perpetual motion?
'Atomic energy.'
cloud chamber (as demonstration and as class experiment),
spark counter.

OUTLINE YEAR II

(Note that this is not a syllabus. It would be misleading if taken as one. It is only a skeleton outline offered to teachers of other Years for reference.)

Forces

Short review of forces: turning effect of a force.
Forces between magnets, electric charges; weight.

Electric Circuits

Extensive series of class experiments with circuit boards:
building circuits with small lamps to indicate current,
simple 'current balance' (current found to be the same all round the circuit),
current measured by 'lampsworth' of lamps in parallel
current balance
ammeter.
(*For faster groups*. Voltmeter introduced as 'cell counter'.)
Electrolysis: simple class experiments and demonstrations; copper plating.
Demonstrations of currents through gases: sparks, candle flame, neon tube.
Electron stream in 'vacuum': fine beam tube; C.R.O.
Forces between charges. Charges in motion and currents.

Forces and Energy

Forces: pushes and pulls; muscular sense of force;
soap film; friction, fluid friction; weight.

Introduction (without explanation) of the newton as unit of force.

Energy: résumé from Year I of idea of energy as something provided by fuels and needed for 'useful jobs',
 description of energy forms, with experimental illustrations,
 discussion of energy changes, with experimental illustrations,
 discussion of force and energy changes: work as a measure of transfer of energy from one form to another,
 machines: comparison of output energy and input energy,
 foreshadowing of idea of conservation.

Heat and Temperature

Simple measurements of heat (mass of water) $\times$ (temperature rise).
Estimate of specific heat by electrical heating (without meters).
Idea of heat as a mode of motion: model of a gas.
Temperature (treated briefly).
Effects of heating: expansion of solids, liquids, gases; pressure changes of gas; melting, evaporation, boiling.
Atomic and molecular pictures of solids, liquids, gases.
Heat transfer: class experiments on convection, conduction, radiation; spectrum demonstration.

OUTLINE YEAR III

(Note that this is not a syllabus. It would be misleading if taken as one. It is only a skeleton outline offered to teachers of other Years for reference.)

Introductory Demonstrations

Samples of the year's work.

Waves

Waves along rope, etc., wave models.
Ripple tank: extensive series of class experiments, investigating the way circular pulses and continuous waves and straight wave fronts travel, are reflected and refracted and interfere.
 Introduction to idea of 'rays' as guide-lines for the motion of wavefronts, and to the idea of an image for waves reflected from a wall.
 Use of simple hand stroboscope to observe continuous ripples and make simple measurements.

Optics: Behaviour of Rays; Images; Instruments

Straight rays; shadows; ray in water; curved ray in water + brine.
Simple pinhole camera as class experiment;
 and conversion to lens camera.
Demonstration of image formation with smoke box.
Class experiment with simple lens: looking at real image, virtual image; rough estimate of 'f'.

Discussion of images as basis for understanding all optical instruments.
Class experiment to make a telescope.
Rays of light and cylindrical lenses: an extensive series of class experiments to study lenses as image formers; and to make models of optical instruments with real rays.
Class experiments: magnifying glass, compound microscope.
Experiments with eyes.
Reflection and refraction: behaviour of rays demonstrated; (laws); interpretation by particle model discussed.
Diffraction and interference (Young's Fringes) in demonstration and class experiments. Comparison with ripple tank.
(Discussion of theories of light.)
Spectrum.

Motion and Force (informal introduction to experiments)
Class experiments: *timing accelerating trolley by tape and vibrator.*
Free fall; rough measurement; investigation with tape and vibrator.
Inclined plane and pendulum demonstrations.
Frictionless motion: Newton's Ist Law.
('Frictionless' demonstrations with CO_2 – for schools with Year IV apparatus: constant velocity; free fall; projectiles.)
Simple investigation of force, acceleration, mass with tape and vibrator (= informal illustrations of Newton's IInd Law).
Projectiles: demonstrations, class experiments; guinea and feather; pulsed water jet; monkey and hunter. Independence of motions.
Idea of gravitational field strength.

Qualitative Kinetic Theory
Models of molecular picture of gases.
Brownian motion (unless seen in Year I).
Diffusion in air of H_2, CO_2, bromine.
Change of gas pressure with temperature. Absolute scale.
Expansion of air.
Boyle's Law.

Electromagnetism
Extensive series of class experiments with electromagnetic kit:
magnetic fields of currents; simple galvanometer,
magnets and their fields; electromagnets; applications;
'Catapult force' on wire carrying current *in magnetic field;*
models of moving coil meter, motor;
commercial meters and motors;
empirical investigation of electromagnetic induction.

Experiments with bicycle dynamo, a.c., oscilloscope, transformer. (may be postponed until Year IV)

Voltmeter as a cell counter; use of voltmeter. (Formal treatment of p.d. in terms of energy transfer postponed to Year IV.)

Model power line: class experiment and demonstration for discussion without measurements.

Electrostatics

Electric fields; charges and forces; electroscope; induction.

Electron stream in electric fields: fine beam tube.

A Simple Theory and its Use

Breaking a magnet; simple theory; predictions; testing prediction for a ring-magnet.

OUTLINE YEAR IV

(Note that this is not a syllabus. It would be misleading if taken as one. It is only a skeleton outline offered to teachers of other Years for reference.)

Newton's Laws of Motion

Introductory experiments: tape and vibrator for free fall, multiflash for free fall; for trolley on hill, tape and vibrator for trolley on hill; for constant acceleration.

Measurements: force and acceleration; mass and force: mass and acceleration.

Motion with no force: terminal velocity in fluid; CO_2 pucks.

Measurement of 'g'.

Illustrations of inertia property; comparisons of masses.

Forces in absolute units; calculation and measurement of forces.

Bernoulli effects and connection with Newton's IInd Law.

Momentum changes and Newton's IInd Law. Experimental illustrations.

Conservation of momentum and Newton's IIIrd Law: experimental illustrations.

Measurement of bullet speed by momentum method, and by time-of-flight.

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

Experiments to measure changes of K.E.

Discussion of energy changes involving K.E.

Kinetic Theory

Models of atoms and molecules in solids, liquids, gases.

(Brownian motion.)

Boyle's Law: demonstration; model; theoretical discussions.

Kinetic theory prediction of expression for PV (several methods).
Kinetic theory leads to estimate of air molecule speed.
Diffusion of bromine to illustrate prediction of high speed.
Kinetic Theory Discussion of diffusion, speed of sound, etc.
Estimate of diameter of air molecule by diffusion of bromine.

Conservation of Energy: Experimental Basis

Simple experiments to measure heat as
(mass of water)×(temp. rise).
Description and critical study of the great variety of 'Joule' experiments to measure the conversion between heat and mechanical energy, etc.
General conservation of energy:
calculations assuming conservation.

Energy and Power

Illustrations with lamps and motors.
Simple measurements of pupils' useful power.

Electric Currents (continued): Potential Difference: Power

Revision of electric circuits; water analogy; electrolysis.
Moving electric charges give same effects as electric currents.
Introduction to p.d.: lamps and motors run on different supplies;
class experiment with voltmeter and lamp;
test of voltmeter with 1 cell, 2 cells ...
water circuit with pressure-difference meter.
Discussion of coulomb as unit of charge:
current in amps as coulombs/sec.
p.d. as energy transfer per coulomb in joules/coulomb.
E.M.F.
Experiments with transformers, bicycle dynamo and C.R.O.
(Study of a.c. with very slow a.c. Probably postponed to Year V.)
Relationships between current and voltage:
Ohm's Law, temperature effects; other materials; transistors; measurements of resistance.
Power measurements and calculations.
Model power line extended to a.c.

Electron Streams, etc.

Diode; C.R.O.; shadows; deflection by electric field; heating of target; stream yields negative charge when collected, etc.
Ions in flame. Positive rays.
Electric field strength; calculation for parallel plates from p.d. and separation.

Millikan experiment: description, model, film; and full discussion of this – which is the only experiment in the course that really shows electricity comes in 'atoms' of charge.
Demonstration and class experiments with C.R.O.
Energies expressed in electron.volts.

OUTLINE YEAR V

(Note that this is not a syllabus. It would be misleading if taken as one. It is only a skeleton outline offered to teachers of other Years for reference.)

Motion in a Circle: Central Acceleration

Motion in a circle: illustrations; discussion of idea of central acceleration,
example of satellite: acceleration calculated from drawing.
Derivation of $a=v^2/R$ (alternative methods),
application to satellite.

Electron Streams: Measurement of e/m

Demonstrations (revision) of electron-stream experiments.
Magnetic field applied to electron stream: demonstration.
Discussion of force exerted by magnetic field on current; and on stream of charged particles.
Measurement of force on known current-element by current balance.
Grand experiment to measure e/m for electrons, using fine beam tube and magnetic field calibrated by current balance.
Measurement of e/M for hydrogen ions (electrolysis): comparison of e/m and e/M: atom model?
Positive rays: description without demonstration; e/M.
Simple atom model: electrons and positive body.
Mass spectrograph, Nier type. Isotopes. Atom model.

Planetary Astronomy (to teach development of successful theory)

Facts and early history; Greek theories – uses and meaning of a theory; Copernicus; Tycho; Kepler and Galileo; summary of the problem.
Newton's gravitational theory: use of $a=v^2/R$, and test of it with Moon's motion; Kepler's laws and universal gravitation; planets' masses; comets; shape of Earth; differences of g from pole to equator; Moon's motion; tides; precession;
planetary perturbations; discovery of Neptune.

Theories

Planetary system; Atoms, rough picture, more details.

Simple Harmonic Motion

Qualitative study of S.H.M. with many illustrations. Description as projection of circular motion. (No mathematical definition or investigation: formulae for period of pendulum, etc., not derived.)

Class experiments: empirical investigation of pendulum period.

Waves

Revision of properties of waves; $v=n\lambda$; stationary waves.

Diffraction and interference; revision of Young's fringes.

Grating: simple introductory experiments.

Spectra: simple observations.

Radioactivity

Simple experimental study of alpha-, beta-, gamma-rays; illustrations with cloud chamber and counter.

Radioactive changes, treated very briefly.

Alpha-particle scattering (illustrated by cloud-chamber photos) as evidence of atomic structure.

Rutherford atom model (discussion *and* film).

Modern Atomic Physics

(Brief descriptions of the following, mostly by assertion with illustration by film.)

Photoelectric effect:

'coarse' photoelectric effect.
(Negative electricity ejected by light.)

'medium' photoelectric effect. (More light ejects more electrons but not more energetic ones; longer wavelengths fail; shorter wavelengths eject electrons with more energy.)

'fine' photoelectric effect. (Apart from work to escape, all electrons ejected with same energy for same wavelength of light; that 'quantum' of energy varies as frequency of light; and those 'quanta' or 'photons' arrive at random in a stream of light.)

X-rays; diffraction by crystals.

Quantum behaviour; photons arrive one by one at random (shown by film); photons build up an interference pattern of Young's fringes (shown by film).

Electromagnetic spectrum.

Theories of light.

Matter waves; electron diffraction (shown by film); wave-particle behaviour; suggestions for atom models.

APPENDIX I

THE AIMS OF SCIENCE TEACHING: TEACHING SCIENCE FOR UNDERSTANDING

(This is an account, with minor modifications, of a paper read by Professor E. M. Rogers at several recent conferences on science teaching and of a lecture at the Association for Science Education meeting in Birmingham in January 1964. This is not a formal statement of the aims of the Nuffield Science Teaching Project but it is offered here as an informal guide to some of the opinions and thoughts which have played a part in the Project.)

We have met to discuss the teaching of science. Science has grown and been taught for many centuries but now in this scientific age we face grave problems of a worldwide need to know some science and understand it. Throughout the world we need skilled scientists, we need technologists who can draw upon a full knowledge of science, we need other technical people with scientific training and everywhere educated citizens, inside scientific work and outside it, need to understand science so that they can live in this scientific age. For many of our pupils, school will provide all the teaching of science they will meet. School is responsible for the good name of science. Others will go on to further training in science and engineering. For them, too, school should provide a well understood preparation, a basis of knowledge and attitude – for them, too, school is responsible for the good name of science.

We are many of us involved in discussion of ways and means, of syllabus construction, apparatus, buildings, and training of teachers; but first I hope you will consider with me the aims of science teaching, because a clear discussion of aims can guide all the rest of our planning – and may even modify our work seriously.

In all we teach, what we teach and *how* we teach are controlled consciously or unconsciously by our *aims*, by the outcomes we expect. Suppose you were teaching an emergency programme to train diesel engine repair-men. What would you teach and how would you teach it? ... Suppose instead you were coaching a group of pupils for success in physics examinations that ask for definitions in proper wording and calculations with carefully memorized formulae. What would you do? ... And now suppose that you and I are all of us to teach young people science in a way which gives them a clear understanding that will be of lasting value to all educated citizens. Many of our young people, though not scientists themselves, will later on have to work with scientists; all will find that science has a practical impact on their lives; and all will live in an intellectual environment where science plays a very important philosophical part. What should we teach them, and how should we teach? ... That is my question for this discussion.

I am thinking of our young people when they are grown up, not when they are learning science at school, but a dozen years later when they are out in the world: a young man in a bank presently to be a manager, an important person in business or industry, a civil servant, a history-teacher in school or university; or, above all, the parent of young children giving the next generation a first view of science. Again I ask my question: what are our aims in science-teaching for those people, and how should we teach for those aims?

A dozen years after school educated adults will not remember the facts clearly, or even the general principles unless they understand the science we teach them. If they understand, they may retain some sympathetic understanding all their lives.

We all say we want to teach for understanding, but what does that mean for the general pupil? Much of the welfare of civilization, and perhaps even its fate, depends on science. Does our school science teaching educate people to understand this dependence? Scientists have a characteristic way of thinking and planning and working, which we call the scientific attitude or scientific method or science itself, that offers intellectual resources and guidance to all. Do we send our pupils out delighted with that understanding of science, and ready to turn it in new directions? Do the next generation of scientists and engineers make the most possible progress? Can governors and administrators who learnt science at school confer intelligently with scientists on the vital problems of our age? In general, does our science teaching make its proper contribution to education? Even in the matter of the actual science we teach, are we meeting our pupil's need and hopes?

Young children are thrilled with the idea of scientific experiments and knowledge. Many a small boy is eager to learn physics and chemistry. When we show him a plain test-tube his tongue hangs out with enthusiasm. He enjoys playing with the first magnet he sees. Yet a few years of science classes – including, say, some qualitative analysis or a study of magnetic-field formulae – will deaden the enthusiasm in many. Some emerge determined to be scientists – but even they usually have a strange picture of science as a sort of stamp collection of facts, or else as a game of getting the right answer. For the majority, well-meant teaching has built a wall around science, an antagonistic wall of ignorance and prejudice. At best, for educated non-scientists, that wall is a wall of mystery and misunderstanding, enclosing the scientist as a magician who knows all and can do strange things that ordinary people cannot understand.

Most serious of all, the parts played by experiment and theory are misunderstood. Experiment is pictured as a blind trying-out-of-everything in which success is assured if enough money is provided for trained workers and elaborate equipment. Theory is either thought to be absolute knowledge – completely real and true – or else abstruse unreal mathematics 'which only seven men and Einstein in all the world could understand'. Instead of such extremes we wish educated people could know from their own experience that experiment is alert, open-eyed and open-minded putting of questions of Nature; a necessary basis for knowledge, but never the whole of knowledge as we now build our science: and that theory is a growing structure of understanding which combines experimental knowledge with imaginative thinking and intelligent reasoning. In short, we want well-educated people to feel that they understand science and the people who practise it, and to know that 'science makes sense'.

In general education we need not try to equip everyone with a complete survey of scientific knowledge (that can be stored in books or left to the professionals), but we do need to give an understanding of science and its contributions to the intellectual, spiritual and physical aspects of our lives.

I will illustrate the sense of this important word 'understand' by some words in French.

SAVOIR	(I know my friend's height, I know how much he weighs.)
CONNAÎTRE	(I am well acquainted with my friend's feelings and interests.)
COMPRENDRE	(I understand my friend. If I understand him very well I can answer the surgeon who asks, when my friend is in great pain, 'shall I operate on him?')
(SAPIENCE)	(This is something given by Heaven, for which we may only hope.)

The English language has only one word for 'know', but I will give some English nouns to describe these different levels.

SAVOIR	Facts and principles: information
CONNAÎTRE	Knowledge
COMPRENDRE	Understanding
(SAPIENCE)	(Wisdom)

In this list I hope we can move our teaching *downward*, placing more emphasis on knowledge than on information. (Information can come from books, from an encyclopaedia on the shelf.) And I hope we can seek something deeper than knowledge, something that I call understanding. Then perhaps we and our students may sometimes catch a glimpse of the wisdom which is there in our science as one part of mankind's heritage.

Perhaps another description of 'understanding' will help in discussions. We each of us say, of one piece of physics or another, 'I never really understood that till I came to teach it.' In the same sense may expect even young pupils to be able to 'teach' something they understand to others. We ask them, in homework or examinations, to describe an experiment or explain an argument *in their own words* to, say, a hypothetical uncle who is sympathetic, intelligent but ignorant. This old device is a powerful teaching help and of great use in setting the tone in examinations.

How can we teach science for understanding? I mean science taught in school to future scientists and non-scientists alike: to give scientists the right kind of start, so that they become constructive imaginative masters of their art not just servants of rule; and to give non-scientists a vital part of their education. For years, many of us have put our trust in the discipline of thorough formal training, definitions to be learnt and principles to be stated, drill in problem solving, and careful measurements that follow detailed instructions. Such teaching has been defended on several grounds such as the following (to which I have added my own parenthetical comment).

1. A good thorough grounding in science shows pupils the nature of science and gives a real understanding. (However genuine this aim, I doubt whether that succeeds with real pupils. The topics seem to be crowded and unfinished. The teacher seldom has time to point the moral.)

2. Acquaintance with the main facts of a science itself is a valuable part of education for civilized life. (Facts are soon forgotten or muddled, particularly when delivered with authority and speed. If education is 'what is left, after what you learn has been forgotten', the providing of fact-content should not be the sole aim in science teaching.)

3. The discipline of thorough study, including learning material that is boring or difficult, is valuable in itself. (Under criticism from psychologists, this kind of argument has lost favour in the field of classics. In science, it is likely to lose favour for the same reason. Also it is likely to be crowded out by other aims.)

4. Study of science gives training in scientific method – that is, it makes people more scientific, a virtue to be transferred to other studies and other activities in general life. (This gives a cogent reason for any studies which *do* yield such benefits. Investigations show that such 'transfer of training' does not occur easily or in great measure. To encourage it, we need to modify our teaching, as we shall see later.)

5. A taste of science in school gives some pupils a chance to decide they will be scientists. (This is true; but it may not be necessary to offer the samples in the traditional form.)

Yet the results are disappointing. Our young scientists arrive at the university well crammed with older material but far behind in modern physics; and their lack of deeper understanding makes progress slow. (Kinetic theory, for example, is a way to a formula rather than a fruitful model of molecules in random motion, a model to help in discussing diffusion, viscosity, conduction, molecular specific heats. Radioactivity comes as a list of names and properties rather than powerful evidence that helps us build speculative models.) And our non-scientists go out into life without any clear feeling for science itself. Many a layman actually boasts he does not understand science.

All of us who look critically at the teaching behind these results agree on one point: we are trying to teach too much material. If we could teach less, and teach more carefully, the results would be better in quality and more lasting in time.

And most of us agree on another point: we aim our teaching too much at formal knowledge and training instead of understanding. Why do pupils not thrive on training? Here we can get a helpful comment from our psychologist colleagues. They warn us that careful training in some piece of knowledge (e.g., accurate weighing or in scientific methods) does not transfer to other fields of knowledge or to life in general. Or rather, the pupil does not often transfer the training. He does not often profit from it in general education – he only gains some specific training. This is such an important matter in our planning of science teaching – for future scientists and technologists as well as for non-scientists – that I would like to remind you in some detail of the account our psychologist friends give us.‡

We ask the vital question, 'Will students transfer training, in some skill or habit or the use of some idea, from science to other studies or to life in general?' If the answer is 'no', our new schemes must relate merely to better training inside a science, and offer little promise as a part of general education. If the answer is 'yes', our hopes should be grand indeed. In earlier generations, classics, history, mathematics, as well as science – in fact most of higher education – claimed cultural values on the ground that their teaching would transfer to many other fields of the pupil's education and there be retained as part of his mental equipment. Educators pointed to the high levels of scholarship and culture 'produced' by a thorough classical education. In this they seem to have risked some confusion between *post hoc* and *propter hoc* – we might suggest their classical scholars had the intellect and background to succeed anyway.

However, since early this century, experimental investigations at first said 'no'‡ to our question about transfer, then later studies showed that it can occur to some extent. It certainly does not take place as easily as educators and the general public hoped. If it did not occur at all, higher education would seem almost worthless except for special professional training. Fortunately there is some transfer – language teaching can improve intellectual skills, mathematics can give a sense of form or give training in careful argument, and so on – but *only in certain favourable circumstances*. In our present discussion, it is essential to know what these favourable circumstances are and to try to provide them. We ask the psychologists who have experimented on this. Here is the essence of their reply:

‡ In the course of the last half century opinions on the difficulty of transfer of formal training have differed and experts still disagree today on amounts of transfer – it is difficult to make fair comparisons and even more difficult to interpret the results fully and correctly – but the account here summarizes the general opinion.

‡ One of the earliest experiments was a trial by the psychologist William James. He measured his speed in learning French verse. Then he switched to English verse and practised techniques for several weeks, making considerable progress. Then back to French verse. No improvement, no gain from the English practice.

1. Transfer is easy, likely to occur, when there is common ground between the field of training and the field to which we wish it to transfer, or when there is similarity between the influencing and influenced functions.

For example, if we train a pupil to weigh accurately in a physics laboratory, it is almost certain that this training will transfer to another physics laboratory, and he will weigh the more accurately there. It is moderately certain that he will carry his good training to a chemistry laboratory; but much less likely that he will carry it to any weighing in his own kitchen or in his business, and it is very unlikely that training in accuracy will reappear as a habit of being accurate in other activities.

Another example: training in argument learned in geometry is likely to be transferred to later geometrical studies and perhaps to algebra, not very likely to be transferred to work in physics, unlikely to help the pupil to think critically about arguments in newspaper advertisements, and very unlikely to make him a better economist.

This is what the earliest experiments showed. This is what threatened to make liberal education seem hopeless. A study of Latin would not improve the general use of language, mathematics would not sharpen the wits, science would not make its students more scientific. Only technical education – direct training for use in a job – would bear fruit. (In support of this disastrous conclusion, investigators pointed at the professional scientists, whose training should have made them tidy and systematic in all their general life and well-organized, logical, critical and unbiased in all their general thinking – in fact they range as widely from a common average as those in other academic groups.)

Happily for liberal education, later and more careful experiments showed that there is *sometimes* more extensive transfer. Our intuitive judgement is right when we believe higher education makes *some* lasting contributions that spread outside immediate or technical training. But, only *sometimes* ... only *some* contributions. Such generalized transfer is far more rare, far harder to achieve, than pupils and teachers hope and claim. In fact it is likely to occur only in special circumstances. Those circumstances, on which the hopes of liberal education should now rest, are outlined in 2 and 3 below.

2. Far reaching transfer does occur sometimes when the common element is one of aim or ideal. Then the essential vehicle is the emo-

tional attachment (or 'sentiment') the pupil develops – the extent to which he associates feelings of enjoyment, interest, inspiration with his studies. The more he enjoys his science and is inspired by its skills and methods and the more he likes discussing its philosophy, the more likely he is to retain and generalize the teaching.

Thus, reverting to our examples: suppose a pupil develops a *delight* in accurate weighing and forms an ambition to be accurate in other things. He walks on air, buoyed up by his newly acquired skill, and he does transfer some of that to other fields of study and to his general life.

Again a pupil who decides to take some scientific methods‡ as his ideal guide can, and sometimes does, use those methods in other studies. And, above all, a pupil who enjoys feeling he understands some science may transfer that link of understanding to his later life so that he works and talks intelligently and successfully with scientists.

3. Transfer is more likely if the pupil knows of its possibility and seeks it.

With that warning about transfer we must choose modest aims for science teaching if we wish to be realistic and hope for results that will be visible and lasting. We must not expect to train our young people to be 'scientific', with the full knowledge and practice of some mysteriously ideal scientific method. We shall have little hope of finding our non-scientists living their lives after school with a good understanding of science, transferred from science courses to life in general, if we fill them up with information and tell them we must get it back in examinations in identical wording, or if we drag them through artificial calculations based on memorized formulae. Instead I suggest we should teach less material and omit some topics so that the syllabus is not too crowded, so that there is time to teach for understanding. Then pupils will emerge ready and able to read any more they wish.

What topics should we omit? Each of us should make his own examples. My examples will be chosen from physics because it is my own special field. In many schemes of school teaching hydrostatics is taught very well and in great detail. I suggest that it can

‡ To most of us who are practising scientists there is no unique 'scientific method' such as the idealized scheme set forth by Sir Francis Bacon and still advocated by some philosophers. However there *are* scientific methods – the ways in which we gather knowledge and build an increasing sense of its validity.

nearly all be omitted. Hydrostatics is not undesirable; but it is unnecessary. Studies of the Principles of Archimedes are not important as preparation for other topics in physics; and as they are taught they do not, I think, give pupils great insight into science. In many a school, pupils weigh things in air and water till it is almost a mechanical habit.

Another example: specific heats do not play an important part in modern science until advanced work on changes of specific heat with temperature brings us to quantum theory. Yet younger pupils laboriously measure specific heats without much understanding. They follow cookery book instructions for a method that has not been used in research for over half a century. They boil a lump of metal and throw it into water. The size of the lump may be carefully chosen so that it carries over just enough hot water to compensate for heat-loss on the way over. Instead of this messy method, any modern scientist would use electrical heating.

I do not suggest that either of these topics must be omitted. I merely mention them as examples of material which seems to us less important nowadays, and has lost some of its value in science teaching by over-emphasis of instructions. As a third example, I suggest that in elementary teaching some of our work with Newton's Laws of Motion is dull and sterile. Of course our pupils must meet those great Laws, with simple experimental tests to clarify them. And they should, I believe, put them to the use for which Newton himself formulated them: a great gravitational theory of the solar system. But if we examine our present teaching, we find that the main use of Newton's Laws is to solve artificial problems on Newton's Laws! I suggest we can save some time and trouble there.

And for the things that we do teach we should choose topics that have many uses. I do not mean practical applications, but rather linkages with other parts of physics. Science should appear to our pupils as a growing fabric of knowledge in which one piece that they learn reacts with other pieces to build fuller knowledge. We must be careful to introduce any piece that we teach with an indication of our purpose, saying clearly how we are trying to build more science. And after we have taught a piece of science we should look back on it and talk with our pupils about the way in which that piece fits in with the rest and builds more. Of course there will be plenty of factual content because we must use solid science in the building.

In our teaching of chosen topics we must be careful to teach for a sense of understanding and not just give formal definitions to be memorized or statements of principle or laws to be used mechanically – that would be asking our students to behave as a rubber stamp, to reprint on every examination paper the standard things that we have taught them. Our examination must be different. And so must our practical work. Pupils will need to do some experiments on their own to gain personal experience of science. Think of the pupil who learns a piece of physics thoroughly; trying his own experiments, watching demonstrations, discussing with the teacher, doing his own thinking. He makes this knowledge his own, and says 'I understand this'. That is a proud possession, giving a sense of power, a sense of strong knowledge which can be of lasting value in his education.

Practical work is essential not just for learning material comment, but for pupils to make their own personal contact with scientific work, with its delights and sorrows. They need to meet their own difficulties like any professional scientist and enjoy their own successes, so that the relation of scientific knowledge to experiment is something they understand. (Curiously enough it is when he discusses his own experiments that many a beginner catches his first glimpse of the role of theory.) So we should give our pupils experiments to do on their own – really on their own – in the laboratory. They need a teacher who will give very few instructions and leave them to work on their own; they need some encouragement from the teacher, and some questions about their experiments – and a wise teacher can provide that environment. Above all the pupils need plenty of time to do their own experiments and then to think and argue about them. They do not need new or expensive apparatus so much as a change of attitude.

Working on their own, children will do far fewer experiments in the time available; and to make up for that the teacher should do more demonstrations.

As an example of practical work: we give quite young pupils a spiral spring wound from steel wire, and ask them to find out by their own experiments all they can about its behaviour. All will load it with weights and measure stretches and perhaps plot a graph. Finding the simple Hooke's Law relationship gives lasting delight to many young experimenters. We do not falsify the story by telling children they have made a new discovery. We agree that it is new and delightful for them but we admit that it is an old law discovered by Hooke 300 years ago. (And we tell them that Hooke was delighted and proud of it too.) But then we encourage them to go farther. Some will continue to stretch their spring far beyond the elastic limit. Some will notice torsional motions and will investigate. Others may try the effect of heating and cooling. And still others will make springs of copper wire for further experiments. With plenty of patience and some encouragement (but no prompting by suggestion of particular problems) this becomes an open experiment that continues for some weeks.

To critics who say that a class experiment which continues through several periods is not feasible in school teaching I reply: (1) it *has* succeeded, in Nuffield physics trials and elsewhere, and (2) to pupils this is a continuing set of experiments rather than a single experiment perpetually left unfinished – it is much like a biology class getting out microscopes period after period, to pursue a set of experiments with increasing skill. And to teachers who foresee discipline troubles I point out the world of difference between children doing experiments because they (most of them) want to and children following detailed instructions without a strong motive other than success in marks.

As another example of our treatment, if we want to encourage understanding: we provide apparatus for simple electric circuits, but we do not at once draw circuit diagrams for pupils to follow. A child of ten can wire up an amplifier from a circuit diagram without understanding. Instead we give general instructions and simple apparatus, and plenty of time. Then experimental work becomes 'doing and finding-out and abiding-by-what-happens'.

With good teaching to promote understanding, and quiet experimental work in the laboratory, and critical discussion guided by the teacher, we might hope to promote understanding of science; but we shall fail completely if we ask the wrong kind of questions in homework or in tests or in examinations. It is no good to insist in class on understanding and then ask for formal answers in examinations such as a definition of coefficient of cubical expansion to be returned in the exact words of the book, or a mechanics problem to be solved by putting numbers in a memorized formula. Therefore we must remember our aims at every point in constructing homework and tests – otherwise pupils will be guided in the opposite direction when they take the tests and they will conclude that, after all, science is a set of formal statements unconnected with the real world or with clever, sensible thinking. We *can* make questions that test understanding – even questions that pupils themselves see in that light.

We can make homework questions that encourage pupils to learn by their own thinking. The marking of answers to such questions is harder but more interesting: and it is part of our teaching.

[There followed some examples of questions that can be used for examinations or homework as part of teaching. They are omitted here because they are given in the Paper on Examinations, which follows.]

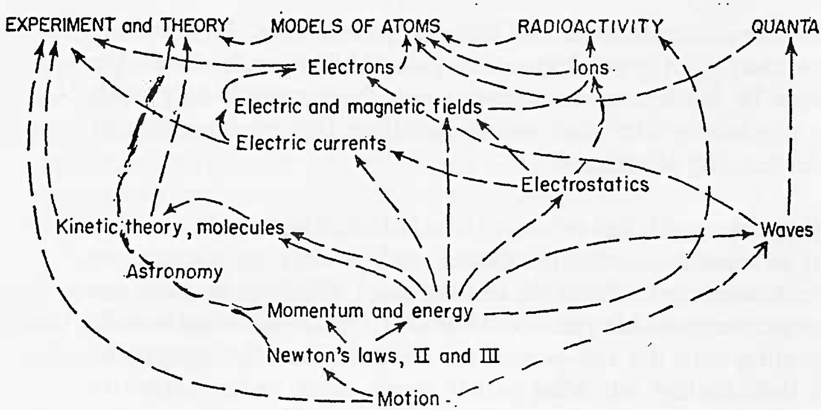
Some of our questions should be quite general ones. Though they show clearly, in a pupil's answers, whether he understands the science he has learnt, we have to mark them more loosely, with less precision – but what are we teaching for, examinability or understanding of science?

Rather than teach fast to cover the whole field of bare-bone syllabus, we should reduce our syllabus with a clear conscience, yet make a connected scheme. As an example, I will show how one can construct one suitable syllabus. Note that I construct it *backwards*, beginning with the end-points, my ultimate aims for my pupils; and then finding out what earlier topics seem to be needed to support those aims and to provide the ground work for understanding the later teaching.

Suppose we decide, in a physics course, to include some 'atomic physics' and choose to teach: radioactivity; electrons individually and in moving streams; and something of atomic models. All that will come near the end of the course; and if it is to make any sense it must be preceded by some teaching of ions, effects of electric and magnetic fields on a stream of charged particles; measurements of charge; and a good knowledge of energy. And those will need some electricity and magnetism, some kinetic theory of gases, and some Newtonian dynamics; and the latter needs a beginning in studies of motion (see sketch overleaf).

There we have already an impressive syllabus of physics to be taught – if we remember that we are hoping for much discussion and experimenting in class. So we now look forward through our 'syllabus skeleton' and ask where our teaching has opportunities to contribute to a general structure. We see that we must aim at doing some justice to models of molecules and atoms. We see that pupils must have good chances to arrive at some experimental laws.

And we hope for some example of *theory* in science, even for these young people. Even with school children we can discuss, quite simply, the use of laws, reasoning, experimental tests so that they think of science as an intelligent fabric of knowledge in which experiment and imaginative thinking are woven with reasoning. Atomic theory, so powerful in chemistry, can be described, but the actual building of it is too sophisticated for pupils to see as a clear example of great structure. So we might add the growth of planetary theory from empirical beginnings to Newton's overall gravitational explanation, as an example of the growth theory.



In this syllabus, some topics which do not seem so important nowadays have been omitted or recommended for a briefer treatment. Most of those are topics of physics which have been taught with great skill and care in the past; so that demonstrations, textbook material and even examination questions are at hand and one may well regret their loss – yet we trust that teachers will understand that our treatment represents no disrespect to those topics but only necessary economy. Other topics have begged for inclusion; notably some teaching of 'atomic physics', as recommended in the recent report published by the A.S.E. and the Nuffield Foundation.‡

That is just to show you how I make a syllabus that I myself happen to like. (It is *not* identical in detail with the Nuffield physics programme.) Another teacher should make his own version, of course. The making of such a syllabus map is itself a very valuable discipline for each of us.

In my discussion so far, I have concentrated on the teaching of science to future *non-scientists*. But now I hope that you will see

‡ *The Modern Physical Science Reports*, published by the Association for Science Education and the Nuffield Foundation (1965) and obtainable from the A.S.E., 52 Bateman Street, Cambridge.

that this development of teaching science for understanding is needed equally strongly by the future scientist or technologist, if we are to do our best for him. For later training in science our school pupils need a foundation of good understanding – of some things well learnt, and understood as clear knowledge, rather than a memory packed full of details. The details are so easily and quickly added at more advanced stages.

If we need more technologists, as so many countries do today, we must prepare them with a good understanding of science. I think of two groups in technology: the technical man who mends an amplifier or runs a telephone exchange and the technologist who designs new things – designs not just invests – who puts a full knowledge of science to practical uses.

We need many skilful technical men, in every country; but some of their special training for their work is best done after schooldays, when they are starting at their jobs. Thus they need not amass their whole store of factual scientific knowledge at school; they can do that in a technical college or at work. School owes them a more valuable basis for future work: an understanding of science, which will enable them to learn their technical things with understanding.

We also need technologists, at the top level of designers and organizers, in every country. Such a man must be clever, creative, and equipped with scientific knowledge right up to the frontiers of research. He is a scientist by training and activity, but his chief interest is in new *uses* for science rather than in entirely new science. We know how such people are trained in universities and technical colleges – all except a few rare geniuses have to go through a long training in science and technology. With good intentions, we plan to give them more technical training, less pure science. I suggest that there we make a mistake. The technologist must have a tremendous knowledge of science; and he must understand the science that he puts to such grand use. He too needs an early beginning in understanding and much study of pure science – study with real delight if he is to keep it and use it.

Science is the intellectual nursery for the next generation of scientists and technologists. Technology, like the mule, is strong and clever, but cannot breed its own next generation. This is because the next generation of first-class technologists needs an endowment of fresh outlook and knowledge, and new wisdom, if they are to work as creative people. It is the scientists who must give the next generation of technologists essential training or they will lack the deeper understanding which is part of their preparation.

Therefore, all through, for non-scientists, scientists, technicians, and technologists, our duty in schooldays is to teach science for understanding.

We should not hope for great results to spread quickly across the world, or even through a group of students. In such important changes we may expect slow growth. There is a major influence that sets the stage for science teaching before school starts it: the attitude of parents towards science in the home. So, in teaching physics for understanding, we hope for great results in this generation of children but greater still in two generations, when these children can tell their children in turn 'Science is delightful, interesting, powerful; science is great thinking and clever doing; science makes sense.'

APPENDIX II

EXAMINATIONS

(This is an account, with minor modifications, of a paper read by Professor E. M. Rogers at recent conferences on science teaching. This is not a formal statement of policy or practice of the Nuffield Science Teaching Project but it is offered here as an informal guide for discussion. The paper does not refer to O-level examinations alone, but covers a much wider range – before O-level, O-level, A-level. So some of the examples of questions given fall outside the present project. They are offered as illustrations of the general approach.)

Examinations have many purposes and uses:

to measure pupils' knowledge of facts, principles, definitions, laws, experimental methods, etc.
to measure pupils' understanding of the work of the course.
to show the teacher what pupils have learnt.
to show pupils what they have learnt.
to provide pupils with landmarks in their study and checks on their progress.
to make comparisons among pupils, or among teachers, or among schools.
to act as prognostic tests for directing pupils towards careers.
to act as diagnostic tests, for placing pupils in fast or slow streams in school.
as an incentive or spur, to encourage diligent study.
to encourage study by promoting competition among pupils.
to certify a necessary level for employment in jobs after pupils leave school.
to certify a general educational background for jobs.
to act as a test of general intelligence for jobs.
to award scholarships, university entrance, etc.

These have been analysed and discussed by many, and I shall not discuss them directly here. There is one more function of examinations:

to exhibit our aims to our pupils, so that examinations become a vehicle to aid in achieving our aims.

This is an overall function that pervades all other uses and aims – but it is a function that is often left unmentioned. And this is what I shall discuss here, because I see that examinations – whatever else they do – control the success of any teaching plans.

Besides the profusion of aims and purposes, there is also a wide choice of types of examinations:

oral questions to test knowledge of facts or skill in reasoning.
oral discussion to test understanding – with information and help interjected by the examiner as they appear necessary.
colloquies to test speed in learning a new idea.
essay questions to test proficiency in language or skill in integrative expression of knowledge.
short questions to test knowledge of facts, principles, formulae, experimental results, methods, etc.
problems to test ability to use knowledge and principles.
'objective tests' that offer a choice of ready-made answers – to be marked by a machine that detects the electrical conductivity of a pencil line.

The merits of these could be discussed at great length, but we should probably wander off on personal preferences. Any of these *can* be arranged to serve any of the purposes listed above; but, to do justice to the overall purpose with which I am now concerned, some forms of examination offer better prospects. For example, an objective test that asks the candidate to choose the best among five printed answers is likely to put emphasis on recall of facts – though that is not necessarily so. Therefore, after discussing aims and their relationship to examinations, I shall offer comments on some types of examinations.

Suppose, for example, we are teaching anatomy to future medical doctors and our aim is to make sure they learn the name of every bone and muscle. Then the examination ought to make a quick, extensive sampling of mechanically memorized vocabulary. Almost any type of questions will suffice: though an essay seems clumsy here and objective tests seem easiest and perhaps best. Suppose on the other hand we are teaching physics to our pupils as part of their general education, to be used later in life as a background of science rather than as a training for direct use. We have long tried teaching physics thoroughly to the non-scientist, giving him a good training in the facts, laws, principles, and methods of physics. The results are disappointing; educated adults are often ready to *boast* they do not understand physics.

We are not surprised to find the facts – both detailed information and memory of formal definitions, etc. – are forgotten or at least become vague with lack of use. But we are distressed to find that so little useful understanding remains – understanding of physics or of science or even of scientists. Psychologists warn us not to expect much 'transfer of training'. When pupils acquire skills and knowledge in one science, they will not easily 'transfer' these gains to another science, and still less, to life in general. We always hope for such transfer – in fact it is the *raison d'être* of liberal education – but we are warned that we must be content with only a little transfer; and we must expect to find it happening only when pupils develop a strong interest, an ideal, or an intention to generalize their knowledge.

Suppose, then, we want to teach physics in a way that gives some understanding that will last and transfer to life in general. With hopes of giving a lasting contribution to pupils' education, some of us are trying to aim our teaching at giving understanding rather than filling students with information (which will fade or become muddled) or training them in formal knowledge (which seems unlikely to transfer to later uses). We shall, for example, teach fewer topics, but teach more carefully; we shall encourage pupils to do more creative thinking and less memorizing of formal statement or results; and we shall ask pupils to do experimental work themselves, so that the work is their own experiment rather than a matter of dutiful carrying out of detail instructions. If we are to do that we must change our examinations to fit our change of aims and treatment: our examinations themselves must show our aims.

Consider the relationship between examinations and successful teaching for a particular aim in other fields. In some fields of study, (e.g. French grammar) both teachers and pupils regard examinations as necessary routine burdens that take time and may even help the teaching. In others (e.g. creative arts), examinations may do severe damage to the course – the chief benefits of those courses are probably things that cannot be tested in any limited examination; and a test of superficial matters instead would be unfair to good pupils and damaging to the reputation of the course.

Consider a course in French literature; there, examinations raise an essential question; should we test grammar (with ease and accuracy) or test literary appreciation (with difficulty, doubt and unfairness)? Many teachers choose the grammar test, and most pupils prefer it. Yet the important thing for our pupils – whether the course is for their use as future ambassadors or for their general intellectual growth – is an insight into the thoughts and literature of another people; a feeling, perhaps, for 'how a Frenchman thinks'. The teacher of the course justifies his grammar examination by claiming that: 'while the test will serve for marks, the real value of the course is in the reading and classroom discussion; and the pupils know that'. Not for long. Even the most inspired pupil takes account of the examination and draws his own conclusions.

A physics course presents the same dilemma; should we test information or test understanding? If we are aiming at understanding, as most teachers claim in *any* physics course, we must examine our examinations very carefully.

Suppose we give an inspiring course in which we use well-taught subject matter to give experience of experiment building knowledge, to show the nature of scientific laws, to illustrate a theoretical argument to establish scientific thinking as reasoning with carefully chosen data. If we then ask in the final examination, 'how long does a stone take to reach the bottom of a 20-metre well, starting from rest?', we deny our own claim. (And we lead our pupils into nonsense if we ask the artificial question 'how far will a small stone fall in 200 seconds?' and allow them to use a formula for free fall in a vacuum!)

A single 'formula question' like that does little damage; and it gives comfort to those pupils who learned in some earlier class that physics consists of 'putting numbers in the right formula'. It may even serve as discipline to enforce reading and learning. It also gives the beginner an encouraging start by letting him begin with a small job that requires practically no thought. Out of kindness, then, we should give a few such questions. But if we give many, in minor tests or in major examinations, we shall spoil the course; pupils will prepare for them; and next year's pupils will hear and pay little regard to our deeper enquiries in class or our philosophical discussions – 'learn the formulas the night before the test' will be the advice handed on. And a visitor who has come to see our work, will ask wisely: 'May I see your examinations?' Then he will raise his eyebrows and he too will go home unconvinced.

The success of the course depends vitally on the flavour of *every* test and examination. So we should give much thought to making sure that all the questions are as relevant to our real aims and teaching as possible – within the framework of the teaching programme. Then the making of examinations becomes an important duty that requires skill, experience, and a clear knowledge of the aims and the way the teaching is done, as well as of the syllabus content.

In meeting with a group of examiners to compose an examination paper, I find both dangers and delights in the contributions of my colleagues. New examiners produce new bright questions, but these are often clever rather than simply enquiring. In an enquiring examination, the pupil should not have the additional burden of guessing the examiner's clever intentions. On the other hand, I regard it as my duty to help new colleagues to develop into skilful examiners in searching for understanding. So I welcome their suggestions of questions; but, in conference with their framers, I analyse those questions very carefully for aims and suitability. In early examinations I eventually provide many of the questions myself; but, in later ones, my colleagues 'beat me at my own game' – to my delight – and I am very glad to use the questions that they then devise.

If we are teaching for understanding of science, we should ask questions that enquire visibly into the pupil's knowledge: ask for reasoning, ask for the candidate to show his clear understanding, ask him to describe scientific work. In short, we should give him problems that he can answer if – but only if – he is following the course and achieving some of our aims. Obviously, that 'if – but only if' is an ideal of examining that we can only strive towards.

Further, since our most important aims are long-term ones that may not appear as benefits for months or years, our examinations cannot be tests of full success. The best we can do is to make them encourage success rather than prevent it.

Some questions will ask for 'recall' of information. Only one or two should ask for what I name 'cheap recall', of a small item that can be learned by rote. Even those should be useful ones such as the following:

1. Density of a substance is defined as ... ?

2. If 1000 kg of salt water occupy 0·8 cubic metre, the density of salt water in MKS units is

   ____________ . ____________
   Units

and not ones that just ask for numbers to be put in formulae, like the following:

3. How long does a stone take to fall from rest down a 20-metre well?

We begin to require useful thinking when we ask for 'expensive recall': several items of knowledge to be chosen and put together with reasoning or constructive thinking. For example:

4. *a.* A man drops a stone down a 20-metre well and measures the time from releasing it till he hears it hit the bottom. Estimate (very roughly) the % error he makes by calling this the time of free fall. (Speed of sound = 1100 ft/sec.)
   b. Explain how you arrived at your answer.

To assure pupils that we do not want them to memorize formulae for substitution, I issue a public guarantee at the beginning of the term that *formulae will be provided free in any examination.* In fact, we print many formulae (without explanation) on the front of our examination paper. Nevertheless, the doubting beginner memorizes $s = v_0t + (1/2)at^2$ just before the first short test. Then he finds the test begins thus:

5. In the relation $s = ut + \frac{1}{2}at^2$,
   a. What does u stand for?
   b. What does ut tell us?
   c. Explain where the $\frac{1}{2}$ comes from.

(Thus, the test *gives* the formula, then asks questions about it.)

In printing the examinations, we may either ask the pupil to write his own answer on blank paper, or give him a space for his answer on the question sheet itself. The latter seems preferable for short answers because *it indicates the length of the answer expected* – also because it ties the question and answer together for the pupil's review when he gets his examination back after marking. Such a review can provide very valuable teaching when we use questions of this kind. (Reducing such a question to the standard 'objective' form with a choice among five ready-made answers may damage an enquiring question very seriously; that is almost certain to reduce the question to one needing only 'cheap recall' or clever guessing. When pupils are allowed to compose their own answers, the examination must be marked by a physicist, not by a machine – but we believe that the tedious work of marking such examinations is both a serious duty and a valuable part of our teaching.)

We make each question as enquiring as we can. If we *do* ask a simple question about a body being pulled along and accelerating, we may add a further enquiry: 'Would the acceleration be the same on the Moon?, in a freely falling lift?, under water? Give reasons for your answers.' That will show whether the pupil has a feeling for the concept of mass. We find that questions asking for descriptions, critical choices, or even sensible guesses, can often serve our purpose better than arithmetical or algebraic calculations. At least half of our questions should involve little or no mathematics. When a question starts with a simple calculation and then asks enquiring qualitative questions about the result, the latter should carry most weight in marking. To critics who object that qualitative questions are 'loose, careless, examining' I reply, 'Please try some. If you make them, you will find that they need not be loose or easy. And they do reveal what pupils are learning and thinking, most relevantly.'

Such qualitative questions cannot be marked with the same objective precision as definite 'cheap recall' or numerical questions. If we sincerely believe that great precision of marks is a necessity – and if we trust our marking for that, which I do not – we must restrict ourselves to more formal questions accompanied by a marking system that is both definite and deadly to our modern aims. If, however, we only want to know whether pupils have followed our teaching, and gained from their own work, with reasonable success then a more elastic, vague and humane marking system will suffice. We should reflect that in our personal interviews with people we are considering for some job – one of our most important types of examining – we are humane but quite vague, and yet consider that we know quite well whether the candidate is suitable. I suggest that we should relax our customary insistence on precision, and even learn to laugh at it a little, for the sake of enabling our exams to do justice to our teaching. For that matter, those of us who read the report *The Examination of Examinations* of an international enquiry by the Carnegie Foundation, several decades ago, realize how far from being reliably precise many of our careful formal examining systems prove to be when they are themselves examined!

Yet, the feeling remains that among many *short* questions only those that ask for calculations or mathematical proofs can be made 'really hard, to test the best pupils'. That is one reason why I add some longer discussion questions to my examinations. These are 'vague' general questions relating to the material of the course that offer pupils over a wide range of ability enormous scope to show what they know.

These questions serve several good purposes. They support our claim that we are seriously concerned with general understanding.

They give the very good pupil a chance to show his skill and knowledge: and they give some weaker pupils a good chance too, because they feel they may write freely and do themselves justice. Other weak pupils dislike the looseness of the question: then they must depend on the short problems.

But – as my colleagues always ask at examiners' meetings – how can we mark the answers? I suggest a marking scheme with very coarse mesh A, B and C which will be described later in this paper.

There is good correlation between the rough marks for general questions and the marks for dropping a stone down a well, etc. – the A's can also calculate and reason: the C's have not followed the course. The correlation is far from perfect and where there are disagreements I welcome the compensations that they effect. Even if the correlation were perfect, I should retain these questions for the sake of pupils' attitude towards the course, now and in the future.

All physics courses, whether for scientist or non-scientist, intend to give a lasting understanding of science – though their reasons for that intention may differ, and the amounts of factual knowledge they must provide may differ – and they should do their utmost to maintain that intention. There are obvious exceptions, such as a crash course to teach physics to radio repair-men in an emergency; but those are a matter of training, not teaching science. Some physics courses that are required as auxiliary preparation for other fields (e.g. for future nurses) are often treated as crash training courses, with a serious loss to education – they could teach less material and give greater understanding and yet yield just as much *remembered* content at the end. Many pupils in such auxiliary courses say they have no interest in physics and want to keep the material as factual and easily learnt as possible. Yet many of them who would rightly resent an increase of technical toughness (e.g. harder algebra) will ultimately respect an increase of *intellectual* demand, in fuller understanding. We should demand understanding, but we should scale our standards to pupils' abilities.

At the other extreme, the eager future scientist, anxious to proceed towards all knowledge and every skill, also needs to understand the physics he is learning. True, a general understanding could wait and be developed in retrospect some years later; but the young scientist deserves an insistence on understanding from the earliest years: otherwise he may never reach his full potential.

With our aims in view we should now consider styles of questions and their marking. The value of a question lies in the answer(s) it can elicit and not in its particular format. Yet some styles of questions make it easier for the pupil to give the kind of answer we seek (if he knows it). When we are aiming at understanding a question may need to be fairly long in wording if it is to express the examiner's wishes clearly. And it should allow considerable latitude in the wording of the answers, to give understanding precedence over rote memory or guessing. So I find the objective test types of little use, and rather harmful. They bring pupils back to memorized facts and clever tricks. Even when a five-answer question is itself a good one that asks for 'expensive recall', the choice among ready-made answers seems to emphasize answers rather than reasoning. We can convince an intelligent pupil that reasoning is still being tested, and we can point out the economy in marking; and yet, with an average group, a continuing diet of such questions seems damaging. So I prefer to use the following two types of question, but I make no claim that they are essential or best:

a. Short questions that show clearly what is wanted, followed by a space in which the pupil writes his own answer on the question paper. In many cases these questions consist of several parts of increasing difficulty.

b. General, long, questions, usually asking for a long answer where the pupil himself sees he has considerable choice of answers.

Among these, the ideal questions are those that make every pupil – slow, average, and fast – say 'This is a question I can answer well. I can do myself justice' – although the answers we expect, and get, differ widely according to the abilities of pupils.

Making examinations is itself a valuable process of heuristic gymnastics for teachers when they meet as examiners to make questions and then criticize them bitterly with the ruthless clear vision of scientists.

The process of reading and marking examinations sympathetically is just as important as the making of suitable questions. In marking, we should adopt the attitude of one scientist talking to another, albeit in simple language. I have in mind the kind of talk that one hears in a research room when neighbouring scientists come in and stimulate the research man with critical comments, irritate him with bright helpful suggestions, or even waste his time by exchanging ingenious questions about physics with him. In other words we must not insist on a pupil's answer taking a particular form, or even being the particular physical reason that we expect. We must reward every piece of intelligent thinking, as we should in conversation with a neighbouring scientist; but we should punish stupid answers, or lazy 'anti-scientific' ones. To train examiners for this we must not just tell them which answers are to be rewarded in some specimen questions that we offer for training; nor must we just preach sermons about broadmindedness to them; we must carry them through a series of examiners' conferences with real examinations and answers written by real pupils, so that they themselves 'learn by doing'. They learn how to mark those examinations and they learn a very important thing: that the humane, enquiring examination questions that we need *can* be marked quite sensibly without too much doubt and trouble.

In such discussions with examiners, it will become clear that the suitability of a question is often a function of the material content of the course. A question may be a very good one for a particular class because it draws, constructively, on several things that have been taught, and yet it may be a very bad one for another class which missed one of those necessary pieces of teaching – in the latter case the question hangs on guess-work instead of creative use of knowledge. Those of us who realize the important constructive part that examinations can play in teaching for understanding will not grudge the time and trouble that we therefore have to take in tailoring examinations to fit our teaching.

At this point, I must follow my own precept: I must not just preach sermons about examinations but I must encourage my colleagues to do some examining. So the remainder of this paper gives summary comments on examining for understanding and some examples of questions.

Examining for Understanding

Examining for understanding is neither very mysterious nor very difficult; but it does require hard work and a change of guiding attitude.

Consider 'examining' in another field: interviewing applicants for the post of hall porter, who has to handle heavy parcels, sort letters and deal with enquiring visitors. We do not simply trust to reading his paper qualifications or rely on his standard answers to standard questions such as 'Are you strong?' or 'Will you work willingly?' We put the applicant to simple trials of the things involved in the job. We ask him to shift some heavy loads, we give him some unexpected reading, and we may even entangle him in discussions. We make the test relevant to the real needs. Though we do not trust those naïve tests completely, we do think they are relevant to our real expectations. In examining in science we think out what activities and attitudes we have been trying to teach for, and we try to make questions to test for them. Of course we frame those questions to make use of material items taught in the course. And in framing them we look for the kind of knowledge and understanding that enable the pupil to teach to the other people what we (and his own experimenting and thinking) have taught him. In a way, we ask the pupil to 'teach' the examiner.

1. If pupils understand a piece of science, they should be able to use it intelligently. So we offer them a problem requiring the same knowledge as a problem discussed in class but we describe it with a different context and in different words. (For example, class discussion of a rocket accelerating is followed by a test question on a car decelerating.) We may call this '*simple recall*' as distinct from 'cheap recall' of a memorized fact. In that way we avoid the danger of a stereotyped question eliciting a memorized answer, whether of definitions or of solving procedure.

2. If pupils understand how scientists use their knowledge, they should be able to draw upon several pieces of knowledge and put them together, with some reasoning, to solve a problem, or throw light on some event ('*expensive recall*'). We make some questions of this form, being careful to be sure that the vocabulary of facts and ideas on which the candidate may need to draw has been well covered in the teaching. (This might seem to require each teacher and each class to have a special examination, tailored to fit its syllabus. But an agreed outline of material and treatment can make the examining of a whole group of schools feasible with no greater unfairness than when an examination is given to a group of schools following any prescribed syllabus.)

3. We want pupils to know that scientists use imaginative guessing at some points of their developing knowledge. We should enrich a question that asks for '*expensive recall*' by an occasional addition that asks for sensible guesses. And we can then ask the candidate to criticize his own guesses, and say which he prefers and why (intelligent guessing).

4. Teachers often say of their own knowledge that they never fully understood it till they came to teach it. We should expect a pupil

who has studied some piece of physics to have some ability to hand it on to others, if he understands it. So some of our questions ask the candidate to describe, in his own words, an experiment that he himself did or a discussion that he was involved in and understands. (*Teaching recall.*) (For an examination common to many schools this does require the experiment to be done in all those schools, a syllabus condition no worse than present ones.)

5. For many pupils, understanding is neither so fully formed nor shaped in such orthodox patterns as we expect from mature scientists. So we set some questions that are very vague and general so that each candidate feels free to fashion his own answer. (*Open or loose question.*) Yet we add explanatory notes to such a question so that candidates are not faced by the wrong problem, that of 'guessing the mind of the examiner'.

The marking of answers to such questions looks hopeless at first. In practice, a loose but otherwise reliable marking is easy after one round of training. We ask the marking examiners to class every answer A, B or C. Every answer which shows that the pupil does reasonably understand the matter in question gets B. (Score 7 out of 10.) Outstandingly good answers get A (score 10 out of 10), not to be awarded unless the reader meets an answer which he feels positively deserves it. Poor, bad, or irrelevant answers get C. (Score 3 out of 10 or even 0.)

We warn examiners that there may not be a single 'right answer'. They must accept many varieties of sensible answers, adjusting their requirements to the candidate's vocabulary and judging more by the way an answer is explained or illustrated than by its agreement with some official viewpoint.

In such marking of these questions, different examiners agree reliably after a little training, usually working more by general feel than by a strict marking scheme of items. The latter is likely to lose sight of the 'wood' of understanding and concentrate on the 'trees'. Furthermore it fails to take note of contradictions between separate items of the pupil's answer. Overall impression marking will call an answer bad if it contains a very serious mistake even if there are other good items in it – that is what we do when we interview applicants for a hall porter. Although this marking is rough, it gives us what we want: assurance of some understanding. And other questions with many parts of increasing difficulty contribute marks on a finer mesh.

In addition to providing assessment, and guidance for the teacher, examinations also tell the pupil about our teaching and expectations. If possible, a question to test understanding should seem to the candidate himself to ask for understanding. The loose, general questions mentioned above give most candidates a feeling of an open field in which each can do himself justice – the weak candidate thinks the question easy, and so does the very good pupil – but they give different answers. Nevertheless we should not mind awarding a wide range of answers a mark of a B. We should merely be saying that as many have made a reasonable success in general understanding.

Specimen Questions

A. *An exam question for 12-year-olds who have handled samples of various materials, done some simple weighing and measuring and probably arrived at a feeling for 'density'.*

Suppose you have several cubical blocks of wood, all the same size, all painted with the same grey paint, which you are not allowed to scrape or damage. One of the blocks has a lump of metal concealed inside it, that someone hammered into it before it was painted.

1. How could you find out which block has the metal in it? Give a reason for the experiment you suggest.

2. If you can think of other tests, mention them here.

3. The metal lump might be in the middle of the block, or it might be near to one face. How could you find out which?

(*Notes*: Part 1 is simple recall, from class experiment in laboratory.

Part 2 provides for the fact that there are several acceptable answers. The examiners do not have a single right answer that they demand. They will accept any sensible one and even give some marks for a suggestion that shows some thought but would not work. The question did not say brass or iron; and if candidate mentions use of magnet with a warning that it will distinguish iron, he gets a bonus mark.

Part 3 asks for intelligent guessing.)

B. *An exam question for 12-year-olds who have looked at various natural crystals, tried growing crystals, made simple crystal models with piles of wooden balls, and discussed the idea that crystal-forming may support the idea of 'atoms'.*

Suppose you have an uncle who is intelligent and interested in science but never learnt any science at school. He heard you say that you have been learning about crystals at school and that crystals tell you about atoms. He says 'I don't see any connection between great big crystals and atoms.' Write down what you would say to him if you were trying to explain.

(*Note*: This is a loose question to be marked A, B, C. The question itself must be worded so that it gives confidence and interesting excitement.)

C. *A question for 12-year-olds who have been doing simple class experiments in the lab, with batteries, lamps, switches, etc.*

You have a battery and a small electric lamp. When you connect the battery to the lamp it lights brightly.

1. Suppose you have two (equal) lamps and that battery. There are two different ways of connecting the lamps to the battery to make them both light. Draw the two arrangements.

2. One of the arrangements of 1 makes the two lamps light more brightly than the other arrangement. Put a ring round the brighter arrangement.

3. Neither of the arrangements of 1 makes the lamps light quite so brightly as the single lamp did. Suggest a reason for each case.

4. With the same two lamps and two batteries you can make both lamps light brightly. Draw the best arrangement.

5. Freddie Jones follows your instructions for 4 but his lamps fail to light at all. Tell him what he has done wrong. If you can think of several different mistakes, tell him each of them.

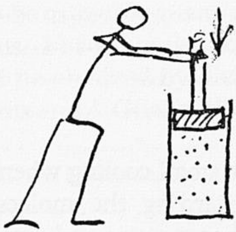
6. Tell Freddie how he can test your suggestion(s) of his mistakes.

(*Notes*: This ranges from simple recall to intelligent guessing. Part 1 carries little or no marks. It is only there to elicit groundwork for the later parts. Freddie Jones is a fictitious child who makes mischievous mistakes. He appears in homework problems.)

(All the specimens below are intended for 17-year-old pupils. In an examination there would be a few cheap recall questions to encourage candidates with an easy start; then questions like the specimens below. There would be some that ask for calculations, chosen to avoid cheap recall, and usually ending with a request for an explanation of the method used. Then some longer 'essay' questions. The scheme shown below, with a few lines for each answer to be written on the question paper, is to be preferred to 'objective test' types with the right answer to be chosen from five offered answers, because the form here gives pupils better opportunity for independent thinking. Since the answers of many candidates are quite similar, marking is quick.)

D. *A problem given after considerable discussion of a simple Kinetic Theory of gases.*

a. A gas in a cylinder with a frictionless piston is suddenly compressed by a man pushing the piston inward. The gas grows hotter.



1. Describe, in terms of molecular behaviour, the mechanism or process by which the gas grows hotter.
   ....
   ....
2. Where or what is the heat that is gained?
   ....
   ....
3. Where does the heat that is gained come from? What provides it? *Note*: The piston grows no cooler.
   ....
   ....

b. 1. A compressed gas in a cylinder with a movable piston is allowed to expand by pushing the piston out. Explain briefly why the gas cools.

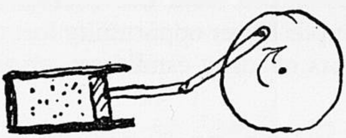
....

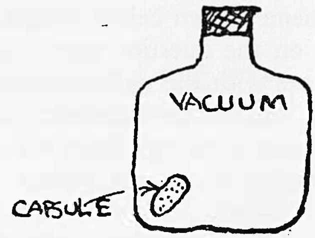
....

....

2. If the piston is connected to a frictionless flywheel, what happens to the heat lost by the gas?

....





c. A small capsule of compressed gas is placed in a large bottle from which all air has been pumped out, so that there is a vacuum. The capsule splits open and releases the gas. Explain why in this case you would NOT expect to find the expanded gas any cooler.

....

....

....

....

d. Most real gases do show a small cooling when released as in (*c*). What does this suggest regarding the molecules of such real gases? (*Hard*. Make an intelligent guess and give a brief reason for it.)

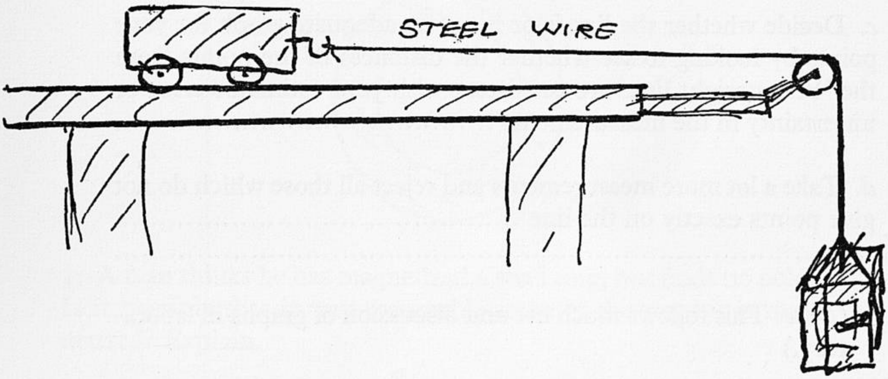
....

....

....

(*Notes*
a (1, 2, 3) are simple recall from class teaching.
b (1) often produces wrong answers, despite success in (*a*). This suggests that we need (*b*) to make sure the molecular story is understood.
c. Expensive recall and/or imaginative thinking.
d. Intelligent guessing. Note that we warn candidate that this is very hard. In an average O-level group 30 to 50 per cent might get (*c*) right, but only a few per cent at most succeed with (*d*).

E. An experimenter makes a truck accelerate by pulling it with a load hung on a wire over a frictionless pulley, as in the sketch below.



In despair at not getting any really exciting acceleration of the car along the track, the experimenter attaches to the end of the steel wire a large steel safe that weighs several tons. He expects an acceleration of the car along the track several thousand times as great as the acceleration of vertical free fall. Is he right? Why? About how much acceleration do you expect? Be very careful in wording your reply to be as nearly quantitative as you can without accurate measurements. For example, you might say (wrongly): 'The acceleration will be obtained by dividing the acceleration of gravity by several thousand.' Give a clear justification for your answer ....

....

....

....

....

(*Note*: Expensive recall.)

F. Suppose that in your laboratory experiment investigating some unknown relationship, you find that your plotted points on a certain graph are very nearly in a straight line. Which of the following statements best describes what you should do as a good scientist? (Choose one only.)

a. Examine the distances of the points from the 'best straight line' and from these estimate the accuracy of your experiment...........

....

b. Explain how you could have done the experiment to make all the points come out on the line ....

....

c. Decide whether the line is or is not an adequate graph for your points by looking to see whether the distances of the points from the 'best straight line' are consistent with your estimated error or uncertainty in the measurements ....

d. Take a lot more measurements and reject all those which do not give points exactly on the line ....

....

(*Note*: This follows much use and discussion of graphs in laboratory.)

G. What would you mean as a scientist if you described an experiment as a good experiment, or a successful one?

(Obviously there is no single right answer to this. You are invited to give your own opinions and comments to, say, an intelligent non-scientist who says, 'How do you know whether you are experimenting or just playing around with apparatus; and what is the difference between research and routine technical measurements?' Give examples from your work in this course if you like.)
.... (a whole page offered for answer) ....

(*Note*: Loose question. Mark A, B, C. Examiner expects many different acceptable answers.)

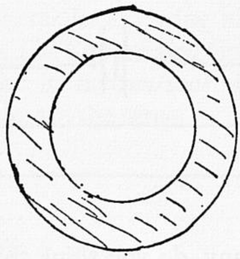
H. Describe the meaning and use of 'laws' in physical science, discussing examples such as Hooke's Law, the Law of Conservation of Momentum, etc.

(Suppose you are answering the questions of a neighbour in the course who has somehow missed all discussions and reading that relate to laws. He asks, 'What are laws? Are they true? What makes nature, or apparatus, obey them? ...' Suggested limit one page.)

(Obviously there is no single right answer to the question 'What is a scientific law?' You are invited to give several opinions.)

(*Note*: Loose question. Mark A, B, C. This is a hard question, but not so hard for pupils as for adults. Young candidates may give a very short answer which still shows some understanding.)

I. In the light of a simple theory of magnetism, comment on or answer each of the following using a diagram where helpful.

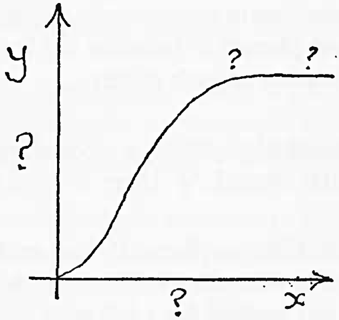


1. A man thinks he has magnetized a steel ring, but finds no poles. Is it possible that in any reasonable sense of the word it is magnetized? Explain.

....

2. How could you test your explanation?

....



3. The sketch opposite shows a graph of the magnetization of an iron bar (using d.c., not a.c.).

a. Interpret the stage shown by the nearly horizontal part of the curve.

....

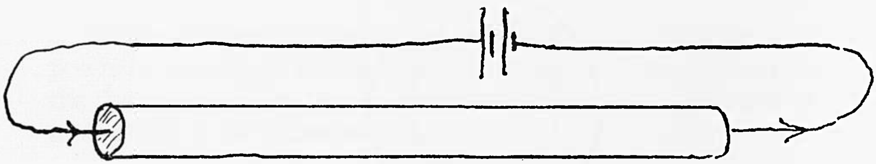
b. What is (probably) being plotted upward on this graph, that is, on the y axis?

....

c. What is (probably) being plotted along on this graph (that is, along the x axis)?

....

4. (*Hard.* Make an intelligent guess.) A student, asked how to magnetize a solid rod of steel, replied mistakenly: 'I would use a battery to drive a current through the bar, as shown in sketch.'



What magnetization, if any, do you think this treatment would produce?

....

(*Notes*: (1) and (2) are simple recall. (3) is expensive recall. (4) is entirely new, asking for an intelligent guess drawing on expensive recall. This is a 'trick' question, in the sense that it cannot be used again – once the question is published, future candidates can find the answer and will not forget it.)

J. A central agency, some time in the future, sends experimenters A, B, C, etc., out to various planets to measure the local acceleration due to gravity g at the surface of each planet.

1. A reports at the surface of planet P_1 a stone dropped from rest fell about 10 ft in the first second. 'g' there is roughly ....

2. Experimenters B and C go to planet P_2 and make very careful measurements, arriving at answers $g = 18{\cdot}6$ and $18{\cdot}8$ metres/sec². Experimenter D, who has applied for a job with the group, is sent to join them and they give him the measurement of g as a test. He obtains $17{\cdot}7$ metres/sec². They calculate his error and report it as $5{\cdot}32$ per cent. Criticize their report.

....

....

....

In calculating the percentage error of D, they could divide by 18·6, 18·8, their average 18·7, or by 20. Why is 20 just as good a choice?

....

....

....

3. Experimenter E, sent to planet P_3, takes a spring balance marked in kilograms and a standard kilogram with him. He observes there that when his kilogram is hung on the balance the reading is 5·0. What is the value of g there? In reporting his value of g he gives it in newtons per kilogram. The Supervising Government Coordinator objects that g should be in metres/sec^2. Explain briefly to the coordinator why the units are the same.

....

....

....

4. Experimenter F measures g with a simple pendulum. His assistant notes that F makes some mistakes in his measurements. In calculating g with the formula $g=4\pi^2L/T^2$, he uses a value of L which is 2 per cent too big and a value of T which is 3 per cent too small. His result is therefore about........per cent too........

5. Experimenter G travels by rocket to another planet and wishes to measure g there. Through incompetent packing his clock for timing free fall is broken in transit; but he arrives with two barometers in good working order.
Barometer A is an ordinary mercury barometer with its scale marked in inches.
In barometer B the atmosphere pushes a piston against a good steel spring; so that atmospheric pressure is measured by the distortion of the spring. The scale of B is marked in 'inches of mercury'.
In the laboratory on Earth both barometers read 30 inches before starting. On arrival at the other planet, barometer A (mercury) reads 45 and barometer B reads 90. Estimate the value of g there.
$g=$..........

(*Note*: To judge the value of a set of questions like this one needs to know the work of the course in detail. This question was given to pupils at an early A-level stage who had made rough measurements of g; had discussed the meanings of mass and weight with the help of a problem about taking a spring balance to the Moon; had derived a value of g from pendulum measurements; and had discussed accuracy and percentage errors and the value of some rough estimates in science.)

PREFACE TO YEAR I

This is a year of gaining acquaintance with materials and their properties and behaviour, and instruments, and the way in which scientists do things, and just a little of the way in which scientists talk. It is a year of seeing and doing, with very little to be learnt by heart.

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

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

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

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

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

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

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

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

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

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

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

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

Before using those instruments, children should use some more familiar ones. So we start with samples of material on view – brass, glass, lead, sand, water ... and ask children to make simple measurements and weighings to give a feeling of density. (To make that easy and quick, we offer rectangular samples of whole-number dimensions in centimetres and direct-reading balances. And our rulers are graduated in centimetres, with no millimetre marks.)

We let notebook records be short and simple; and we do not – yet – burden the story with discussions of accuracy or long arithmetic for great precision.

That brings us – going backwards in the syllabus – to the beginning of our course for eleven-year-olds: a shelf of many materials to be looked at and handled. The children do not need to write notes on these, in fact they should not, or the pleasure of enlarging acquaintance may well be dulled by formality. (In our own childhood, some of us have scratched a window pane with a diamond or watched a water-flea's heart beating, or choked with chlorine, but we didn't write a neat notebook report. Nor did we write an explanation, saying the diamond ploughed the glass because (!) it is harder, or a story that diamond is harder because its atoms are close packed in a tetrahedral 'molecule').

Treated like that, our collection of samples (staying on the window-sill for weeks) needs no lecture from the teacher; but, farther along the line, crystals may start a discussion that will lead to talk of atoms arranged in regular array. 'How small are they?' ... 'Suppose atoms were as big as marbles? Listen ...' Pour marbles on the table, then peas, then sand, then powder, then water ... 'How small? Would you like to look at powder? Here is a magnifying glass for each of you.' Then a microscope – really just to get used to using a microscope – to look at powder and sand and fibres of paper; and to watch salt crystals growing.

Children will meet magnets, and play with them, in Year II and study magnets and fields more seriously in later Years. In this first Year, however, we should provide some magnets to show forces being exerted when things are a visible distance apart. In early years, many pupils regard attractions as obvious but they should extend their knowledge to repulsions by handling magnets now. Cylindrical bar magnets will roll away from each other; but the strong push between modern horseshoe magnets is even more impressive.

After this first round of making acquaintance with materials and instruments, we ask pupils to do some simple weighing and measuring. We provide direct-reading balances and rectangular samples of materials with whole-number dimensions in centimetres, so that the work goes quickly. The aim is to let children learn about materials rather than to train them in techniques of accurate measurement – yet. Nor do we want them to spend long on arithmetic or build up a feeling that mathematics puts stumbling blocks in physics. (Again and again in these early years we want them to see the wood, not study the trees. Detailed study of a tree or two will be there as well, in some class experiments!) Therefore, we hope that schools will have, and use, these balances and blocks and resist temptation to use more professional equipment that they have in stock – that would miss the point of our hopes of moving faster towards exciting physics.

Since some of the samples are of different size, the idea of density as a useful description arises naturally. Pupils also try liquids: again a rectangular box with whole-number dimensions avoids delays that are irrelevant to our main interest. That leads on to the question of weighing air, an exciting business that the children discuss and carry out. Later in the year, we shall return to air pressure, and a simple kinetic theory.

We have been asking children to think about atoms and calculate densities. This is a good time to give them some constructing that needs fine fingers but not much reasoning. We provide materials for a simple microbalance – a straw for a beam and a needle for pivot. Carefully made, this can be used to weigh a grain of sand, or perhaps a dozen grains, or even a single hair. We show a specimen ready made, then give each child materials and plenty of time. Only a real trial with real children will convince one how long that time must be – and after a teacher has carried this through with a class he will agree that the time was worth spending. We must help; we must give time and encouragement, but we do not make the balance for any child unless he is handicapped. A child who does not get his balance made may do without, or he may take it home to finish it. A child who does get his balance finished may certainly take it home and keep it.

Then we suggest weighing a grain of sand, or perhaps 10 grains, and the cry at once arises: 'Where are the weights?' We offer a scrap of paper. 'But how much does that weigh?' 'I don't know but I cut it from this sheet of paper. You may have a sheet and here is a pile of 500 sheets.' Then with encouragement children will start making their own 'weights'. We suggest weighing grains of sand, a dead fly. ... When 10 grains of sand have been weighed, we ask for a rough estimate of the number of grains in a handful, or the size of a pile of a million. Some children will want to weigh several batches of 10 grains – if none do, the teacher may suggest it – and that can raise a first discussion of statistics – a very important matter in modern physics, whose teaching should begin early.

Above all, this little balance is a thing to make oneself and enjoy having, rather than something which is annoying because it is too difficult or spoiled because someone else makes it for you or someone else asks difficult arithmetical questions over it. In fact, this balance illustrates a general principle regarding experiments and topics in this course – or in any new science course that aims at understanding – one cannot judge its full value until the second year of teaching it over again. When one has tried it one year and found how long it takes and what delight the owners have, and learnt to be patient with questions and how to praise the results, it becomes easier to run the next year. And then one finds intriguing opportunities to lead from this experiment to other topics that need an opening question.

During the year we shall use metric units more and more; so we take several opportunities for class experiments that give practice in weighing in kilograms, measuring in centimetres, etc. We shall give each child a paper centimetre ruler to take home.

We let some homework questions carry children's thoughts from large-scale measurements down to atomic sizes. Here and elsewhere, we show how scientists sometimes value rough estimates;

and we encourage children to make 'scientific guesses' (and, later on, to judge their reliability). We tell them a scientist is a sort of detective, who not only finds clues but spends a lot of thought trying to build knowledge from his clues.

Two sets of class experiments give opportunities for children to work at their own pace and find out as much as they can. One is an 'open' experiment with a simple seesaw or lever. 'Find out what you can about arrangements of loads for balancing' is the instruction. We do not expect many children to arrive at a formal rule of moments. Our chief aim is to provide a field for their own experimenting; and we want experimenting to encourage some reasoning, within the child's compass. We hope children will spend a number of periods finding out more and more about the balancing of the seesaw. And we hope many will carry it home.

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

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

Our next supporting experiment is an estimate of the size of a molecule. Each child places a tiny drop of oil on a clean water surface. The child measures the size of the drop himself and the size of the patch. We show children how to work out an estimate of molecule length by a short cut in arithmetic. This is an 'atomic measurement' that a child can take home with pride. For that matter we hope that schools will let children take the apparatus home, to give a demonstration of measuring a molecule.

Forces have cropped up at intervals, and now we look at forces in some class experiments. A force is a push or pull at this stage – and children feel magnets repelling as well as rubber bands pulling.

From this simple study of forces we go on to forces doing jobs for us, and we begin to mention work and energy informally, with many illustrations, to start acquaintance. With energy – the other main 'concept growing by familarity' of this Year – we have to proceed carefully. Atoms may be common in public talk, and children will accept our use of them. If they ask questions that is all to the good; but leaving knowledge unfinished will not do much harm in the long run. Energy, however, is a stranger word, likely to bring more misleading prejudices. So we must start by many simple demonstrations, raising a brick, pulling out a spring, twisting, compressing, etc., asking again and again 'Could you do that without using your muscles and needing food; could a horse do that without hay; could an electric motor do that if it is not connected to the mains?' We build up the idea of fuel being needed to do those jobs of work for us. We measure 'work' simply in foot.pounds (or kilogram.metres) and count the cost of that measurement. We do not say dogmatically that one cannot get the job done without fuel, but we give a strong impression that we think it very unlikely.

Then we go back to the lever experiment and point out that it will give us a big force for a small one if we choose unequal distances. It is a 'force multiplier'. We ask if it will also 'multiply' energy for us. We look at the input force pushing down and the output load being raised and find we have no gain or loss. We at once say that that is the important thing about energy: 'You do not gain or lose.'

This is a very informal discussion – like a child's first visit to a foreign country – with experiments to see and try, but little reasoning and no formal definitions. We want children to enjoy working with the idea of energy; and we want them to look forward to using that concept as a very capable servant.

Our survey of forms of energy runs on 'by popular request' into nuclear energy. Here, too, we must not just teach by assertion, and certainly not by 'special pleading'. We show a cloud chamber, preparing for it by simple class experiments in fog-making; then we offer diffusion cloud chambers for a class experiment. At the end of the year, we demonstrate another way of 'seeing' the projectiles from radioactive nuclei; a simple counter that counts alpha-particles by visible sparks. These are things for a first look at radioactive atoms, with little or no explanation. We leave them, with a promise to return.

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

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

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

In looking forward to this Year we should think of the pupil who learns a piece of physics thoroughly, trying his own experiments and watching demonstrations, discussing with the teacher, doing his own thinking. He makes simple knowledge his own, and says:

'*I understand this.*' That is a proud possession, giving a sense of power, a sense of strong knowledge which can be of lasting value in his education.

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

KEY TO MARGIN REFERENCES

C = Class experiment
D = Demonstration experiment
H = Suggestions for optional experiments at home
F = Film
T = Teaching of material (lectures, discussions with pupils, etc.)
P = Problem
* * * = Commentary (notes on methods, aims, etc., offered to teachers)
‡ = Reference to footnote
§ = Reference to a comment made by a teacher during trials.

(The experiments are numbered serially through the Year, irrespective of the classification C, D, F or H. The same numbers will be found for each experiment in the *Teachers' Guide to Experiments and Apparatus*. Where (a), (b) ... are added to the number these refer in some cases to separate parts of the same group of experiments, in other cases to alternative versions of an experiment.)

'CONCERNING THE NATURE OF THINGS'

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

Donald McGill 1963

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

Chapter 1

MATERIALS AND MOLECULES

Exhibition, crystals, weighing

EXHIBIT FOR ACQUAINTANCE

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

A wide variety of specimens of natural and man-made materials should be available to the children. We should have an exhibition of many samples, such as a long shelf with blocks of metal, rocks, samples of crystals, large and small, and some bottles of liquid, etc. These exhibits should stay there on a bench or window-sill or in a corridor and be available to help children become acquainted with unfamiliar materials and to look again at the familiar ones. Children should be free to look closely at them and touch them as much as they like. To begin with all should be labelled; later on some of the labels may be removed. D1

There should also be specimens of certain materials in sufficient quantity for children to handle them in a lesson. When children are given these, they should be encouraged to feel them, handle them, smell them. D/C 2a

And a few balances and centimetre rulers, and perhaps measuring vessels, strategically placed, may suggest experiments. Balances are likely to be fairly popular; but few will use the rulers. Measuring lengths seems to be a rather artificial scientific activity at this age; and the idea of measuring lengths to calculate an area or a volume does not occur to these pupils because the *need* for those results is not obvious. So we should not press the use of instruments. However, we may encourage the business of measuring by giving out paper scales, marked in centimetres, that children may take home and keep – see the miniature copy in the box. These will start an interest in metric measurements, if they are unfamiliar, and will raise some interesting questions of measurement at home.

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

Blocks of:	COPPER, IRON, BRASS, ALUMINIUM, LEAD (including lead shot), A BRICK
Blocks of:	WOOD, GLASS, BAKELITE, FOAMED PLASTIC, PERSPEX, RUBBER
Igneous rocks:	GRANITE, basalt
Sedimentary rocks:	LIMESTONE, sandstone
Metamorphic rocks:	MARBLE, SLATE, schist
Various crystals:	large and small, some coloured (e.g. salt, alum, PHOTOGRAPHIC HYPO, WHITE 'COFFEE SUGAR', copper sulphate, chrome alum, calcite, mica)
Various powders:	crystalline and 'formless', e.g. flowers of sulphur
Textile materials:	silk, cotton, wool
Substances with smells:	bleach, paradichlorbenzene, camphor, naphthalene, curry powder, a block of kitchen soap
Household materials:	sugar, soda, salt, vinegar, olive oil, gelatin, starch, chalk, plaster of Paris
Man-made composite materials:	plywood, concrete, ceramic, grease-proof paper, Formica, a tungsten carbide drill
Food:	wheat, sugar, (?) flour

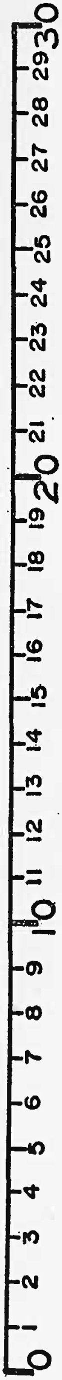
Liquids in bottles:	water, glycerine, oil, alcohol, mercury, olive oil, bottle of pitch (or a cardboard box with pitch in it and a hole for the pitch to ooze out slowly), bottle containing ice and water
Gases:	bottle labelled 'air' bottle labelled 'ammonia' bottle labelled 'CO_2' (try it on a candle) bottle labelled 'vacuum' (prepared beforehand) gases in balloons‡ (prepared a *short* time beforehand: air, (coal gas), CO_2, (? hydrogen)

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

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

‡ Balloons can be filled with the help of a large aspirator. Fill the aspirator with water, then let the water out; drawing in gas until the aspirator is full of gas. Then drive water in from the tap, to drive the gas out into the balloon.
Balloons leak unless the neck is twisted and knotted beyond recovery – and even tied with a tight thread round it as well. If one ties the balloons loosely so that the knot can be untied for the balloon to be used again it will leak and the experiment will be a failure. One must regard these balloons as expendable. Both hydrogen and CO_2 leak out through rubber balloons; yet if teachers can fill balloons just before the class hour they will find the cost both of time and balloons well repaid.
If balloons prove too difficult to prepare, polythene bags might be used instead. They should be inflated until they are just taut, with the neck twisted and taped. Suitable food bags can be obtained from chemists.

§ A teacher in trials commented: 'Enlightening remarks heard: polystyrene squeaks, floats, holds heat. Hardwood and softwood produce different sounds when knocked. Practically every member of the classes "discovered" something within first five minutes.'
Another teacher reported: 'Girls were very interested in textile fibres.'



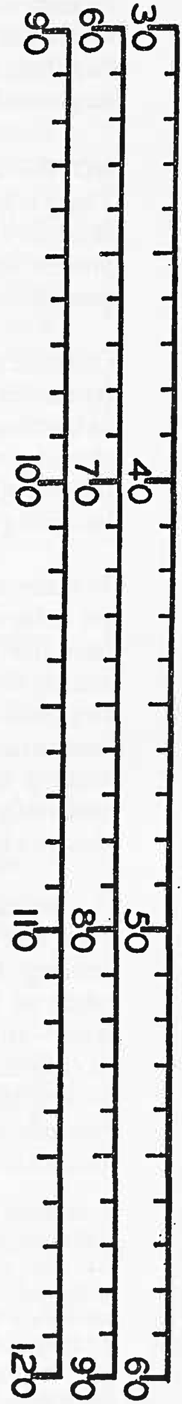
CENTIMETRE RULER

This sheet gives you a paper ruler marked in centimetres. You may take it home and keep it.

To measure large things, you should join together the separate pieces of the scale marked along the edges. Cut them out with scissors so that they make a narrow tape. Join the sections with paste or paper clips or staples or sellotape to make one long tape. Be careful to join them fairly accurately with the same mark on the two pieces overlapping where they are joined.

Please make some measurements with your tape and bring a note of them to class. Here are some suggestions:

- length of your foot
- width of your foot where it is widest
- height of a neighbouring boy or girl (mention age)
- height of a parent or other adult
- width and height of your front door
- length and width and thickness of a book
- length of a bus
- length of an egg
- width of a thimble
- the length, width and height of a room in your house (or your classroom). Write each of them down in centimetres, then in metres. Work out the volume of the room in cubic metres.
- diameter of a clock face
- diameter of someone's watch face
- diameter of a drinking glass; also its circumference. Then divide the circumference by the diameter to find a rough value for π
- your own diameter (at waist)
- the difference in height between two people (such as father and mother, two sisters, or two other pupils in your class)
- the circumference of your upper arm, round your biceps muscle, first when your arm is slack, then when you are holding a heavy load, with your arm bent up at the elbow.



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

NOTE-TAKING?

There is no need for making notes here, which will only slow down children's gaining of experience and turn a light-hearted discovery process into a heavy-footed directed procedure. That is true in general of much of this Year's work.

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

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

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

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

§ 'Notebooks given out. There was a general groan and the comment: "Here we go." But they cheered up when told they could put just what they wanted to in the notebooks.'

In our preliminary trials, we asked teachers to try doing without note-taking in the early stages. We asked them to do their best to discourage note-taking but at the same time to reassure pupils that they were not losing something important. In many cases that was not successful at first: teachers did not feel comfortable and pupils worried about not having notes to revise later for examinations. When the specimen 'Nuffield Physics' examinations were given to classes in 1964 and 1965 there was a remarkable change. Both pupils and teachers saw that mechanical revision from notes would play a much lighter part in our examinations. Then note-taking took on a genuine scientific flavour much more happily: it became a matter of recording easily what one did and what one saw, rather than storing up for 'revision'. Revision itself began to seem somewhat less important.

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

Vacuum? If children do not ask what to do about the vacuum D 2b
bottle, the teacher will have to open it under water anyway. But if
the children do not ask how the vacuum got there, the pump that
the teacher used beforehand should remain hidden!

FORCES: ATTRACTIONS AND REPULSIONS WITH RUBBER AND MAGNETS

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

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

For this Year, a very simple feeling for force – which many children T
may already have – will suffice; and we hope teachers will post-
pone any careful discussion of forces and their measurement to a
more mature stage in a later Year. However, we do need to bring
pupils' feeling for force to the surface and to attach the name
'force' to it. So we should give them the following short play with D 2c

forces. This is suggested as fifteen minutes of play, with only a simple comment. It would be unwise to expand the discussion. It can be given now, as part of the exploration of materials, or later, just after the 'Springs Investigations', Experiment C 33, or later still when we begin discussion of doing useful jobs, just before C 70. Most teachers in trials reported that they found it better to leave this play with forces until one of the later stages.

We give each pupil:

- a rubber band or piece of elastic thread to stretch,
- perhaps a spring to stretch (but experiments with springs will come later this Year),
- a piece of string to pull and feel tension,
- a weight (e.g. 1 kg) to hold, to feel the Earth's pull.

In each case we just say:

'Feel the pull. That is what we call a force.'

All these contribute to the concept of a force as a pull, an attraction. Pushes (repulsions) seem to be less familiar and we should encourage children to feel them by providing magnets. So we also give each pupil a pair of bar magnets to play with and feel repulsions as well as attractions (with no mention or discussion of 'poles' till next Year). D2d

CRYSTALS

Children should handle crystals themselves, as well as just look at them in the exhibition. If some large specimen crystals of alum, sugar, etc., are available, these should be handed round now. But, more important, each child should have some small crystals to examine for himself. These need not be large exhibition specimens, but they should not be so small that a magnifying glass is needed. C3 H3

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

Crystals under the Microscope. When children come to use magnifying glasses and microscopes for class experiments, a short time from now, they should certainly look at hypocrystals to see if they can find more details; and they should certainly look at a C3 H3 whole series of sugar crystals, ranging from those of very fine sugar to 'coffee sugar' and perhaps even see irregular rocky large crystals on a string.

Then they should at all costs use their microscopes to watch salt crystals forming and to look at the shape of the tiny crystals made by brine as its water evaporates. There are so many other substances that are easily watched under a microscope as they crystallize, that teachers will be tempted to try substitutes for salt when they find it needs special arrangements. Suggestions from colleagues will range from hypo (which some children know) to phenyl salicylate, which is utterly strange. But we urge teachers strongly to use the common substance, salt, that children already know so well.‡ Instructions for making salt crystals are given in the description of the class experiment with microscopes C 12. Only after success with salt should other substances such as salol be tried, if there is then time.

Class Experiment to see Crystals forming

Before pupils embark on crystal growing, they should see an example of rapid crystallization. Give each pupil (or each pair) a test-tube containing a little melted photographer's 'hypo' that has cooled back to room temperature and remained liquid and ask them to watch what happens. Some pupils may notice the temperature change too, but we should not suggest looking for that. The forming of solid crystals is what we hope they will see. C4

The hypo, which has been melted some time before the class and allowed to cool, will probably remain liquid although it is below its melting point. However if the teacher finds many of the prepared samples have solidified of their own accord, he should add a drop of water to each test-tube of crystals when he does the original melting. If there is just enough water to make the crystals a little 'mushy', like wet snow, that trouble will not occur. The tubes of melted hypo should be shielded from dust.

‡ At the Commonwealth Conference on the Teaching of Science, 1963, our hosts in Ceylon showed us the very fine new syllabus of science teaching that they were building for their schools. On the one hand they emphasize *ideas*, giving teachers clear indications to promote discussion – and on the other hand they bring in many simple class experiments and demonstrations. For all those experiments they try to use *common materials*, things that children will find at home. That choice is a very wise one in beginning the formal teaching of science – one that we should remember here.

Crystal Growing. Start a crystal-growing experiment in the laboratory.§ The usual method is to grow some small 'seed' crystals in a saturated solution as it evaporates; tie a small seed crystal on a thread and hang the thread in a jar of strong solution. Children find it difficult to do that tying. A good suggestion for making seed crystals and starting growth easily is: C5

> Dip a piece of thread into saturated solution; lift it out and hang it up to dry. Small crystals will appear on it. Hang this in saturated solution that is free to evaporate; and after a few days, as the crystals are beginning to grow, break off all but the best. A very fine shape can then be obtained.

This will take some time so it should be started early and continue through later topics. If children want to grow crystals at home, give some instructions for it. T

If possible, supply alum to take home. Teachers in trials report this as a very popular activity; well worth the trouble of giving instructions and providing materials. The expense in materials is small; alum is cheap – much cheaper if the laboratory buys it wholesale than if children buy it in small quantities retail. So we hope the school will make plenty of alum available, preferably free.

This is a case where the school can make a very important contribution to education at home. Anyway children will try other crystals, such as washing soda, that they find at home.

> 'Take some alum home, dissolve it in a little hot water adding alum until no more will dissolve. Pour off the clear solution into a tumbler and let that stand on a shelf for a week. Look at it every day. Hang some strings in it from a pencil across the top, to offer a starting place for crystals. H5
>
> 'Try the same with table salt, sugar and, if you like, with Epsom salts.'

§ A teacher in trials reported: 'The children were really absorbed in tying cotton on to the seed crystal, etc., possibly due to the fact that *everyone*, not every *other* one, was responsible for a crystal growing experiment.'
Another reported: 'Regular shapes of crystals noticed. Salt under lens caused excitement, "They're *square*!" '

INTRODUCING THE IDEA OF ATOMS THROUGH CRYSTALS

Both teacher and children should ask questions about crystals, and we should encourage the suggestion that some things must be arranged in a regular array inside crystals, things too small to see – 'atoms'. Otherwise, it is difficult to see why crystals make such regular shapes, and how 'they know how to make the same shape every time'. (Of course professional crystallographers will warn us that the same material makes a great variety of shapes, as judged by the layman, although they are to him all of the same fundamental pattern. To children, at this first careful look at crystals, the idea of some standard shape is likely to seem quite clear.) T

'Atoms?'

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

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

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

Some teachers find that wallpaper gives a good illustration of a pattern of 'atoms' within a larger pattern of 'molecules' within the whole covering of the wall representing the whole crystal. T

Crystal Models

The teacher should show models of crystals ready made with large visible balls stuck together, and point out that those models agree with the way in which crystals seem to keep their shapes. D6

Class Experiment: making Crystal Models. Now that children have grown some crystals and have met the suggestion that crystals may be made of some tiny 'atoms' arranged in some regular way, they should try building their own crystal model. It is best if they can use common materials that are easily obtainable so that each can make his own model and even perhaps continue at home. Marbles from a toy shop are of a convenient size for 'atoms' in the class experiment models. Those marbles are not all of uniform size but we find on experiment that they are uniform enough for pupils to be able to pile them in an array, using a little care. (Trials with smaller glass balls, from chemical suppliers, have led to troubles with balls getting spilled and lost; and those small balls have not proved easy for children to work with.) C7

We give each pair of children five dozen marbles and a small tray in which to build their models. At first we tell them to try piling marbles and find out how best they may be packed together. Then we suggest building a pyramid on a square base in the tray. Start with the lowest layer five by five: 25 marbles packed in a tray that just holds them in a square array. Then add another layer on top making a square four by four balls, and so on.

Pupils should look at the shape of the 'crystal' which they are building and at the angle between its faces. They may notice that even if their crystal is 'imperfect' – because some balls have been removed so that its shape is spoiled – the angles between faces are still the same as before. They should compare that with the behaviour of real crystals, such as alum.

The tray in which pupils build their crystal model is important: it must be the right size to hold the base layer of marbles comfortably, and yet it should not be an expensive tray of wood or metal. For one thing we are anxious that schools should provide plenty of this equipment without great expense, if possible in a form that can easily be taken home. For another, marbles are not all the same size and so a tray with some flexibility will make it much easier to build a model. Therefore we suggest the trays should be made of thick paper or thin cardboard, like a postcard, cut into squares with the edges bent up and stapled.

(As a deluxe form of equipment, we suggest polystyrene balls instead of marbles. These are available in sizes ranging from $\frac{1}{2}$ inch diameter to 3 inches, costing 1*s* 6*d* upward per dozen. These are more uniform in size and just as easy to handle, but the total cost is likely to be six times as much.)

Crystal Model Demonstration. Meanwhile the teacher should build his own crystal model and discuss it with pupils from time to time. D8

This model should be a larger one, built of polystyrene balls $1\frac{1}{2}$ inches diameter on a square wooden base. Start by building a small pyramid of spheres; 3×3 in the lowest layer; then four balls on top of those and then one to complete the model. Let the crystal 'grow' by the addition of more balls (see *Experiment Guide*).

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

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

Cleavage. Show the cleavage of a large crystal of calcite, by placing a razor blade on it with the right orientation and giving the blade a sharp tap with a hammer. D9

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

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

This is a surprising and important demonstration. It is practically meaningless to all pupils except those in the front row unless a large crystal is used. Therefore *the large calcite crystal must be* *regarded as expendable material* – like acids in chemistry – and a new crystal obtained for every class that is taught. If it weighs only a few grams it is far too small. The demonstration will become a dangerous trick for the teacher and an invidious swindle for all the pupils beyond the front row. A calcite crystal weighing dozens of grams is needed; and although it is necessarily 'expended' its cost will be well justified.

Films and Photographs of Crystals (Optional). We suggest the following:

a. The 25 minute film 'Crystals' by Alan Holden. This is a PSSC film on growing crystals, which would delight any teacher and most children. It can be hired from Sound Services Ltd, Wilton Crescent, London, S.W.19. Dr Holden is a crystal physicist at Bell Telephone Research Laboratories, and joint author of the book about crystals and crystal growing referred to above. D10a, b OPT.

We have differing reports from schools where this film has been shown in trials. Some say that the film is too long for children to enjoy the whole: others say the film is very useful and a delight to children. The key to successful use seems to be to show the film in two stages, part in one lesson and the rest in the next.

It is essential that no film should be a substitute for pupils seeing the actual growth of crystals under a microscope for themselves. The real experiment should come before any film.

b. Show a photograph of snowflake crystals if available. D10c OPT.

A Question about Atoms. Ask: 'How small must atoms be compared with your hand?, a pin?, a flea?' and leave the question unanswered.

Atoms moving in among Each Other. As a class experiment, each pupil should dissolve some salt in water in a small beaker and watch it. We ask what has happened to the crystals. To an adult scientist this seems so trivial an experiment that one would not expect to take the trouble to do it; but to these young pupils it is drawing attention to something they have not worried about before, and in the hands of a wise teacher it will lead to an interesting discussion. C11a

As an optional demonstration we may also raise a question about volume changes when salt dissolves in water. With an able group of pupils this can promote interesting discussion. But if this question is raised at all there must be a demonstration.

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

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

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

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

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

LOOKING AT SMALL THINGS: MAGNIFYING GLASS AND MICROSCOPE

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

Microscopes: A Note to Teachers

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

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

The J. Willmer Home Experiments Endowment
C/o A.S.E.
52 Bateman Street
Cambridge

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

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

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

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

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

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

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

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

Class Experiment. Pupils should look at anything they want to, C12a
first with a magnifying glass and then with a microscope: sand, salt, blotting paper, talcum powder, a hair, their own handwriting, blood and then red ink, a fingerprint, natural asbestos, salt dissolving, some rocks such as granite. (The teacher should suggest only a few of these, and leave children to enjoy finding others.§)

In this work, children should certainly see crystals of salt, and they C12b, c
should watch crystals growing in warm brine placed on a hot microscope slide. We recommend giving children salt rather than materials such as salol, which forms crystals more easily, because salt is a common substance that children already know about. At this early stage of doing science, we hope children will deal first with material which they already know at home. Salt has the peculiarity that its solubility does not change appreciably with temperature. Therefore we cannot produce crystals by making a hot saturated solution and then just letting it cool down. Instead we must compel crystals to form by letting some of the water of our salt solution evaporate. So that the microscope slide itself must be

§ A teacher in trials said: 'Children found this section exceptionally interesting. I am sure they would have cheerfully carried on had I not been present! They spent about four periods altogether looking through magnifying glasses and microscopes.'

hot, and the solution should be warm or hot, so that evaporation into the air is copious. Heating the slide in hot water will not suffice – or, rather, crystal-forming will be slow. It is better to warm the slide over a small bunsen flame. We suggest that there should be several small bunsen burners running for communal use. As in so much experimenting – ranging all the way from a young child's first experiments to a professional research man's work – much is gained by a first rough try to see if the process will succeed. Once children have made salt crystals and looked at them, they become mysteriously skilful in making more. The brine should be a concentrated, practically saturated solution, available in a beaker from which children can take a drop at a time.

Notes

Again, no note-taking is necessary. A child who really wants to *
sketch what he sees may do so, of course, but he is a very unusual *
future biologist. Unless he is genuinely keen, we should encourage *
a child who asks about taking notes to hurry on and enjoy seeing *
things. *

The outcome of this experiment should be 'I have seen things with *
a microscope', or even 'I can make a microscope work.' Though *
untrue, that is an unusual and refreshing boast. *

These are familiar activities and instruments for us. But to children *
they are new and strange and deserve plenty of time. If playing with *
magnifying glasses and microscopes extends beyond two periods *
let it continue next time with an easy heart. It will be clear *
when this work is becoming casual messing about, and then chil- *
dren can move on to the next, entirely different experiment while *
others are still working with microscopes. *

Problems and Questions for Teaching

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

In that book there are many more problems than a class will have time to use in the course of a year. Teachers will need to make a careful selection. Too many problems will only give a sense of rush or else dull pupils' interest. On the other hand, too few problems will leave the teaching without that essential help towards critical constructive thinking that we hope our questions and problems will give. It is difficult to arrange a book of problems with clear classification to enable teachers to select at a glance those they want for their particular class. Therefore we feel it will be necessary, and very wise, for teachers to look through the problems some weeks ahead. That will not be wasted trouble, because teachers will find they can foresee and make good use of the help that problems ahead can give.

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

In this *Guide*, we shall give a few *sample* problems from time to time. These will be printed in a box. For example, see Problems A, B, C (p. 292), which relate to the early study of materials.

These are not specially recommended problems, suggested for a higher priority than others in the book of problems; they are only placed here as reminders to teachers of the part such problems can play in our programme.

WEIGHING THINGS: SOLIDS, LIQUIDS, GASES? (CONCEPT OF DENSITY?)

Weighing Solids

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

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

(Teachers should remember that there is a long and strong tradition *
of beginning physics with careful measurements of volumes and *
masses, and calculations of densities with considerable care over *
arithmetic. That is in some ways an admirable occupation for small *
fingers manipulating instruments; and it affords careful, if extremely *
boring, 'training' in arithmetic. Yet, however skilful and success- *
ful the teaching of it, the outcome seems to be technical skill *
rather than a sense of understanding physics; and the practice of *
those careful measurements and calculations takes considerable *
time. So, in our programme, we are anxious to experiment with *

teaching that does not emphasize formal work. If we regret losing *
that, or fear pupils will be hampered later on by lack of it, we *
should reflect that at a much later age the techniques can be *
acquired very quickly, and the arithmetic can be carried through *
with speed and understanding. So those of us who are skilled in *
careful teaching in this region will need to minimize the usual *
emphasis.) *

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

Materials. Looking at small things

A.§ 1. In which form, solid, liquid or gas, is matter easiest to compress or make smaller by squeezing? (For the liquid and gas think of a bicycle pump filled with water or air; you put a finger over the end and then try to push the handle down.)

2. Which two of these three would be closest to each other in amount?

a. The weight of a cubic foot of a solid

b. The weight of a cubic foot of a liquid

c. The weight of a cubic foot of a gas.

3. Which of the following changes – of state – brings about the larger change of volume?

a. solid to liquid (melting)

b. liquid to gas (evaporating or boiling)

4. From your answers to (*a*), (*b*) and (*c*), which two forms of matter would seem to be most like each other, solid and liquid, liquid and gas, solid and gas?

5. If matter is made of tiny particles pressed together (tightly or loosely), how closely would you expect the particles to be packed in:

(*a*) a solid? (*b*) a liquid? (*c*) a gas?

B. Suppose you have three stoppered bottles, each is half-filled with liquid and all are the same size. One bottle is half-filled with water, the second bottle is half-filled with bicycle oil, and the third is half-filled with golden syrup (or treacle).

1. What differences would you expect to notice when each bottle is slowly turned upside-down?

2. A garage mechanic says 'Motor oil is thicker than bicycle oil.' What do you think that remark means? Give a scientific description.

§ 'Considerable trial of different phrasing required during next lesson before they understood what the question was about. Then the answers came out in a rush.'

3. Is it correct to say that each of the bottles in the question is half-empty? If not, why not.
4. A can of lemonade has *two* places marked on the top where you should make holes to pour out the lemonade. Why two?

Discussion with Teachers: A Light Approach to Density

In the next few pages we suggest a programme of work in class experiments and discussions to lead to a general idea of density. We want pupils to develop a familiar feeling for density as a thing we know about a material – a useful qualitative concept rather than a quantitative definition and scheme of measurement. With an average or slow group of pupils, this might simply take the form of comparing equal-sized blocks of several materials; first by holding them (perhaps blindfold), then by weighing them with a lever balance. Even if we go no farther, that will establish general knowledge such as iron weighs three times as much as aluminium, for the same size of chunk, and many times as much as plastic foam.

Blocks of other sizes and other materials are provided in our suggested equipment. We could lead the teaching on to a discussion of weighing different sizes and working out the weight of some standard size, such as a unit cube, but we find (from our trials with actual classes) that this imposes discouraging barriers and delays on many pupils. Pupils *can* calculate the volume particularly when the measurements are simple whole numbers – for which we have arranged. Pupils *can* divide the result of their weighing by the result of their volume calculation, particularly when the latter is a round number. But many who can carry out the arithmetic do not see the point of the calculation – they carry it out obediently, without feeling the necessity.

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

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

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

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

> 'Here is a block of wood 2 centimetres long, 1 centimetre wide, 1 centimetre high. Here is a little cube of wood 1 centimetre by 1 centimetre by 1 centimetre. How many cubes are there in this block? ...
>
> 'Here is a block of wood 2 centimetres long, 3 centimetres high and 1 centimetre thick. If you could saw it up into cubes, how many cubes would you see on the front face? (This deserves a block of plasticine that we can make marks on.) How many cubes would you count altogether? ...
>
> 'Here is a block of wood that is 2 centimetres long, 3 centimetres high and 5 centimetres thick. How many cubes would you see on the front face? How many layers from front to back? Can you count the cubes altogether?'

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

‡ Teachers who realize how important density may be in more technical studies will be tempted to make the next move – which seems so small – into a discussion of density, however little interest their pupils show. Against that temptation, we wish to give the very strong report – extracted from our preliminary trials – that again and again, such an excursion into more formal teaching of density, where the arithmetic of the pupils is not up to it, or their interest is not aroused, has led to damaging delays and loss of spirit. We urge teachers not to let that happen.

If the pupils do find it easy to 'count the cubes' in various blocks, then they can do a few division sums to find out how much each cube weighs. Success at this level is likely to mean either that we have a fast group or that we are already spending more time on density than it deserves in this particular programme. (See previous footnote.)

With a fast group we should discuss the idea of weighing the block, measuring it, calculating the volume (but still calling that 'counting the cubes') and working out the density. Even with them, we should not labour the calculation or extend the experiment to a long series of measurements – or we shall meet the comment: 'That was not like a physics lesson – it was more like arithmetic.'

In a conference of Nuffield teachers who had just been teaching this part of the course, we discussed both the difficulties of teaching density and the needs for it. Here are some of the 'needs' they mentioned:

1. To provide a purpose for a series of class experiments. (Not necessary in this course, where we have many class experiments that seem to carry pupils further.)

2. To teach accurate measurement and the use of precise instruments. (Although a great many pupils will need to acquire such skills later, we suggest, as a matter of policy, deferring practice now. We even doubt if such teaching at this early stage in school lasts or transfers successfully. Certainly, if the work is boring we shall expect little lasting gain.)

3. To give opportunities for practice in arithmetic. (The practice has not proved to be helpful to our physics teaching in this course.)

4. To bring out the value and use of a general physical quantity such as density. (This is admirable, but does not seem to be appreciated until a later age of development.)

5. To provide a clear understanding of density as a measured and calculated physical quantity because it is used in physics from now on. We asked ourselves where density is used in our course, this Year or the following Year, and found only an indirect use of the density of air and the need for some understanding of the relative densities of air, water, mercury. No need for a fuller use of density,

involving calculations, appears unless we ask for it in homework problems. We pursued this question through Years III, IV, and V, with surprise and some uneasiness. It is very difficult to find places where knowledge of density as a quantitative measure is really needed. Yet we realized that in the later Years it should be available as a concept in dealing with physical problems. We agreed, wryly, that by A-level density must be a familiar concept, to be used quickly and reliably. But we also agreed that, if necessary, density and density measurements could be taught to an A-level pupil in a quarter of an hour – if he had somehow missed all teaching of it. Most teachers would feel uncomfortable at such an extreme postponement, and we do not advocate it. But we do suggest leaving density, except for a very fast and capable group, until the need arises in a later Year.

Therefore, the following details go beyond what we hope will be done with most groups and apply in full only to very fast groups.

Class Experiment: Blocks and Balances
Each child, or pair of children, should have a supply of rectangular blocks of different materials, and easy access to a balance. C13

Discussion of Apparatus. *Quick weighing.* The balance should be a quick-reading lever balance so that we do not have to teach techniques of weighing at this stage but can let children make many measurements in quick succession whenever they want. (Therefore the laboratory should have as many of these balances as possible: at least one for every four children. In our programme, this is not a luxury, but an important part of our scheme to speed up certain parts of early learning in order to give room for other teaching. As in the case of microscopes, if children have to queue up to use the instrument, that will defeat our purpose and turn attention away from personal experimenting. And it will threaten to change the teacher's work from that of useful guide to that of a bus-station manager.)

We hope that even if the school laboratory is well equipped with equal-armed (chemical) balances teachers will not bring these into use this Year, because they will take up too much time and will divert attention to special techniques which are not likely to be needed later.

Sizes and measurements. It is important that physical principles do not get submerged in complicated arithmetic, so each solid block should have dimensions that are integral numbers of centimetres,

say 3 centimetres by 4 by 5 centimetres, to the nearest $\frac{1}{2}$ millimetre. *
That is better for our purpose than 2·83 centimetres by 3·46 centi- *
metres by 5·42 centimetres, which will take far longer to measure *
and bog down subsequently in heavy arithmetic. With a physicist *
doing the teaching, skill and careful use of a ruler to measure with *
precision (and full and proper use of arithmetic) will come later, *
never fear. Those of us who have tried round-number blocks find *
that progress is worth far more than precision at this stage. *

It is sometimes difficult to obtain blocks with dimensions that are *
accurately whole numbers of centimetres, within a small fraction of *
a millimetre, without involving unwarranted expense. If a school *
has blocks whose dimensions are 'inaccurate' by one or two milli- *
metres, pupils may be dismayed and attempt to use long arithmetic. *
We hope that teachers will *not* encourage that but will help the *
pursuit of the general concept by laughing at pupils' worries and *
telling them that, as good scientists, they may take the round num- *
bers as quite near enough for the present important comparisons. *
Precision will come into its own, as the children gain perspective, *
much later on. *

Blocks of the commoner materials can be supplied in quantity; but T
the less common or more expensive blocks will have to be shared;
or children can draw upon a 'cafeteria table'.

Weighing and Measuring. As a preliminary to an experiment of T
weighing the blocks, a blindfold guessing game will make a very good start with some classes. One child covers his eyes and receives one block after another from his partner, trying to guess which block he is given. If pupils include a sniffing test, offer a block cut from a block of kitchen soap among the samples.

Notes. If the children are fast writers each may make a simple T
record in his notebook of the material of the block, its mass and its dimensions. Many of the blocks should have the same dimensions, then the weighings alone will provide a very satisfying sensory comparison of densities.

Policy. This work of measuring blocks is much less familiar, less *
obviously useful, than most of us expect. The work should neither *
be hurried nor extended into a tedious drill.§ *

§ 'They found this whole process not difficult but rather dull, so we didn't press it too much.
'This week, nobody stayed behind after school.'

(A class that finds weighing and recording a slow business should soon be diverted to other activities such as heating materials (C 19), making a microbalance (C 22, preceded by D 21), or an extension of crystal growing.) * * * *

'Counting the Cubes.' Some children will need clear *encouragement*: show a centimetre cube (or an inch cube) and say 'How many of these are there in that block? Can you *count the cubes* in the block?' If a well-packed box of sugar cubes is available, it will help to illustrate the business of 'counting the cubes'. As one teacher reports 'it rapidly resolved any lingering doubts'. If, elsewhere in the school, the cubes and sticks of wood that are now used in teaching mathematics are available, these too may help our teaching here. Wooden 1 cm cubes are available cheaply. T

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

Density

Some of the blocks should have different (whole number) dimensions. With a fast group we let that raise the question of devising a new quantity – density – to make the comparison among the materials. The teacher should elicit the suggestion that, to find out which materials are denser, we cannot just weigh them but had better find out how much one cubic centimetre of each will weigh. It takes much more time to coax a suggestion like this out of a class, and the coaxing may amount to little more than posing a question and, while waiting for an answer, giving more and more hints as time goes on. Yet with a fast group the question and the waiting do good: they encourage these young scientists to think – and they give a truer picture of science. T * * * * * *

Problem C: Questions on Orders of Magnitude, Standard Form, and Rough Guesses

This is a long set of problems, accompanied by considerable explanation, suggested as teaching aids in this Year and later Years. Because it is so long this set of problems is printed as an Appendix (*see* p. 292) at the end of this Year; but we hope teachers will refer to it now, and use some of its questions.

Because we make an early start with atoms, we need to deal with very large numbers and some very small ones. Unless pupils can express them with the powers of 10 as a form of shorthand, difficulties of arithmetic will make this work practically impossible. We hope that after some practice with our preliminary scheme of 'separating out the noughts' pupils will be ready to try the professional way of writing large and small numbers in 'standard form'. The first few parts of problem C are intended to give encouragement and a little practice. Those lead into questions about accuracy and rough guesses 'to the nearest order of magnitude' – meaning to the nearest power of ten.

Then we ask for *very* rough estimates – like the Fermi guesses mentioned in the General Introduction – and we hope pupils will enjoy trying them.

Of course these problems, especially the final ones asking for rough estimates, are only suggestions to show things we believe will be useful in teaching. We hope the teachers will not only select from them but will make up their own problems and invent their own stories for rough estimates to suit their pupils.

Problems on 'Density' (for fast groups); on 'Atoms' (for all)

Fast Groups. Problems like Problem D. At once, when the measurements have been made, and the children have written (rough estimates of) densities in their notebooks, we should put the new idea to some use; and in homework, if there is any; otherwise for a short time in class, ask some questions like Problem D. Such problems are intended only for those groups who do formal work on density. T

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

Using Density Measurements *(For groups who do work on density)*

D. 1. You have weighed a block of marble. A sculptor who wants to cut a statue out of marble orders a marble block 40 cm long by 30 cm wide by 20 cm thick. How much will it weigh?

2. After the sculptor has chopped away a lot of marble he has an irregular shape that weighs 40 kilograms. How many cubic centimetres has he got left?

E. (Note: This problem does not involve density directly, and can be solved by careful thinking and arithmetic.)

1. *The problem of the apples*

(To ensure a greater chance of success, when they are working alone, pupils should have careful preparation – except for a fast group – by working out Problem E. (1) first.)

A farmer who grows apples in his orchard packs them and sends them to a big shop in London. To make quite sure the apples are not harmed, he packs them in a big box with sheets of cardboard between each apple and the next. Each apple is inside a small box of cardboard like this (sketch).

The little cardboard box that holds each apple is 2 inches wide, 2 inches deep and 2 inches high. If you could measure the length of the farmer's big packing box, and its width and its height, how could you find out how many apples it would hold? (The cardboard used to keep the apples apart is too thin for its thickness to matter in this story.)

Suppose, instead of his big packing box, the farmer only had:

a. A little box 4" long × 2" wide × 2" high
b. A little box 6" long × 2" wide × 2" high
c. A little box 6" long × 4" wide × 2" high
d. A little box 6" long × 4" wide × 10" high.

How many would (*a*), (*b*), (*c*) and (*d*) each hold?

Now suppose the farmer measures his big packing box and finds it is 40 inches long inside, 20 inches wide and 10 inches high. How many apples does it hold?

Did you get the right answer to the last question? How did you get it? Suppose you were going to work for that farmer and had to find out how many apples could go into each packing box, and you had many different sizes of packing box. Would you have to think out very carefully how many apples fit into the length of each box, how many apples fit into the width, how many apples fit into the height, and then would you have to think out very carefully how many rows and layers that would make? Or could you give yourself a simple rule to use for every box? There is such a rule. What is it?

2. How Many Atoms?

Scientists can now measure the size of a single atom. An atom of iron is so small that if you put it into a small box, the shape of a cube, that would just hold it, the box would be about $\frac{2}{100,000,000}$ of a centimetre wide, the same distance thick and the same high. Look at the iron block that you measured and suppose that the atoms are arranged very simply in it, in a cubic crystal pattern (the teacher should show a model).

a. How many atoms would there be in the length of your iron block and how many in the width and how many in the height? Work those out roughly.

b. Then how many atoms would there be in the whole block?

c. Now look at the weight of your block. How much would one single atom of iron weigh? Work it out roughly.

For All: Problem E on Atoms. We should give children a very important problem that asks them to think about atoms – as part of our method of introducing the idea of atoms in preparation for further study. We suggest that Problem E should be given now, even though the essential second part will be extremely difficult for slower groups and will need a great deal of help and encouragement from the teacher. T

The essential part of that problem, E 2, on the number of atoms in a block of iron does not involve density directly but can be done by simple arithmetic. We offer it here as an important problem to encourage children to think about atoms and to give them a first glimpse of the very small size of atoms and the very great number of them in a visible piece of matter. For this we simply announce the 'size' of an atom (of iron) and use that piece of data for a numerical problem. That would give science a very poor reputation if we did it often – teaching by unsupported assertion – but in this case we use it for an early introduction, and within the Year children will do a simple experiment to estimate molecular dimensions themselves.

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

After using problem E 2 in trials, we think it so important that we *
urge all teachers to use it: but we also know it proves too difficult *
for many children unless special preparation is given. So we suggest *
that the main problem E 2 should be preceded by E 1 for home- *
work a *week before*. In that preparatory problem we have purposely *
chosen 2 inches as the side of the cube for an apple because we are *
going to give 2 Ångström units as our rough estimate for the side *
of a cube that holds an atom of iron. (Australian and Tasmanian *
apples are now being packed in cartons subdivided into cubes just *
about 2 inches by 2 inches by 2 inches.) *

We hope that teachers will succeed in coaxing children through E 2, *
estimating the number of atoms, giving as much help as their class *
needs. See note below on help with arithmetic of big numbers. *
Even if the work is not fully understood, it will form a valuable *
beginning provided we give praise for partial success and do not *
insist on clear understanding yet. *

Problem E 2 is very difficult, because its numbers run to such *
extremes; also, for some children, because it talks about strange *
things like atoms instead of familiar things like the length of a *
kitchen table, which have been measured in arithmetic class long *
ago. This is a problem to let pupils wrestle with,‡ giving some *
encouragement but not demanding an answer from everybody, and *
certainly not dictating a properly worked out answer. Rather leave *
this problem to go home and be puzzled with. Science is real and *
earnest and worth puzzling about. *

Suggestion for Introducing Powers of Ten. The following T
informal scheme has been suggested and tried out by a teacher in our trials. It will help pupils to see the problem and solve it in a simple way, as preparation for a full use of powers of ten with a multiplying number.

> 'We need to deal with very big numbers like 250,000,000. You will soon get tired of writing a number like that in full. Worse still, you will find that multiplying big numbers by each other, or

‡ One teacher tried posting this problem on a school notice board and found it promoted good discussion and competition.

dividing them, is clumsy. It would be much better if we had a short way of writing big numbers. Try this way:

'Make a column for the figures and a column for the noughts. Label the left-hand column, FIGURES and the right-hand column, 0's. Then instead of writing 250,000,000 write 25 in the figures column and 7 in the noughts column:

	FIGURES	0's
250,000,000	25	7

'Now suppose you want to work out 250,000,000 multiplied by 200,000,000. Those two big numbers could be written like this:

250,000,000	25	7
200,000,000	2	8

and the multiplication sum could be written in this way:

$$\begin{array}{rcc} 250{,}000{,}000 & 25 & 7 \\ \times 200{,}000{,}000 & 2 & 8 \\ \cline{2-3} & 25\times 2 & 7+8 \end{array}$$

In all this business, adding a 0 in the right hand column means multiplying by 10 so the result of our multiplication sum must have 25×2 in the left hand column and 7 noughts plus 8 noughts in the right hand column. So then our sum looks like this:

$$\begin{array}{rcc} 250{,}000{,}000 & 25 & 7 \\ \times 200{,}000{,}000 & 2 & 8 \\ \cline{2-3} & 50 & 15 \end{array}$$

$$= 50{,}000{,}000{,}000{,}000{,}000$$

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

'Instead of writing 250,000,000 with those two columns 25 and 7 we can tell the story of the second column in a different way. The 7 in the second column means 7 noughts; but that really means 7 lots of multiplying by ten. There is a professional way of saying "multiplied by ten seven times", that is 10^7. If we use that, we can write 250,000,000 as 25×10^7.'

After some more practice with that form, pupils may then be ready to make one further change, the reduction of the first number before the power of 10 to one which has only one digit before the decimal point. If this last form ('standard form') seems to add a sense of difficulty, teachers should postpone that and stick to one of the earlier forms all the way through the present important arithmetic for atoms.

In the example above, we have not done any division. We hope the teachers will extend the method to one of division by big numbers. Then very small decimals, such as the diameter of an atom in cm, can be avoided for the moment, by using fractions with a big number in the denominator.

'Nothing succeeds like success' in this arithmetic as in all teaching. We believe the encouragement of success in these early stages of using big numbers will carry a class through, and make our questions about atoms both possible and pleasing.

Weighing Liquids

Extend the weighing of samples to liquids by providing a rectangular Perspex box, so that the volume can be calculated easily. That box too should have whole-number dimensions in centimetres. For height, it should be marked inside with scratches, or a mark with a greasy pencil near the top and half-way up. C14

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

Children should first weigh this box full of sand, then water, then some other liquids. In the case of sand, and wheat or rice as well, if that is tried, ask: C14

> 'What does that weighing tell us? ... Yes, there are spaces between the grains. I suppose it will lead to an "average" density for the sand and spaces combined.
>
> 'What would the density of a sand grain be like? ... Yes, that would be different.
>
> 'Does that same question arise in the case of weighing water for density?'

That may raise discussion of atoms again.

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

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

F

'Lead is heavier than feathers.' Do you think that this statement is true? If not, what statement could you put in its place?

G

A piece of marble weighs 102 gm. It is gently lowered into a measuring cylinder, containing 56 cubic centimetres of water; the reading on the measuring cylinder rises to 94 cubic centimetres. What is the volume of marble in cubic centimetres?

H

1. You are given about 50 steel ball-bearings, all look alike and all are very small. How would you find:
   a. the weight of one of them?
   b. the volume of one of them?
   c. the density of the steel?

2.
   a. What is your weight in lb?
   b. What is your weight in kilograms? (1 kilogram = 2·2 lb)
   c. If you could just lift a pupil who weighs as much as you do, would you be able to lift a big cube of cork of 0·6 metre side (nearly 2 ft × 2 ft × 2 ft)? The density of cork is 0·25 gram per cubic centimetre.

3.
   a. If you were given a hollow rectangular plastic box and a ruler, how would you check the accuracy (correct, exact reading) of a measuring cylinder marked in cubic centimetres?
   b. Which is likely to be more accurate, your measurements of volume with the box, or your readings of the height of the

water in the cylinder and the manufacturer's markings of the measuring cylinder?

c. Suppose you had a tall glass measuring jar which the maker had forgotten to mark. How could you put marks on it for 200 cubic centimetres, 400, 600, 800, 1000 yourself?

Measuring Cylinder under Test

In dealing with liquids, children should also see liquid poured D15
from the measuring box into a measuring cylinder just to check the marks on the cylinder so that the instrument can be used later.

Teachers who are familiar with experiments on volume and shape for young children may feel tempted to put their measuring jars to the opposite use; trust the marks on the jar and investigate the volume of a sample of water poured from jar to jar – or even use the jar to test the box. However tempting, that would completely reverse the logic of our present teaching and we urge teachers not to attempt it. See the discussion below.

In some classes, the teacher will find that his colleagues in chemistry have already introduced the use of measuring cylinders. That does not mean that we had better omit the experiment of testing a cylinder in physics. In chemistry the graduations of a cylinder have to be taken for granted. It is now our turn, in the physics class, to ask how the marks were put there and to let children do a simple experiment of making their own test.

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

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

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

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

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

Note to Teachers: Children's Ideas of Volume

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

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

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

Cognitive psychologists have done interesting and important work in observing the development of concepts such as this idea of invariant volume; but there are differing schools of thought concerning the results. The observers have tried to find out what it is that children understand, at a given age, *when they have been taught in conventional ways*. There are new teaching experiments, including our own, which offer, in essence, to alter the data which have formed, so far, the basis of the research of those observers. If such

teaching furnishes experience which few children now have, then *
in the future observers may observe quite different things. We *
therefore believe that in making changes of method and attitude *
such as ours, we are not justified in making strong positive or *
negative predictions of what can be done at each age. We believe *
that the only way to find out how and when various things can be *
taught successfully is to try various ways of teaching them. *

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

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

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

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

While we wait for suggestions from children about methods of weighing air, some will ask how we know that the pump has done
its job. At once give a demonstration of a bottle being pumped out D16a
by the pump and then opened under water. Water with a little ink will make the experiment clearer.

We ourselves may take vacuum pumps for granted, but to children the idea of taking away invisible air is strange. To help them to visualize the process, show the following demonstrations:

1. Pump smoky air out of a flask. (A very good way of filling the D16b
flask with smoke which will not hurt the pump is to put cigarette smoke into it. More roundabout methods of producing the smoke may well divert pupils' attention to the chemistry.)

2. Pump air out of a polythene bottle, or out of a hollow doll made of stiff rubber or a large syrup can. This experiment is usually done to demonstrate the effect of atmospheric pressure outside; and it should probably be repeated later when we come to that. Here attention is directed to the pump taking away something from the inside. D16c

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

When the bottle has filled with water there is usually a small bubble left. We know that that is probably dissolved air that has come out of the water; but we should be careful not to assert that too strongly, because children have no reason to expect it, and it looks much like our trying to explain away a failure of the pump. We should say, T

> 'Yes, that may be a little air that the pump didn't manage to get out; or it may be some air that was dissolved in the water and has come out when the water was rushing in.'

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

I

If we open a box and see nothing inside it, we immediately say that the box is empty but, of course, it is not empty; it is full of air.
Write three sentences, giving a reason in each, for supposing that air is really there.

J

1. What volume of air do you think comes into and out of your lungs each time you breathe? Is it near to 10 cubic centimetres? 100 cubic centimetres? 1000 cubic centimetres (=1 litre)?
2. What volume comes in or out for a 'forced' breath? (When

you breathe in as deeply as you can and then breathe out as much as you can.)
You can measure how much your lungs can take quite simply by the following method:

Apparatus: large bottle, e.g. 'Winchester quart', sink or bowl, water, measuring cylinder, piece of plastic or rubber tubing.

Procedure:
Fill the bottle with water and have the sink or bowl half-full too. Turn the bottle upside down so that at least the neck is immersed; it stays full of water. Drop the tubing in the bowl and let it get full of water also. Put the end into the bottle through the neck.
Blow into the tube with, as nearly as you can, one normal breath. Remove the tube, put your hand over the neck, and turn the bottle the right way up.
Now use the measuring cylinder to find the volume of water needed to fill the bottle up again; this is one normal breath. Do it again to find the volume of a forced breath, that is, more or less as much as your lungs can take.
This could be done at home if you can find a large enough bottle and a piece of string, and the kitchen measure that your mother uses for liquids. A gallon oil can, a 14 lb syrup tin, or several milk bottles might be used. The tubing could then be a short piece of clean garden hose.

K
Describe how you would do the experiment in J backwards. That is, how much you breathe in (inhale), instead of breathe out (exhale) at every breath. Try it. (Note: blow the water out of the tubing before you start, or else you will have a surprise!)

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

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

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

> 'The pump acts rather like a lift that is getting people out of the top floor of a tall building. A lift doesn't pull the people out. It just offers them a chance to get in the lift, and then the lift carries them out.
>
> 'The lift goes up to the top floor, the lift man opens the door of the lift and waits till a few people have wandered in. Then he slams the door shut. Down goes the lift. Out go the people; walking out if they are human beings, but pushed out by a moving piston in the case of air molecules in the pump. Up goes the lift again; open the doors; more people wander into the lift; slam the door shut; down goes the lift; out go the people. Up goes the lift ... and so on. Think of that happening with a pump taking out air molecules, batch after batch in trip after trip. At that rate you would never get *all* the molecules out; but our pump does a very good job and makes what we call a good vacuum.'§

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

The simple method of weighing a Perspex box before and after pumping the air out is difficult, because a big box will collapse‡ and

§ 'First week was spent just showing how the vacuum pump worked and no weighing was done. I had plenty of suggestions as to how to weigh air the following week, so probably time to "simmer" was worth while.'
'Idea of suction dispelled by 6 boys pushing one side of the door and 6 the other. If 4 stop pushing the others aren't "sucked" in.'

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

a little box shows a very small change of mass. The teacher may be able to give a demonstration of pumping out a 1- or 2-litre flask and weighing it before and after pumping; and then letting water in to find the volume. If the weighing takes a long time, or is not easily seen by pupils, it would be better not to do this experiment now. However, some new teaching programmes (including the Nuffield Chemistry Scheme) are now asking schools to use quick direct-reading chemical balances. These will show the small difference of 1·2 grams per litre very easily. D17

Rather than show pupils weighings in which the difference that we are trying to measure is either too small to show or else measured on a special machine, we urge teachers to try a different approach which will provide a big enough weighing to show on the crude lever balances with which pupils are familiar. In preparation for that new method we suggest trying first a crude weighing that will fail. And then the teacher should ask pupils for suggestions. T

The class is likely to suggest pumping air out of something. If they suggest pumping air out of a thin container, the teacher should again give a demonstration of pumping air out of a polythene bottle and leave the class with the problem of its collapse.

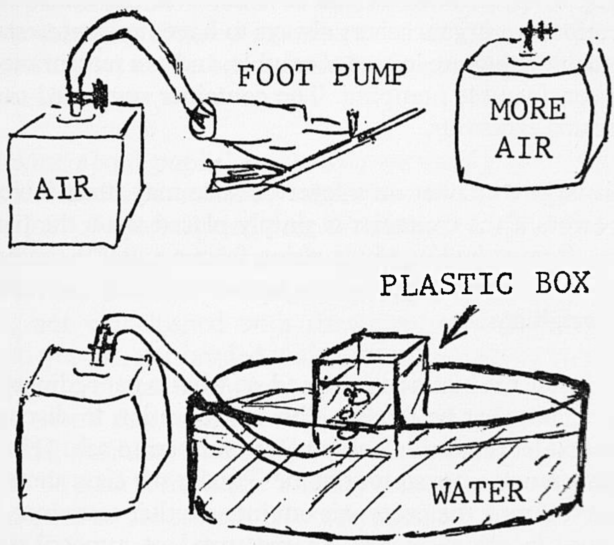
New Method. The weighing and the volume measurement present difficulties here for children. The principle of the latter is apt to get lost in a lot of water pouring. It is probably better to pump extra air *into* a container to give a reasonable increase in weight, and measure the 'ordinary' volume of that extra air by letting it out into a measuring vessel under water.‡ D18

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

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

to do is to let the air out and measure it' spoils the fun of being a scientist and leaves some pupils confused.§

The apparatus consists of a large plastic container with a side tube and tap which allow us to pump in extra air (this is a container intended for liquids such as cider, it is a cube about one foot on a side); a foot pump, as used for pumping up car tyres; a transparent rectangular box for measuring the air, say 10 centimetres by 10 centimetres by 11 centimetres; and a large trough of water so that



the 'extra air' can be collected in the measuring box over water. If a tyre-gauge can be added to measure the pressure in the container, all the better. The container is pumped up to a considerable excess pressure short of bursting, and weighed on a lever balance. The 'extra air' is then let out into the measuring box, in several fillings. Then the container is weighed again to find the mass of air released. Making the weighings in this order, rather than weighing the container 'empty' first, is found to make things clearer for pupils.

§ 'They thought it was not very accurate, and said "have you any bigger container?" so I produced the polythene bottle.
'They saw the foot pump and suggested adding extra air and weighing it.
'The problem of how to find the volume of "extra air" was left, while the first part of the experiment was done.'
'Only after the Perspex box and a tank of water were indicated did they solve it.
'They were thrilled to think that they had designed the experiment.'

The success of this experiment depends on pumping enough air into the large container to show a clearly measurable difference in weight. The containers suggested for this experiment are intended to carry liquid so one does not know whether they will stand a large excess of air pressure. Careful tests show that an *excess* air pressure of 10 lb per square inch above atmospheric is quite safe. Even if a container is pumped until it gives way, the bursting is not in any way dangerous.

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

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

The air that is inside the box is compressed, so what is its 'ordinary' T
volume? How could that be found? This is a question to discuss with the class and let them think about. It is simpler to ask: 'How can we find how much extra air we put in?' Finally the class should be led to suggest letting the excess air out into another container, a rectangular one, in which it can be measured at atmospheric pressure. That suggestion is worth waiting for, because the children then have time to realize what the problem is.

The Air in the Room. As soon as the weighing is done, ask how T
much the air in the whole classroom weighs; and let each child work out a *rough* estimate.

Then discuss the idea of extending that to include the air in the room above, and on up and up ... and raise the question of atmospheric pressure. Do not go further with that now, but promise to return to it later.§

The Notebook Record

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

§ 'Absolute surprise that it is so heavy.'

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

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

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

SOLIDS, LIQUIDS AND GASES: DENSITIES?: ATOMS?

If the class has measured densities, collect values for all kinds of materials from the children and ask for suggestions of additions to the list. Otherwise, just announce some typical values. Encourage rough estimates. Include several rocks from the earth's surface. T

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

Gases appear to be markedly different from solids and liquids; we may ask for ideas about gases in terms of 'atoms' or 'molecules'. Ask how the suggestions might be tested. This question, having been raised, should be left for a while. T

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

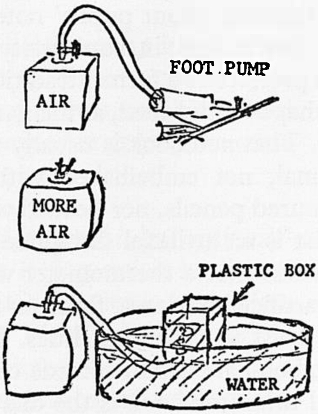
(This suggested record is intentionally given an informal style and we hope that teachers will experiment with even simpler requirements)

Specimen Description
(in words)

We pumped air into a big (plastic) box, until the box had a lot of extra air in it.
We weighed the box before and after the pumping.
The box weighed more after pumping. We think the extra weight must be the weight of extra air pumped in.

Then we let the extra air out through a pipe into a 'square' box filled with water. There was so much extra air that we filled the square box several times. We counted how many times we filled the box with bubbles of air, and we measured the height of air in the box for the last lot of all. Then we could 'count the cubes' of air that came out when we let it all out.

Specimen Description
(in sketches)



Specimen Record (written on opposite page of notebook)

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

The inside of square box measured 10 cm × 10 cm × 10 cm high

∴ each boxful had . . . 10 × 10 × 10 small cubes

and the last lot had . . . 10 × 10 × 5 small cubes

∴ volume of air was (6 lots of 1,000) + (500)

or 6500 small cubes (cubic centimetres)

∴ 8 grams of extra air fill 6500 small cubes

∴ one small cube of air (one cubic centimetre) must weigh

$$\frac{8}{6500} \text{ grams, or about } \frac{12}{10{,}000} \text{ grams.}$$

Melting and Evaporation. Discuss the possibility of turning solids into liquids and then to gases. Give pupils as a class experiment small samples of lead, iron, ice, etc., to melt in a bunsen flame. If there is time, let them melt some sulphur in a crucible and make monoclinic crystals of sulphur, and refer back to crystal studies.‡ C19

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

Some teachers like to try a 'diffusion model' using the pupils' sense of smell. Pupils sit quietly, distributed all over the room, and

‡ The sulphur should not be melted in an open shallow dish or tin lid because it will catch fire. In a deep crucible it may be melted with care. Unless the teacher can take considerable care over this, the sulphur should be melted in a small test-tube. It is possible to make monoclinic crystals of sulphur by melting sulphur gently and then leaving it to cool and crystallize over a considerable time, but this is likely to be disappointing.
Naphthalene is even more of a nuisance when it catches fire and burns with a smoky flame; so it, too, should be heated in a test-tube. In a large class group, it may be wiser to suggest heating naphthalene by holding the test-tube in boiling water in a large bath on a central table, rather than using a bunsen flame. Naphthalene melts at 80°C. If time permits, the cooling of the clear liquid naphthalene down through the melting point gives a good picture of the process of solidification. However, this takes time and should be an 'Optional Extra'.
The melting of ice does not tell pupils as much as it should about the concept of melting point, because the ice in an ordinary room is already above its melting point. Some teachers like to offer naphthalene as 'sham ice' with a high melting point.

the teacher places a small quantity of ether in a bowl on a table in the centre. Each pupil raises his or her hand as soon as he or she can sniff the ether. (Ether seems to be fairly well known among children, from its use for cleaning wounds; and it is better for diffusion than methylated spirits. However, the teacher should use only a very small quantity so that there is no danger of fire or explosion.)

Gases. Scrape some solid carbon dioxide 'snow' out of the bag in which it is made and insert a little in a container which is able to show expansion.‡ D 20a

The easiest container to use is a toy balloon. The neck of the balloon is stretched and held open by several fingers and half a teaspoonful of the 'snow' is quickly poured in. At this stage the balloon is practically flat, with no volume inside. The neck of the balloon is quickly knotted and tied. As carbon dioxide changes from solid to gas the balloon inflates, showing a large change of volume. As an alternative, a polythene food bag may be used; but it is harder to knot and tie up the neck of that sufficiently well. The bag must be tested for pin holes, under water, beforehand. Whichever is used, balloon or bag, knotting is essential. (Note that the change of volume is about 1 to 600. Therefore the balloon is likely to grow, at most, to 3 or 4 inches diameter.)

Water to Steam: Volume-change. If convenient show the enormous range (1 to 1600) when water turns to steam, but that should probably be postponed. D 20b

This demonstration is difficult but should be shown if pupils are keen to see it. A very small quantity of water is injected with a small hypodermic syringe into the barrel of a large glass hypodermic syringe. Then the large syringe is heated in boiling brine to bring the temperature up to the boiling point of water and just above. Pupils will see the steam pushing the piston out. Since this is a demonstration that requires preparation, time and care, it is more likely to be suitable for Year III or Year IV than Year I.

‡ The easy way to obtain the small quantity of solid carbon dioxide that is required, from a cylinder, is as follows: fold a piece of closely woven cloth (preferably of dark colour to make the product easy to see) in the form of a bag. Hold this bag tightly round the nozzle of the cylinder and open the valve at full blast for 5 to 10 seconds. If the cylinder is a syphon type it should be kept upright; but if it is an ordinary cylinder of carbon dioxide it should be tipped upside down during this process.

For an alternative demonstration of the growth of volume when a substance changes to gas, let a small block of solid carbon dioxide evaporate. Cut a tiny cube from a block of 'dry ice', place it quickly under the mouth of a gas jar full of water that is inverted over water. Let the bubbles of CO_2 collect.

Models: A Picture of Solids, Liquids, Gases

There may be the suggestion that gases are made of particles farther apart than those in solids and liquids. T

It may be useful at this point to say:

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

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

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

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

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

§ 'They played "molecular chaos" and "molecular order" extremely well. A chemist colleague who entered the room at that instant saw the point of the game immediately.'

Chapter 2

MAKING A MICROBALANCE

A class experiment with simple materials

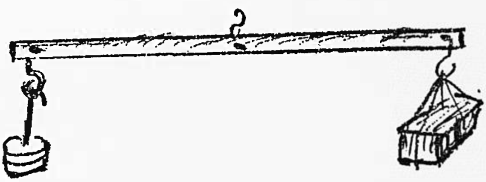
Simple weighing

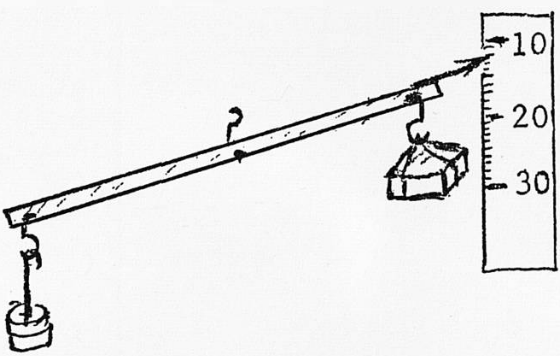
As an introduction to a class experiment in which children will enjoy making a delicate instrument for themselves, we give a demonstration of weighing things with a simple lever balance. That should be simple, crude, clear; so we suggest a plain beam of wood, like a metre rule but *without graduations*, drilled with holes to receive hooks at the centre and near the ends. For demonstration, we recommend that the apparatus should be large and robust. D21

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

1. Weigh a small package to the nearest 100 grams, using a 100 gram hanger and slotted weights.

2. Weigh a letter to the nearest 10 grams, using a 10 gram hanger and 10 gram slotted weight.





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

3. Ask how one could find out whether a letter to the Continent weighs more than the limit for the cheapest stamp, one ounce, which is just over 28 grams, or the limit of 25 grams in other countries. How could one do this with nothing but 10 gram weights, and no smaller ones? Show how this can be done by interpolation (without calling it that).

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

The third weighing shows excess weight by the tilt of the beam, a small pointer attached to the beam reading on a homemade vertical scale. For a scale like that shown in the sketch, to cover the range needed, we start by hanging 20 grams on the left hand hook and another 20 gram weight on the right hand hook where the letter will presently be placed. The beam will then be almost level, and we mark the 20 gram point on the vertical scale. To mark other points on the scale, we keep the left hand load at a standard 20 grams (as we shall do when we come to weighing our letter) and we change the right hand load to 30 grams and put a 30 gram mark on the scale. We change the right hand load to 10 grams and put a 10 gram mark on the scale. Then we are ready to weigh the 28 gram letter by hanging it on the right hand hook, still keeping the 20 gram 'counterpoise' on the left.

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

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

4. Then ask if one could weigh still smaller things on this balance:

a ring, a pin, a hair? Try hanging a hair alone on one end of the balance. The failure will be obvious.

This demonstration should be done very quickly and lightly: it is only intended as a quick introduction to the class experiment, to set the stage for the microbalance.

Microbalance

Then offer children materials to make a microbalance for themselves, with the hope that it *will* be able to weigh a hair. *There should be a set of equipment for every child.*§ C22

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

The teacher should show a microbalance already made (or possibly one like it that is not quite such a good design but contains opportunities for children to suggest improvements). Each child should have his own materials, and plenty of time. * * * *

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

Only a real trial with real children will convince one how long that time must be – and after one has carried it through with a class one will agree that the time was worth spending.§ * * *

§ A teacher in trials wrote: 'Initial reaction of most of the children was "I cannot do it!" Gradually they tried and when they had successfully completed it they were all very pleased with their own handiwork.'

§ Another: 'Some boys, who had seen a microbalance at the end of one period, made them at home *before* doing it in class. I felt that this alone justified the time spent, whatever other advantages there are.'

Give time and encouragement, but do not make the balance for any *
child, unless he is handicapped. *

(If it does become necessary to make the balance for a child, the *
teacher should carelessly take away with him the straw that he has *
pierced and adjusted, leaving the child to make his own. Otherwise, *
the sense of doing one's own experiment gets lost.) *

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

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

L

Twenty sheets of foolscap paper, each 30 centimetres by 20 centimetres, weigh altogether 120 grams.

1. How much does 1 square centimetre of foolscap paper weigh?
2. If you cut a strip of this paper $\frac{1}{2}$ cm wide, how long must it be to weigh 10 milligrams?
3. If the deflection of your straw balance is 5 divisions when a 10 milligram load is added, how many milligrams does each division correspond to? A 'division' is the name that we shall use for the moment to describe a space on the scale.
4. Balance-makers show us how delicate their balance is by giving it 'sensitivity'. We can measure this sensitivity by watching the pointer and seeing how many divisions it moves on the scale for each milligram that is put on the balance. The sensitivity of bigger balances will be given in divisions per gram, or divisions per kilogram, etc. What is the sensitivity of the balance in 3 in divisions per milligram?

M

(Fairly difficult) What would be the effect on the sensitivity of your balance of:

1. Using a shorter straw?
2. Using a wooden skewer instead of a straw (with a larger counterweight if one is used)?
3. How could you be sure that your answers to 1 and 2 were right? Did you try some experiments that helped you to give those answers or were you just guessing? (A scientist often makes sensible guesses, but he always says very clearly that he is guessing.)

N

Suppose you had a piece of paper of a suitable known weight.

1. How would you use your straw balance to find how much a 1 centimetre length of hair from your head weighs? (Be as clever as you can in thinking of any things that you can do to make this experiment as easy and reliable as possible.)
2. Have a look at your own head in a mirror and make a sensible guess as to the number of hairs on it. Say very roughly how much you think all the hair on your head would weigh.
3. From 2, make a very rough guess at the weight of hair a barber has to get rid of every week.

Constructing the Microbalance (see *Experiment Guide*). Each child will need a piece of metal channel to form a base on which the moving part of the balance rolls; a drinking straw, to be pierced with a fine needle for axle; a small metal screw to be inserted as a counterpoise in the short arm of the straw; a piece of card to make a scale for the end of the long arm of the straw. The metal channel can be replaced by a pair of microscope slides held on the sides of a wooden block by a rubber band. C22

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

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

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

Ask each child to weigh one or more grains of sand on his balance. The cry will arise, 'Where are the weights?' Offer a piece of paper about the size of a postage stamp and ask if that will do. 'But how much does that weigh?'

'I don't know, but I cut it from this sheet of graph paper; and I can give you a whole pile of sheets like this, if you like.' C23

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

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

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

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

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

‡ Unless the paper is such that 100 sheets weigh a round number of grams, the arithmetic of working out the value of small squares as weights will utterly spoil this experiment. Therefore, the Nuffield Physics group have arranged for a special graph paper with simple dimensions and rulings and a simple weight per sheet. Teachers using this should remember that paper changes its moisture content easily and thus changes its weight. So this paper will not keep very accurately to a round number weight. We hope the teachers will guide pupils quickly over any objections about minor inaccuracies. As with the early experiment in measuring blocks of metal, etc., we need to point out that much good science is done by taking careful but not tremendously precise measurements. We should do our utmost not to spoil this experiment by worries over arithmetic or even over the general idea of tremendous precision. The balance is very sensitive but we do not now need to make it very precise.
Teachers in trials report a range of values from 460 to 500 grams for 100 sheets. With clear assurance from the teacher, children busy making and using their microbalance were ready to take 500 grams as a rough, round number; and then they did very well. Where a number such as 470 grams became a point of anxiety, the experiment was delayed and almost spoiled by worry about arithmetic. We urge teachers strongly to turn a blind eye to anything up to a 10 per cent error and use 500 grams for 100 sheets.

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

If 10 grains of sand are weighed, ask for a rough estimate of the number of grains in a handful of sand. Or ask how big a pile of sand would have a million grains.

Some children may want to weigh several collections of 10 grains of sand and that will raise some statistical questions if you like.

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

Much of the enjoyment, once the balance is made, comes from T
making one's own choice of things to weigh. However, teachers may wish to keep a number of suggestions up their sleeve with which to encourage some children, such as:

A flake of mica; an inch of thread; a tiny piece of iron wire which is allowed to rust and then re-weighed – a beginning of micro chemistry; a drop of olive oil $\frac{1}{2}$ mm in diameter. The very rare child who wants to weigh electrical forces at this age is a scientist already.

§ *Great* difference found in speed of work within the class. One girl finished calibration and all at end of first double period. Some did not finish until after two double periods and one single period, and then only with the help of neighbours. One remark: 'My brother says you can't weigh 1/1000 gram unless you have an instrument costing *hundreds* of pounds. My brother always thinks he knows best!'
Another teacher: 'Our day was made by one boy who said, "This is super for watching the evaporation of water" – I gave him a drop of ether to use for comparison.'

Chapter 3

ROUGH MEASUREMENT

Weighing, timing, statistics

Measuring small things with instruments such as vernier calipers or a micrometer gauge involves nice instruments but takes up more time, without great interest, than seems worth while in this course. And with young pupils that may give science a mistaken reputation. So our measurements of length are rough – to be made more precise much later, if needed. The measurements suggested below can be done now or anywhere earlier. If this work has been left until now, it will in fact have been brought in by the making of paper 'weights' for the microbalance. * * * * * * * * *

'Just to get used to the metre ruler and centimetres and millimetres that we use in science, measure the length and width of your sheet of paper and write them down in your notebook. Can you find out then how many squares 1 cm by 1 cm there are on your sheet?' C24

Measuring Thickness of a Penny, and of Sheet of Paper

To give further practice, ask children to measure the thickness of a penny. This will raise a problem for thinking, and will provide a useful method for later use. Each child should try to measure the thickness with a ruler that has millimetres (not inch fractions) marked on it. The teacher should ask for results and ask how reliable children think they are. Then ask for suggestions for improvement. Here, as often in this Year, it is worth while to wait a long time for the suggestion to come from children themselves. Some will suggest measuring a pile of pennies. We should praise that as an idea and ask them to carry that out as an experiment. C25

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

'Suppose you have just one good penny and this ruler marked with millimetres, how thick would you find the penny if you could measure very carefully? ... Yes, we do now know that the thickness is 1·3 millimetres, but could you really see that if you had just *one* penny to measure? Even if you thought you could see it, would that be a safe and fair answer to give? ... With just one penny what would be the fairest thing to say? ... If you wanted to be quite safe what would you say? ... Yes, I agree; all we can say is somewhere between 1 and 2 millimetres. T

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

1·3 millimetres thick. What could you say if you measured 100 pennies in a pile?'

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

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

Next question: 'What is the thickness of your paper?' Ask for suggestions. The pennies experiment should help. The large pile of paper that was there in connection with the microbalance weights is still there. The teacher should point to that and ask if that would help. Children should make a rough measurement of the thickness of a pile or a book and calculate the thickness of a sheet and record it in their notebooks. C26

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

A Problem on Atoms

Give the children a very rough value for the size of an atom and ask how many atoms thick that paper is. For paper made of cellulose, containing carbon, hydrogen and oxygen, the average atom diameter is probably only about $\frac{1 \cdot 5}{100{,}000{,}000}$ of a centimetre. Of course paper has a good deal of open space among the fibres; so one can make only a very rough guess. T

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

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

Question O in the box will offer some encouraging practice. Teachers who have tried this find that pupils of various abilities get to various stages in that list before they find it too difficult or boring. So we urge teachers to experiment with it. Although the very small numbers at the end with negative powers of 10 are strange and difficult for beginners, we hope teachers will introduce them – perhaps by means of these examples – because they will save time. * * * * * * * *

Measuring Aluminium Leaf

(*Buffer Option suggested for a fast group.*§) Show a piece of aluminium leaf – a stock of this will be wanted anyway for radiation experiments later – and ask: C27 OPT.

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

This will lead back to the microbalance.§

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

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

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

§ However, a teacher in a trial in a secondary modern school reports 'worked well with top third of top class'.

§ 'Interesting case to see how they considered the balance a thing to be "*used*" at this stage – they set them up in seconds and used them for weighing in a very matter of fact way. They obviously felt most professional.'

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

O

Measuring Lengths: large and small numbers

About one inch from the left-hand side of a sheet of paper draw a long, thin, vertical 'ladder' with 22 rungs.

Count up to the sixth rung from the bottom, and label it '1 metre'. Label the rungs above '1 metre', going upwards 10^1 metres (meaning 10 metres), 10^2 (meaning 100), 10^3 (meaning 1,000), up to 10^{16}. Label the rungs below '1 metre', going downwards, 10^{-1} (meaning 0·1) metre, 10^{-2} (meaning 0·01), . . . 10^{-5} metre. Each rung of this ladder represents a length 10 times the rung below and one-tenth of the rung above. Now write in the following names where their length or size should come on the ladder:

Nearest star . . .	10^{13} kilometres	=	10^{16} metres
Sun to planet Pluto .	6×10^9 km	=	6×10^{12} metres
Sun to Earth . . .	$1{\cdot}5 \times 10^8$ km	=	
Earth to Moon . .	400,000 km	=	
Earth's diameter . .	13,000 km	=	
London to Edinburgh .	640 km	=	
1 kilometre . . .	1 km	=	
Height of Salisbury Cathedral . . .	120 metres	=	
Tall man . . .	? (Guess)	=	
Baby	50 centimetres	=	5×10^{-1} metres
Length of your little finger	? (Measure it)	=	
Diameter of a pencil .	? (Measure it)	=	
Thickness of paper . .	10^{-2} cm	=	metres
Red blood corpuscle .	10^{-3} cm	=	metres

Metric Measurements

Unless the children are already familiar with the kilogram and gram, metre, centimetre and millimetre, so that they have some feeling for the sizes of those units, we should give them practice with them in some simple jobs of measurement. These can be done any time in this Year, early or late, preferably in small doses as an interesting game. T *a.* Measure the length of this sheet of paper in inches, centimetres, metres. Write in your notebook:

length of sheet of paper............................xxxx inches a
length of sheet of paper............................yyyy cm
length of sheet of paper............................zzzz metres

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

c. Look at one metre on your metre ruler and compare it with one yard. How much bigger is it? Would you say that one metre is about 50% bigger than a yard, or 20% or 10%, or 5%, or 1%? c

d. Then how much longer is a 100 metre race than a 100 yard race? d

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

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

The teacher should wait for suggestions and discuss.

For many children guessing the sizes of things in centimetres and millimetres and metres is both a good way of getting used to the metric scale and a valuable introduction to rough measurement. It is good modern science teaching to encourage some rough measurements and estimates as well as precise ones. One teacher in trials reports, 'They love estimating, and challenge me.' * * * * * *

(This is *not* the time to bring in a micrometer gauge. That is perhaps a special reward for a child who is farther ahead and can be * *

‡ If this experiment is tried, pupils should use common objects such as nails, not some special 'smooth cylinders' bought specially for the purpose of making an experiment. We hope this kind of experiment, if tried at all, will feel like an extension into household life.

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

Discussion with Teachers: Rough Measurements

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

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

Yet, when Chadwick measured the nuclear charges of copper, silver and platinum by alpha-particle scattering, relatively rough measurements could prove the case that was suspected in Rutherford's great atomic model. He showed that the nuclear charge (in electron units) is just equal to the 'atomic number', the number of the element in the complete chemical series arranged in order of atomic weights. Those answers were suspected from the general pattern of theory, and had to be whole numbers since the complete atom of [nucleus + outside electrons] is neutral. Much more precise measurements were neither needed nor, at that time, possible. Even before that, the first hint of atomic number measurements came from Barkla's attempt to measure the number of electrons in a carbon atom by the scattering of X-rays. His measurements suggested a number about 6 electrons per atom, more honestly somewhere between 5 and 7; yet this rough estimate enabled the founding of atomic theory to proceed.

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

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

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

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

In a city where a big snowfall has to be cleared from time to time in winter, the example of the man in charge who makes the decision about snowploughs and clearing-men in the middle of the night is a good one. The Chancellor of the Exchequer makes a clever guess of the total consumption of tobacco. A rough guess that the Sun is 300,000 times as massive as the Earth suffices to tell us that the Earth is too light to affect the orbit of the planet Venus at all noticeably in any ordinary astronomy; and in modern studies of high precision, that rough estimate is still sufficient to give us the small effect that is noticeable. A rough guess at our distance from a measured radioactive source is sufficient to tell us what we need to know about safety.

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

Guessing Measurements

Hold a book up (vertically, to avoid foreshortening for children out at the side) and ask for a quick guess of its height, in centimetres. C29a

Ask the children to write it down on a piece of rough paper; then hold a ruler beside the book.

Repeat with a finger breadth, the length of the room, an odd bit of stick, then a book again, etc., asking for quick guesses and checking them visibly at once – not collecting scores or having marks, but promising to go on with this in the next lesson.§

This will prove to be a skill that can be polished up with great success, though it does not seem to last for many months.

The same kind of thing can be done with intervals of time. Ask 'How long in seconds between these two hand-claps?' Then 'How long ago did I drop that book?' C29b

For weighing, try guessing by feeling a one pound weight, a one ounce weight, a book in grams and in kilograms. 'How much do you weigh in kilograms?' For that, we must hand out specimen metric weights to each pupil: one kilogram, one hundred grams, ten grams, and if possible one gram; also one pound. Most pupils find weight-guessing much harder than length-guessing. Yet we should ask for it – and encourage success by giving praise – because we want to build a familiar acquaintance with grams and kilograms. C29c

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

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

Private Note to Teachers. Discussion of the word 'Weigh'

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

§ 'The children thought this was great fun. For some things I went round the class and they all guessed, then we measured it. For others they all wrote down their estimate. In either case when the actual measurement was announced it was greeted by cheers from all those who had the correct answer. After a little while most of them had the right answer and we had to stop before other classes complained about the noise!'

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

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

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

Timing Things

The laboratory should have stopwatches for class experiments so C30a
that pupils working in pairs can make some quick measurements of time in seconds, just to gain familiarity with this new 'instrument'.

Stopclocks could be used instead, of course, if there is one for each pair; but they are not likely to be more economical, and they even do less good teaching. Electric stopclocks are expensive, and perhaps too glamorously modern for this stage: so we do not recommend them.‡

Invent some real jobs for this practice: the time taken by a boy to walk ten lengths of a room and another to run as a move to measure

‡ For demonstrations, however, a *large* electric stopclock is a luxury that is well worth having. It may later on prove to be essential; but for the present an ordinary electric clock or 'broomstick pendulum' will meet all demonstration needs.

his speed; the time taken by another pupil to run up a flight of stairs (with a promise of calculating horsepower later on); the time taken by a cricket ball to fall 4 feet from rest, and to fall 16 feet; the maximum 'airborne' time for a cricket ball thrown straight upwards.

If the laboratory does not have stopwatches or stopclocks, a big demonstration clock, or a clock on the wall with a long seconds hand, or those children's watches that have a seconds hand, should be used.

Mass and Weight

'Broomstick' pendulum. In addition, the laboratory should have a large heavy pendulum for use as a crude clock; two bricks lashed to a broom handle, hung with a nail as pivot from a tower of stools or tables. C30b

It is good for both children and teacher to know that lack of beautiful shiny apparatus need not stop the progress of science – and where apparatus for modern physics is needed and expensive, an economy like this may be wise.

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

To enable schools to try using this crude pendulum, we have specified the parts for it in the Year I General Kit – not because we think a broomstick and nails are difficult to obtain locally, but because we wish to enable all teachers to try this useful device without being burdened by extra work of shopping and construction when they are busy trying out new teaching.‡

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

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

Note on Statistics

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

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

When every child knows his own mass in kilograms, make a one dimensional graph by drawing a line marked in kilograms with a mark on it for each child's mass. (If masses are not known, use height instead.) Include the origin on that graph, and then when all C31

‡ Teachers who have workshop facilities and who enjoy a shopping expedition to obtain equipment will find this device and many others much easier to provide or construct themselves – and much cheaper. So, in later years of working with our programme we expect to find many teachers gathering or making some of their own equipment. However, for those schools whose regulations tie them to purchasing through manufacturers, we are asking that 'General Kits' and other ready assembled kits of equipment should be made available. For any good participation in our programme it would be better to buy those kits than to run a starvation version.

the marks cluster in one region far from the origin, offer to make an 'exploded graph' of that region. Do not make any calculations of average or deviations, but just leave the 'graph' there for people to look at.

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

The Nuffield Physics Group has designed a board with slots to receive pennies or counters, to form a demonstration histogram. It has proved so popular in preliminary trials – and seems to teach such a valuable lesson – that we regard it as a necessary item and not as a luxury that could be replaced by some marks on a blackboard. When using that board, it is important to explain that each vertical slot corresponds to an agreed range of whatever is being catalogued – in the case of weights, one slot might take the range of 5 kilograms between 40·5 and 45·5, for example.§

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

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

§ 'I organized this by giving each boy a brass disc; then they came after performing their measurement and dropped the disc into the appropriate column in the board. This was quick. They felt they were participating and were immensely interested in the result and wanted to measure everything and express the result on the tally.'
Another report: 'Children didn't know their mass – but estimations gave a very good distribution. I really liked this and think it was most valuable.'

Open Experiments

In these early years, we should let children gain information and experience by looking at materials and working with simple instruments; but we should also give them some chance in a rich experimental field to discover rules in the profusion of natural phenomena. It is best if this chance occurs in 'an open-ended' experiment in which there are few instructions, obvious apparatus, but a variety of good pieces of physics to be found. At this early stage, completely 'open-ended' experiments in which the outcome may branch in many directions, or is even unknown, would be unsuitable. So here we suggest 'open' experiments, in which we give some general instructions and provide at least the backbone of the apparatus but leave pupils to work on their own and even to suggest some parts of the investigation.

We suggest offering two 'open' experiments: first, a very simple form of seesaw for experiments on balancing loads; then an open investigation of springs. The seesaw presents some difficulties of manipulation but leads towards a definite law – though children of different abilities will certainly arrive at different versions or even different laws. The springs experiment is easier in manipulation but much more open in the variety of things that children may think of to investigate. So we suggest placing the springs experiment second. Both experiments should be done and each deserves plenty of time.

This is the material that will be found in the two chapters which follow, Chapters 4 and 5.

Chapter 4

LOOKING FOR A LAW OF LEVERS

A simple series of class experiments

BALANCING THE SEESAW: AN OPEN EXPERIMENT LEADING TOWARDS THE LEVER LAW

We offer a very simple form of seesaw, for experiments on balancing loads. It should be simple and robust so that we can encourage experimenting without saying much about what to look for. We simply say: C32

'Here is a seesaw. Balance it on the wedge at the centre. Put some loads on each side. You should put the loads at the marks so that you know when a load is one step out or two steps out or four steps out from the centre. Avoid putting a load $2\frac{3}{4}$ steps out because that would make it harder to find out the scientific story of seesaws. First make the seesaw balance with two piles of pennies, one each side.

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

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

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

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

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

Every child (or every two, for economy) should have his own seesaw and set of equal loads, with a fulcrum on which to balance the seesaw. We suggest the seesaw should be a thin lath of wood about 18 inches long, marked with a pencil line across every $1\frac{1}{2}$

inches, the loads should be small squares of metal; or pennies can be used. We suggest using square counters of metal, 'square pennies', because they can be placed easily and fairly accurately on one of the pencil marks, with their diagonal on it. (Most children will need a suggestion of this placing.)

Note to Teachers

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

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

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

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

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

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

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

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

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

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

BUFFER PROBLEM FOR HOMEWORK OR CLASS

P

The Lever

This is offered as an informal road to ideas about moments. It should not be used to introduce formal teaching of moments. It should not be regarded as requiring a knowledge of the principle of moments – which would then have to be taught in the class at the expense of time and difficulty. So this problem should only be given to those pupils who are likely to enjoy exploring into new territory.

Tommy weighs 5 stone. He sits at one end of a seesaw which is 12 feet long and is supported at the mid-point. Where must Uncle John, weight 15 stone, sit to produce a balance?

Uncle John says, 'I don't like this. I want to sit at one end too.' Tommy says, 'All right, it's quite possible to have you at one end and me at the other, and still balance the seesaw.' Tommy is right, but they will have to move the support (fulcrum) of the plank.

1. Draw a rough diagram of the seesaw in the new position, marking in the fulcrum, and lines with arrows to show the four forces: weight of Uncle John, weight of Tommy, weight of the plank, upward force of the fulcrum on the plank.

2. Draw arrows on your rough picture of the seesaw to show the weight of Uncle John and the weight of Tommy.

3. If you can, add one more arrow pointing downwards to show the weight of the seesaw itself. The seesaw is quite a light plank compared with Tommy or Uncle John, and you can pretend that the whole pull of the earth on the plank is a pull at the mid-point of the plank.

4. The plank does not fall down because the fulcrum pushes it up. Draw the upward arrow showing that push.

5. If all these forces just keep the whole arrangement balanced, what would you expect to find if you added all the forces up? Give your arrows some lengths that agree with your answer to this.

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

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

The Game of Sym. (*Buffer Option* for fast pupils and others who like it.) This game was devised by a mathematical physicist, and ranges from absurdly simple to extremely difficult.§ GAME

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

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

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

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

§ 'This was set as an idea for homework and the levers were taken home.'

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

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

NOTES ON THE DESIGN OF THE SIMPLE SEESAW APPARATUS

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

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

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

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

Adjusting Square Pennies to Uniform Weight. In our preliminary trials, schools were provided with square pennies chopped from brass strip, 1 inch wide by $\frac{1}{16}$ inch. They were not sufficiently uniform in weight for this experiment. In fact, they varied so widely that they spoiled the experiment for some classes.

However we can now suggest a cure, for use in those schools who already have such square pennies, and others who wish to make them inexpensively: sort the pennies into groups by weight, then drill an appropriate hole through all the pennies except the lightest group.

It is far easier to achieve 1% precision than one would expect. The area of the brass square is 1 square inch. Suppose we drill a $\frac{1}{4}$-inch diameter hole through it. We shall reduce its area, and its weight, by 5% – a surprisingly small change for so large a hole. Making the hole $\frac{1}{64}$-inch bigger adds less than 1% to that correction. If a range of metal drills in $\frac{1}{64}$-inch steps is available, trial and error will soon find the drill to be used for each group of pennies to bring them all within 1% of the lightest.

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

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

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

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

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

> 'This little seesaw which you are going to use will tip over to one side and stay there if you put too much load on that side. When you have it balanced it

will not just stay level but will tip over to either side and stay there. That is because of the way it is supported with the wood block underneath.

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

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

Giant Seesaw

Where this balance-board experiment is done with still younger children, the teacher should have a demonstration seesaw 6 ft, or even 12 ft, long and work with bricks as loads. This is worth having even now; and it gives a chance to weigh a pupil: balance the beam at its mid-point on a large fulcrum on the floor, let the pupil stand 1 ft out from the fulcrum or sit 2 ft out, and balance again by adding pounds (or kilograms) far out on the other side. A useful suggestion from a teacher in trials: let pairs of pupils weigh each other, as an application of the lever law, *as soon as they have discovered the law*. This is likely to be a very successful 'carrot' to speed up the investigation. D32b

Steelyard. For a very fast pupil or one with special interests, we may suggest an investigation of the steelyard.§ No special apparatus is provided for that, but the pupil may use a metre stick or dowel of wood hung by a loop of string, carrying loads on loops of string. C32c

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

§ 'Advanced boys were given the school steelyard. One failed to observe until afterwards that the bar was calibrated directly in pounds. He removed the ball weight and weighed it and correctly used the lever law to find the weight of a brick. One certainly needs this kind of thing to occupy the faster pupils while waiting for the slower ones to catch up.'

Chapter 5

INVESTIGATION OF SPRINGS

A simple series of class experiments

Class Experiment

'Make a spring, and hang things on it, and find out how it stretches. Here is some copper wire that you can wind on a pencil to make a spring.' C33a

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

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

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

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

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

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

Steel Springs

Offer spiral springs of steel piano wire, one to each child, even if they are working in pairs – it would indeed be frustrating to have one's partner spoil the spring without having a chance to do it oneself. C33b

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

These simple steel-wire springs are rather dangerous to wind on a lathe. The wire uncoils suddenly when one releases it, and can make serious gashes. Special 'Springs-for-Hooke's-Law' may be expensive to buy from apparatus-suppliers, and we certainly should not spend money on them. It is cheap and easy to get simple, steel-wire springs from spring manufacturers. The makers will supply springs ready wound, cut in short lengths of 2 dozen turns, probably with the coils pulled close together in contact. A suitable spring has coils of diameter about $\frac{5}{8}$ inch – narrower coils will make the behaviour and observations more difficult in the later stages – wound of piano wire of such gauge that a spring of 2 dozen turns stretches about 5 centimetres for every 100 grams of added load. *

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

For children, it is better to have springs with coils separated; so the springs should be prestretched before they are issued – and at this stage it would be better not to do that publicly. To prepare the *

springs, experiment to find what load will stretch a spring a little *
beyond its original elastic limit in the coiled up form, leaving the *
spring with its coils slightly separated. Then apply that load *gently* *
to spring after spring, so that one has a large supply of similar *
springs ready for use. *

Measuring Spring Stretches. Children will need some scale for measuring stretches. An inch scale may be best at this stage; but if children are ready to use centimetres give them that scale. Let them hold the scale beside the spring and make measurements somehow at first; then go round to children and offer a good stand with a firm clamp that will hold the scale in a vertical position beside the spring. Even then, children will have some difficulty in reading the stretches because they do not have a pointer. However, one can encourage them to use the bottom of the weight hanger or the end of the lower hook of the spring and mark its position somehow. This is an experiment that *could* be done with great precision, but young children would need detailed instructions and then the experiment would drag out into something that was no longer an interesting investigation of Nature. So we should accept rough measurements, but encourage care. C33b contd

Notebooks. In their notebooks, children will want two columns, one for load and the other for stretch. They do not need a diagram of a spring being stretched – that is obvious to them and we shall not seem very sensible if we ask them to draw the obvious when they are busy doing an experiment. C33b contd

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

Graph. This is a case for plotting a simple graph, if children are ready for it. Children take kindly to graphs provided they are introduced casually, not as something they 'should have done in maths', and unfortunately have not. T

To prevent the precision of plotting becoming a long burden, it is better to let children plot a rough graph step by step at this stage – and perhaps to encourage some who like neat work to take the graph home and plot it more carefully.

Looking for a Rule

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

This seeking of a relationship is a scientific need that is not obvious to children of this age – it was strange to most of science until the time of Galileo – and we should not expect children to want to find a rule. (See however the Note on 'Constant' in the General Introduction.)

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

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

Like the lever law, Hooke's Law is a clear story about behaviour in T
nature; and the teacher should welcome it and tell children that Hooke himself was so pleased when he discovered it (just 300 years ago) that he kept it secret until he could arrange to make sure that he could get the credit for the discovery.‡

> 'This is a clear simple rule for springs that will be useful in T
> making spring-balances, and even in finding out more about springs. If this kind of thing holds for other springs as well as yours, you have got some powerful knowledge.

‡ Some teachers report from trials that this glimpse of history gave considerable pleasure. Another teacher reported the opposite, that being told that Hooke discovered this relationship three centuries ago, when pupils were rejoicing because they thought they had just found something new themselves, was a great disappointment. This is a point where each teacher must judge the mood of his class.

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

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

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

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

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

Feeling Forces

Teachers who did not ask children to feel forces with rubber bands, string, weights and magnets may want to do that now. (Or this acquaintance-and-naming experiment may be postponed until just before Experiment C 70, when a knowledge of forces is essential for the discussion of energy.) That was suggested as parts (*c*) and (*d*) of C 2. We could say: C2c, d

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

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

§ 'Most of them were able to state a rule in their own peculiar language.'

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

Proportionality

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

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

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

If the laboratory has a board ruled in squares the teacher may give a first lesson on graph plotting with it. Prepared boards are available, which make this specially easy. The points are plotted and lines are drawn on a sheet of plastic, with a chinagraph pencil or a bamboo-tip pen. A grid of black lines is inserted behind the plastic to show the coordinate rulings. The marks on the plastic are easily erased. The teacher should plot a 'bogus' graph, not one that gives the show away by exhibiting the straight-line relationship – leave that for the delight of finding it for oneself. C/D 34

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

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

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

Stretching of Other Materials

The teacher should give a demonstration of other things stretching: D35
a rubber cord, a copper wire, and perhaps fibres of polythene, nylon, lycra, etc. He can show the compression of latex. (Or we could add the compression of latex and the compression of a loose wide spring as a class experiment for faster pupils.) All this should go quickly, because there are no clear conclusions or detailed records to be made; it is a matter of seeing, and increasing one's acquaintance with Nature.

Some pupils may continue on their own with rubber bands at home. H35

Stretching a Wire

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

are likely to go beyond it into the yielding region before they know *
what they are doing, unless they have a general idea what to look for. *

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

For the demonstration, we can have a longer test wire if it is D36a
horizontal. The wire should be carefully anchored to a table at one end of the classroom and loaded by using weights and a pulley at the other end. We make its very small stretches roll a sewing needle which carries a straw as a pointer. We cannot do that by wrapping the wire itself round the needle, so we use an auxiliary thread wrapped round the needle, which is held in a simple bearing. One end of the thread is attached to the test wire near the loaded end. The other end of the thread carries a small load hung over a pulley to keep it taut. As the test wire stretches, the thread moves as well and rotates the needle and pointer.

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

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

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

Class Experiment: Stretching Wire. Then we give each pupil a length of thin copper wire, with a special arrangement for holding it at each end without damaging it. We ask him to pull the wire gently, trying to feel the elastic stretching of it. Then he should pull more strongly and feel the 'cheesy' yielding. That is a surprising experience to young children, and a very surprising experience to many a mature physicist. Therefore in this experiment we must give each pupil a wire for himself. It would be silly to let pupils work in pairs with one pupil relying on what his partner feels. C36b

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

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

Atoms and Elasticity

The teacher should comment on both the strength and stretching of wires and springs, from the point of view of atoms. The atoms T

§ 'All commented on the texture of the wire and the extension which could be produced. The comments were roughly:
'1. Feels like chewing gum.
'2. Leaves a point when it breaks.
'3. It goes thinner. [I gave each pupil a piece of unstretched wire for comparison using a lens.]
'4. It takes on a "silky" look instead of being shiny.
'5. You never know where it's going to break.'

§ 'Some children found it difficult to see why the movement of the straw showed that the wire was stretching. Generally they seemed to think this was a very exciting demonstration. One girl asked "Why does it come to a point?" Another said could she explain it – she then drew on the blackboard a series of diagrams:

They then asked for a second piece of wire, stretched it very slowly and examined it to find the *thinnest part just before it snapped.* They derived much pleasure from this experiment and certainly seemed to have learned something.'

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

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

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

This commentary is not material that we should teach. It is only given here as a guide to teachers in case questions arise.

If the crystal model made of large polystyrene balls D 6 has been made with balls stuck together to make layers that can be moved separately, teachers should show that again now, sliding layer over layer to illustrate these changes. D6 again

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

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

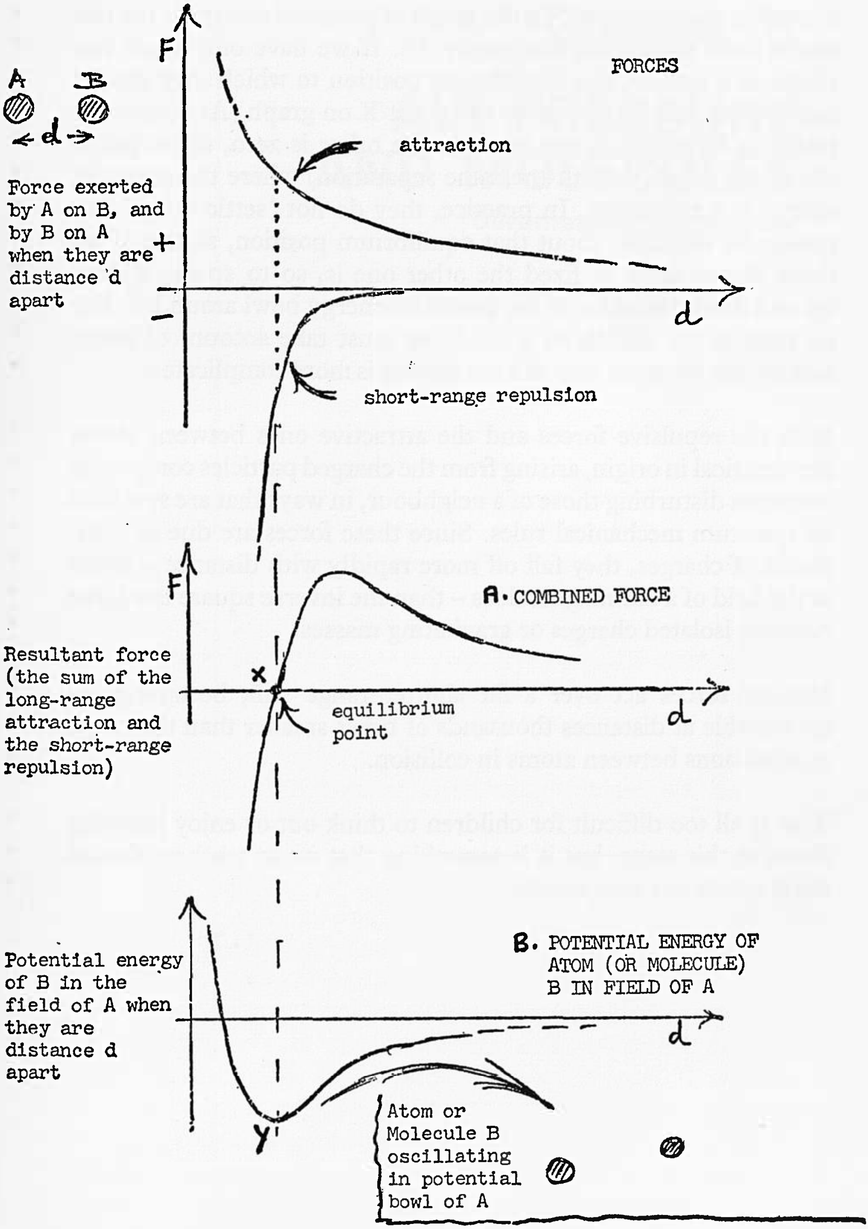
The *very-short-range* repulsions only appear noticeably at still closer approach, a small fraction of a diameter.

Reflect that that is just what we think when we picture gas molecules colliding with each other. (For a macroscopic model, think of two billiard balls repelling as they collide.)

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

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

If we investigate the force exerted on an atom by a neighbour at various distances, the graph of force against distance looks some-



F
FORCES
A
B
d
attraction
Force exerted by A on B, and by B on A when they are distance d apart
+
-
d
short-range repulsion
F
A. COMBINED FORCE
Resultant force (the sum of the long-range attraction and the short-range repulsion)
x
equilibrium point
d
Potential energy of B in the field of A when they are distance d apart
B. POTENTIAL ENERGY OF ATOM (OR MOLECULE) B IN FIELD OF A
d
y
Atom or Molecule B oscillating in potential bowl of A

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

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

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

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

Chapter 6

AIR PRESSURE AND MOLECULES

Barometers; gas models

Atoms and Molecules in Solids, Liquids, Gases

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

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

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

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

Gases

Gases are squashy: let the children compress air and feel its C37
springiness, using a nylon syringe with a finger over the needle end. Or use a bicycle pump – which the laboratory should have, unless many of the pupils have them. Ask pupils how they could tell whether it is the air that makes it difficult to press the piston down, the air that they can feel pressing back, or the piston rubbing against the barrel. Progress will not be held up if the children do not answer this. It is wise not to give an answer but to leave this as a puzzle for children to think about as young scientists. (We have to give an answer only too often, and that is liable to build up a picture of science as a set of answers and even a picture of scientists as answer-givers. We should seize every opportunity we can of leaving a question with children; and only when we notice someone really unhappy should we quietly give him or her the answer that he needs for his sense of security.)

Ask what makes air press on things, or how air presses on things, T
and leave that question unanswered until after further study of air

pressure. Remind children that gases do press on things strongly, and do move easily.

'Shut your mouth and puff out your cheeks and feel your cheek with your finger.

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

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

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

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

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

Much ingenuity has been brought to bear on this problem, in the hope that we could devise apparatus that would show pressure being produced clearly in the form of a force applied to an area and being carried across to secondary pressure gauges, such as U-tubes and Bourdon gauges, in a way that would make the concept of pressure clear to pupils. We do not have a simple method that is wholly successful. Again and again we are led back to the difficulty described in the footnote. The best we have been able to devise is the Evesham pressure-teaching apparatus described below. We suggest it should be used for a rough demonstration accompanied by a short description of pressure; and the pupils should then proceed to measure pressure with water manometers, barometers, and Bourdon gauges – postponing a more inquiring discussion of pressure to future Years.

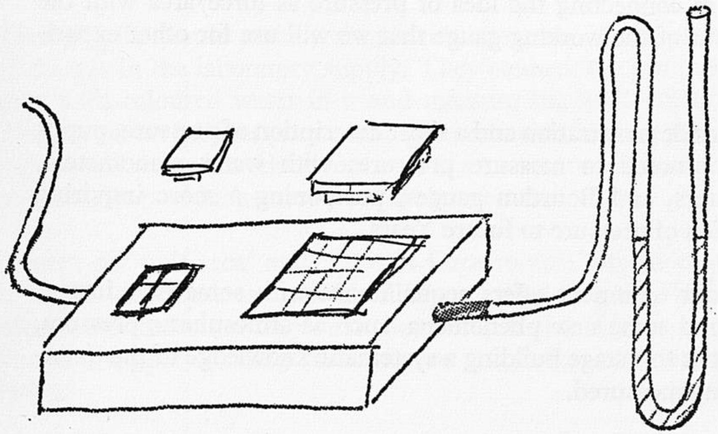
Thus our treatment offers acquaintance with some new instruments and some new phenomena, such as atmospheric pressure, without

‡ This approach seems to be very good, but it leads to trouble. Since it has proved a very tempting field for ingenious schemes, we would like to offer teachers a short account of the essential difficulty.
The general basis of such schemes is to connect a polythene bag filled with water to the manometer which is to be used for comparison. We place a small flat platform, 2 inches by 2 inches, on top of the bag, and place loads on that platform. We hope to find the manometer reading proportional to the load. And when we change to a platform of different area, 1 inch by 1 inch, we hope to see that it is load/area which determines the manometer reading.
However, loading of the platform pulls the surrounding sheet of polythene into such a shape that its tension exerts extra forces on the platform. That happens whether we have filled the polythene bag fully or have filled it only partially, leaving a lot of loose fabric. Those forces modify the story.
Suppose, for example, the bag is confined in a vertical cylinder; and the pressure is imposed by placing a load on a small platform on the open top surface of the bag. The pressure generated in the water inside the bag will be independent of the area of the platform. To see that, consider the force on the closed bottom of the cylinder. There at the bottom, the thin polythene envelope is pushed into contact with the bottom of the cylinder. The pressure of the adjacent water is transmitted straight through it to the bottom of the cylinder and produces the force which would be felt by anyone holding the cylinder. That force is the area of the bottom of the cylinder multiplied by water pressure just above it. Since the polythene envelope is necessarily flat in that region, its tension does not modify the force. But the force on the bottom of the cylinder is simply the weight of water plus the weight of platform and load. Therefore the pressure inside is simply that which would be produced by the load applied to the complete cross-section area of the cylinder. The area of the little platform disappears from the story.

at this stage building a systematic knowledge of the quantity being measured. In treating pressure like that we are not fully living up to our principle of teaching for understanding. Unfortunately this is a region where a difficult concept and unruly apparatus combine to make the essence of the topic too hard for pupils of this age. Yet we need familiarity with pressure gauges so that we can carry pupils on to barometers and the idea of atmospheric pressure and its measurement; so that we can link that in turn with a simple molecular theory of gases. * * * * * * * * *

The Evesham Pressure-teaching Apparatus

A rectangular hardboard box about 15 inches long, 8 inches wide, and 2 inches deep is lined with plastic sheet; and fitted with two brass tubes. Two square holes are cut in the top, one 2 inches square and the other 4 inches square. Square, loose, lids of hard-board are provided to fit the holes. D 38a



One of the tubes is connected to the water manometer. The teacher blows into the other tube; the plastic lining fills with air and pushes up the free hardboard lids until one or both lifts above the top of the box.

At this stage, the lids are loaded with weights placed carefully in the centre of each. Start with 1 pound on each lid and blow in more air gently. When the pressure has increased sufficiently the large lid lifts, but the small lid stays down.

Then load the large lid with 2 pounds, keeping 1 pound on the small lid. Increase the pressure, and the large lid still lifts. Then load the large lid with 3 pounds. Increase the pressure further and the large lid lifts. Then load the lid with 4 pounds, still keeping 1 pound on the small lid, increase the pressure until it can lift a lid. At this point we expect both lids to rise, and both do.

Then load the large lid with 5 pounds, and increase the pressure still more. At this stage we hope to see the small lid rise and not the large one; but in fact both lids rise. This is the weakness of the experiment. To avoid spoiling public opinion of it, the teacher would be wise to warn pupils of some such weakness beforehand. (The failure to give ideal behaviour is perhaps excusable since the last increase of load on the large lid is only 20 per cent, whilst the first one was a doubling of load.)

With still bigger loads on the large lid we may expect to see the small lid lift alone.

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

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

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

Air Pressure

'First, let us look at the pressure of the commonest gas of all: T
the air all around us. We could buy a pressure gauge ready made; and, if it was marked correctly, it would tell us that the air pressure is between 14 and 15 pounds on each square inch or about 10,000 kilograms per square metre, or 1 kg per sq. cm.

'Would you like to feel a kilogram so that you have a feeling for that pressure? If you balance it on your finger end, you are putting a kilogram load on just about 1 sq. cm. What is the pressure on your finger then? Is it 1 kg per sq. cm? ... No, you forgot that the air is pressing on it already.'

Hand out single kilogram weights to pupils and ask them to feel how heavy a kilogram is and to try letting one kilogram press on the end of a finger. If sufficient numbers of pound weights are available, some pupils may want to try piling 15 pounds on a square inch of their hand: 'Place your hand palm upwards on the table. Place something which is one square inch on your palm – a "square penny" from the lever experiment will do – and pile up weights on it until you can feel fifteen pounds per square inch.'

Now we ask pupils to do some class experiments which will give them a feeling for pressure. They repeat the experiment C 37 of pushing the piston of a hypodermic syringe. Then they try pushing in the piston of one syringe when it is connected to another by a pipe full of water. One pupil may push the ingoing piston while another feels the outgoing piston pushing out. The two syringes have different areas of cross-section, but a pupil will not know about the difference of force between the two until he takes both syringes into his hands and feels what happens. C37 C38b

Then pupils should make a simple measurement of the pressure of the gas in the laboratory supply. They connect the gas to a U-tube with coloured water in it and measure the level difference. This may seem a rather uninteresting experiment, not very strongly supported by our introduction, but it is a necessary preliminary to measurements of lung-pressure and air-pressure. C38c

('Force per unit area' and 'ratio of force to area' are more professional descriptions which children would learn without necessarily understanding what they really mean. This is a stage for very simple wording until we are quite clear what it is all about.) T

One needs to give very simple numerical illustrations: 'If the pressure is 3 lb per sq. inch, how much would the force be on 1 sq. inch, 2 sq. inches, 10 sq. inches, the sole of my shoe, the palm of my hand, and so on?'

Measuring Lung Pressure. Then move over to an enormous U-tube on the wall of the laboratory. This should be made of transparent plastic for safety. It should run from ceiling to floor to ceiling and then down to shoulder level for pupils to blow into it and it should be filled half-way up with water coloured with some harmless dye. (The dye should be dilute for the sake of the floor when accidents occur.) Let pupils measure their lung pressure by blowing on this manometer, making notes of the measurement in inches or centimetres of water. Setting up these tall manometers takes considerable time and trouble. If there is a convenient place C39 on the wall of the laboratory where they could be set up and kept available for use, that would be good.

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

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

Unequal Arms. 'Would it make any difference to the manometer T
reading for a given pressure if the cross-section area of liquid were
changed on one side?' As a demonstration show the effect of the D40
local gas supply on a small water manometer, with equal cross-section in both arms, and on another in which the arms are somewhat unequal, and finally on one with very unequal arms. The last one is made by using an aspirator jar with an ordinary glass tube coming out from the spout at the bottom, and bent up to represent the 'narrow' arm of the U-tube, while the main jar represents the wide arm. Apply the gas supply to the narrow arm and then to the wide arm (by a tube through a cork in the neck at the top).

Children will find to their surprise that the level of difference is the T
same both ways. Leave these U-tubes with different arm-proportions for a week as a demonstration. If children say 'That shows that water finds its own level', we should respect this old proverb as part of our heritage of simple science at this stage.

Note to Teachers. The traditional discussion of pressure and *
rules for fluid-pressure-behaviour is a delightful example of care- *
fully built up physics that can be taught well; but that will take *
more time than we should spare in this course, and it would con- *
centrate attention on formal material that children would memorize; *
so we wish to experiment on doing without that material in this *
course. At the moment 'Water finds its own level' will be a *

primitive substitute for some of that knowledge; and the rest of it will be acquired, in passing, in later Years. *
*

Mercury U-tube and Lung Pressure. Install a large mercury-filled U-tube as a permanent demonstration on a wide wall. This should be tall enough to show an 80 cm pressure difference without any danger of spilling mercury; and its bore should be wide enough to show the mercury clearly to pupils at a distance and to avoid capillary troubles: say, at least 4 mm diameter. Let pupils try their lung pressure on the mercury manometer. C41a

This will raise the question of comparing mercury with water for pressure measurements; and we should simply point out that this is a matter of relative density. Weigh a small bottle of mercury and an equal bottle of water and an equal bottle of air, and ask how the comparison should go. This is something better done by the teacher, or children will spend too much time on arithmetic rather than profitable puzzling. D41b

When that comparison yields the proportions $13\frac{1}{2}:1$ for mercury to water, suggest that the pressure gauge will show the same ratio the other way round. Take the mercury level difference for the gas supply and multiply it by $13\frac{1}{2}$, try that for a child's lung pressure – warning him, however, that his lung pressure changes from time to time.

Bourdon Gauge. Introduce a Bourdon pressure gauge by using it to measure excess lung pressure. If the effect of a pupil blowing is not sufficiently impressive, try connecting a foot pump to a Bourdon gauge and pumping gently. C/D42 a.b

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

ATMOSPHERIC PRESSURE

With many children at this age the idea of the atmosphere is half taken for granted, half unknown. Asked if the air is here in the room, a child will say 'Of course it is, I breathe it in and out, I can feel it.' Yet when asked if air is real stuff that you can weigh and put in a box, like water or sand, most children will show uncertainty. Air is not as real to them as water or sand – nor was it to the scientists among our early ancestors. And the idea that we live at the bottom of an ocean of air that exerts as good a pressure as an ocean of water some thirty feet deep is new and strange – essentially unthought of rather than difficult. (James Conant, in his * * * * * * * * * *

excellent discussion of the tactics and strategy of science, quotes *
this idea of 'ocean of air' as an example of a conceptual scheme *
that enabled science to advance.) Children in this course have met *
one aspect of the reality of air when they saw air being taken out by *
a vacuum pump. But now we must push the question further and *
ask them how they know the air is really there and what they think *
it does. *

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

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

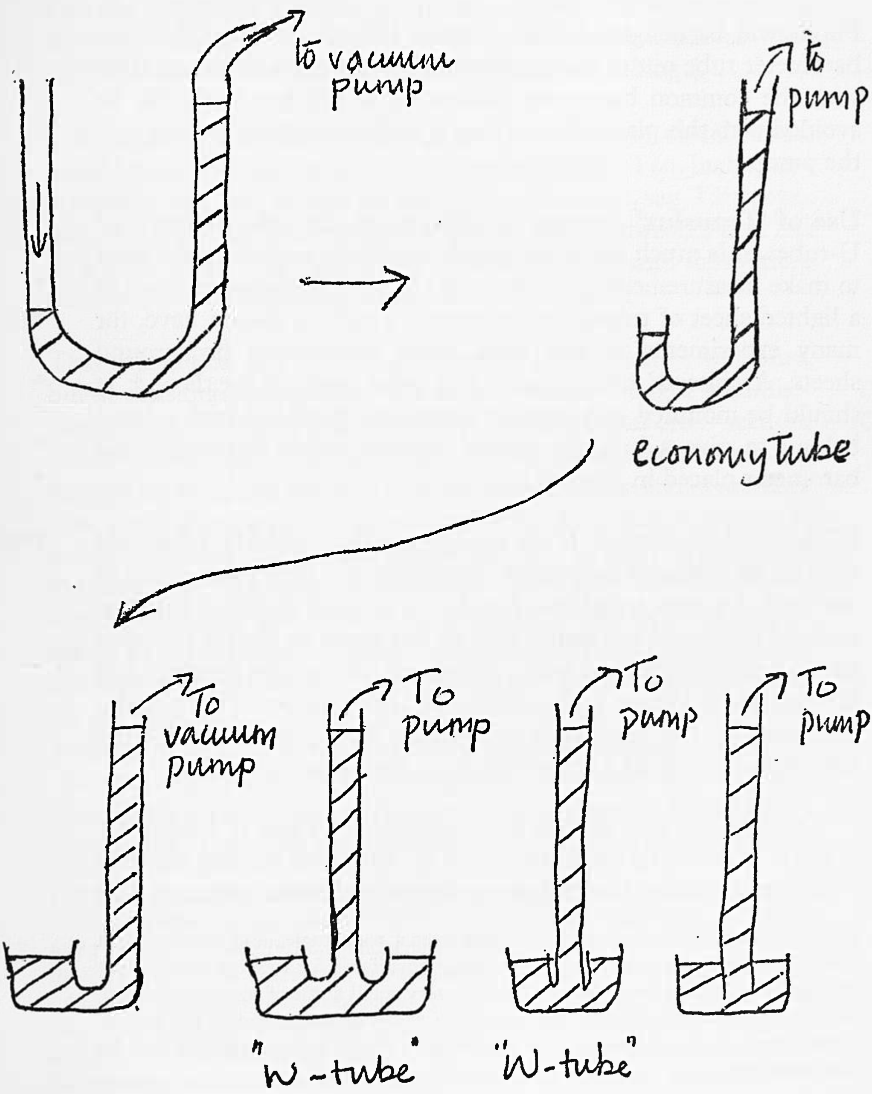
> 'Now look at the U-tube. Both ends open, not connected to D43
> anything. There is the mercury at the same level on both sides. Suppose we wanted to measure the pressure of the air in this room. There it is, pushing on the mercury on the left side, and there it is, pushing on the mercury on the other side. If we want to measure that full pressure, it won't be any good having it pushing on both sides. What must we do?'

Elicit the suggestion of pumping the air away from one side. Bring out the vacuum pump, attach it to the mercury U-tube on one side and pump a little, and ask what is happening. Then pump some more. Then stop and raise the question of damaging the pump by pumping mercury up into the pump. By this time a healthy group of children are frantic to see that happen. Go on pumping and show that there is a definite limit. Ask whether one can be sure that there is a good vacuum – 'just nothing' – on that side. Measure the level-difference of mercury.

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

Barometer

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



tubing; then another with one arm very wide; and then turn the very wide side into just an open dish.

Point out that a glass tube dipping in an open dish of mercury *is* a U-tube with one arm very wide indeed, and show that. Dip a tall glass tube, 4 ft high, in a pool of mercury in an open dish. Connect a rubber tube to the top of that glass tube, and pump the air out of it. 'Watch the mercury go up. What makes it go? Why does it stop?' D 44

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

Pupils will be delighted if the teacher lifts the lower end of the barometer tube out of the mercury. This is a good demonstration with the common barometer (following D 45) but it should be avoided with this plain tube, in case it leads to mercury getting into the pump.

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

Filling a Barometer. If the teacher can do it quickly, he should then fill an ordinary barometer consisting of a long tube closed at one end. An easy technique for this is to pour mercury into the inclined tube until it is nearly full, all but about an inch at the open end. Then close that end with a finger and tilt the tube gently to run the air bubble slowly to the other end of the tube and back again, collecting up the small sticking bubbles as it goes. Then fill the tube to the top, hold a finger firmly on the open end and ask: D 45a

> 'Can you see any air left in this tube? ... Then if I hold my finger here, no air can possibly get in. I am now turning the tube over and putting the end of my finger under the mercury. Can

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

any air get in? Now I'll take my finger away. Watch what happens.'

Again the same barometer height indicates the air pressure. Hold the barometer in a clamp while the measurement is being made. Let children come and make their own measurement if they like.

Then ask the children what they think will happen if that barometer tube is tilted. Try that. D 46a

Narrow and Wide Barometers. The height is the same, however the barometer is filled, by tipping a closed tube or by pumping an open one, and it is the same for a barometer made of wide tubing as for one made of comparatively narrow tubing.‡ D 46b

Calculation. For fast pupils go on from here to calculate the weight of a column of mercury of barometer height 1 sq. inch cross-section or 1 sq. cm, so that we know the pressure in, say, Lb per sq. inch or Lb per sq. cm. For slower pupils, that is probably best left to a later Year. This calculation is more difficult, and looks more artificial, for most children than one would expect. T

This calculation can be changed into an experiment of weighing, but at considerable expense. If a school wished it might manufacture a special Perspex box, 1 inch by 1 inch internal cross-section, and 30 inches long. One can fill that box with mercury, and place it upright on weighing scales. Then one can weigh the actual mercury that would press on a one square inch area. That box is difficult to make, and liable to leak; and one would have to buy a great deal of mercury – in fact, just 14·7 pounds! A cheaper version of that, which would only lead to the metric answer, would be a box 1 centimetre by 1 centimetre cross-section, also 30 inches long. We do not expect to find schools constructing and using such boxes; but we do suggest the idea of a tall box filled with mercury being weighed to find the pressure of the atmosphere directly as a useful 'thought experiment'. With a fast group, this might be a first taste of Galileo's great method of thinking his way through an imaginary experiment. Put with the right flavour, this could catch pupils' D 45b OPT.

‡ If the tube is very narrow, say 4 millimetre bore, filling is harder. If it is still narrower surface tension makes a noticeable difference. Therefore, instead of using a medium bore of tubing and a narrow one, we must use a wide bore and a medium one. As an alternative one teacher in trials suggests placing two open tubes, one medium bore and one narrow, in the same dish and pumping air from the top of both tubes at the same time, using a T-piece for the connection to the motor driven vacuum pump. This is a very clever scheme, though the scheme of two separate barometers described above is probably better for beginners.

fancy. Then, having described the 'thought experiment', the teacher could lead to a practical test by asking just how many cubic inches or cubic centimetres would be needed to fill such a tall box and then weighing a smaller sample of mercury of measured volume.

Then one can say 'The amount of mercury pushing down on 1 sq. inch is balanced by the atmosphere, hence this provides a measure of the pressure of the atmosphere.' (Experiment beforehand with any such tube, and the weighing of it full of mercury, over a table with a good rim; because the tube may well leak under a pressure of 15 lb/sq. inch in its lower regions.)

Puzzle. Ask a strange question:

> 'Suppose we didn't have air all round us but had mercury instead T
> – how high up would that mercury atmosphere have to extend, from the ground to the top of the atmosphere, if it were to make the same pressure that we feel here? What depth of mercury would make the same pressure?'

This is just an amusing puzzle at the moment, best left unanswered. It needs courage in theoretical thinking.

Pressure in Different Directions

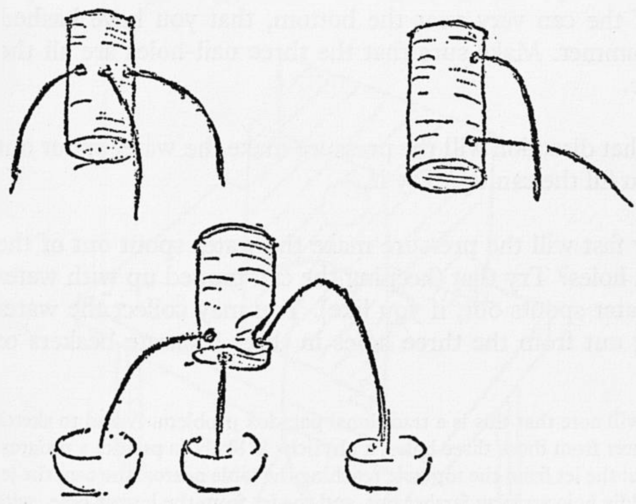
It is difficult to twist a mercury barometer around to show that the T
atmosphere pushes in all directions, always perpendicular to any surface it is offered; but we can show that with water. Encourage pupils to try the experiments suggested below – in class and at home.

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

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

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

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



a. 'Take a tin can and make some holes in it with a round French nail. Try to make all the holes exactly the same size. (If you like, put a piece of wood inside the tin as a backing, and then hammer the nail through the tin into the wood.) C/H47

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

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

b. 'Take another tin can (or block up the holes in the one you used) and make three holes, one hole near the top of the can, one part way down, one near the bottom. Now fill the can with water again and watch how the water spouts out.'‡ C/H 47b

c. 'Take another tin can (such as a can that soup comes in), batter it to an irregular shape with a hammer, and drive a French nail into the battered bottom at three different places all near the bottom, where the metal surface is in three different directions. C/H 47c

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

'1. In what direction will the pressure make the water spout out when you fill the can up? Try it.

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

‡ Teachers will note that this is a traditional paradox problem. Asked to sketch the jets of water from those three holes, a physicist is likely to predict a progression of ranges: the jet from the top hole reaching the table nearest the can, the jet from the middle hole arriving farther out, and the jet from the lowest hole, with biggest pressure, spouting farthest.
Then a thought-experiment warns him that this must be wrong: if the can rests on the ground, water from a hole at the very top (the free surface) will dribble down the side and arrive at the very edge of the can; and water from the very bottom, however fast it spouts out, will also hit the ground immediately, just at the bottom of the can. Yet water from some intermediate level will spout out and arrive some distance away.
Finding the full story is a short interesting calculation, easy for a sixth-form pupil.

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

As a suggestion for an experiment at home, ask pupils to fill a balloon with water and make holes in it with a pin. This is an exciting, messy, experiment which does not usually yield any very clear result. For scientific knowledge, repeating the experiments (*a*), (*b*), (*c*) above is better. H 47d

Air Pressure

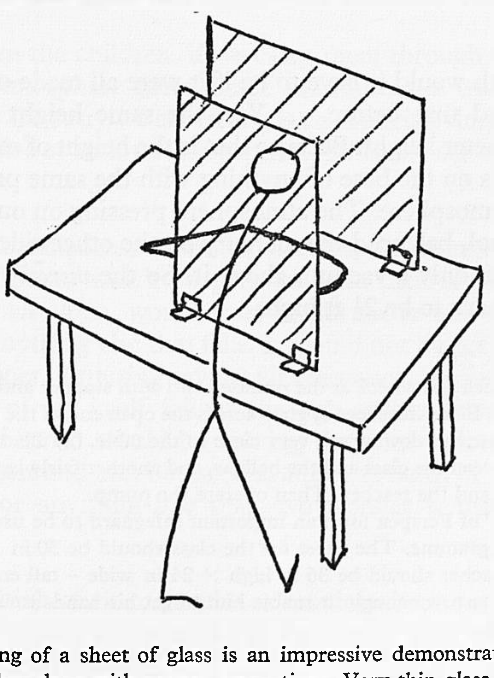
Show the strength of atmospheric pressure with some demonstrations, such as: T

pumping air out of a tin can or a hollow rubber toy; D 48a

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

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

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



‡ This cracking of a sheet of glass is an impressive demonstration; but it is dangerous unless done with proper precautions. Very thin glass, which would make the demonstration easier and safer, is difficult to obtain. Therefore we suggest that if the teacher shows this at all, he should use ordinary window glass with the following precautions: *Contd. at foot of* p. 226.

Suggest to children the experiment of boiling a little water in a large tin can to drive out the air and then taking it away from the flame, corking it up quickly and letting the steam pressure inside collapse so that the atmospheric pressure outside crumples the can. C48e

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

A Thought-Experiment concerning the Atmosphere. This is an argument, a taste of theory – thinking that is fantastic and unreal but yet of help in building our knowledge or understanding – *difficult* but *within* the compass of some of these pupils. T

> 'Remember the question about living in an atmosphere of mercury. How high would the mercury have to be from the floor to the top of the atmosphere if that was all there was to make the pressure that we actually live in? ... Yes, the height would have to be the barometer height, 30 inches or $2\frac{1}{2}$ ft of mercury. Now think about the real atmosphere. How high would that have to be if it went on up and up just as thick as the air is in this room, and then stopped suddenly at the top, and there was nothing more above?
>
> 'Well, how high would it have to be if it were all made of mercury? We asked that before. ... Yes, the same height as the mercury barometer height. Because that is the height of mercury which can press on the base of anything with the same pressure as the whole atmosphere. The atmosphere pressing on one side, on the open pool, balanced the mercury on the other side in the barometer, with only a vacuum above it. So the *mercury* atmosphere would have to be $2\frac{1}{2}$ ft high.

Contd. from foot of p. 225.
(1) Use a bell jar which has a neck at the rounded end with stopper and tube to connect to the pump. Place the sheet of glass across the open end of the bell and hold the bell with that end downward, very close to the table. (2) Place a large sheet of Perspex between the class and the bell jar, and another fairly large sheet between the bell jar and the teacher. Then operate the pump.
Those 'safety sheets' of Perspex form an important safeguard to be used again and again in our programme. The sheet for the class should be 30 in × 30 in. The sheet for the teacher should be 36 in high × 24 in wide – tall enough to protect his face but narrow enough to enable him to get his hands round comfortably from behind.
If these precautions are taken as a matter of course, without much talk about danger, an experiment like the one suggested here will prove valuable. But if either teacher or class invests the experiment with an air of worry about safety, it is better to get rid of the experiment – interest and care should be the watchwords in science, not anxiety.

'How high would a *water* atmosphere have to be? Remember, the water is not so dense as mercury. Mercury is $13\frac{1}{2}$ times as dense as water, so, a water atmosphere would have $13\frac{1}{2}$ times the mercury height; $13\frac{1}{2} \times 2\frac{1}{2}$ ft, about 33 ft.

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

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

Density measurements show that air has a density about 1·2 grams per litre. Mercury has a density 13,600 grams per litre. Arithmetic gives from that a density ratio of about 11,300 to 1. Therefore if we had a uniform atmosphere of air, it would have to be $11{,}300 \times 2\frac{1}{2}$ ft high; or somewhere between 25,000 and 30,000 ft.

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

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

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

This simplified story of air molecules moving up and down and *
rising to the top of an artificial atmosphere, coming to rest and *

dropping down faster and faster again, is not as queer and useless as it sounds; a full version of that was used by Boltzmann to do an important calculation, a derivation of the Maxwell distribution of gas molecules' velocities. We too could do a very interesting calculation with this at a later stage when our pupils can calculate the speed which a freely falling object would have after falling, say, 28,000 ft; they can obtain a rough estimate of the speed of air molecules. Treating this as a case of free fall, we obtain a speed of over 1,300 ft per second, compared with the 1,600 ft per second that a proper calculation yields.

MODEL OF A GAS

Are air molecules really in constant motion? T

> 'Scientists think of air molecules as moving about very fast and bouncing off everything they meet. That is not just a wild guess; though molecules are too small to see, we can see their actual effects. Look at some tiny specks of ash floating in air. You can get those by putting a little smoke in a small round box under a microscope.
>
> 'Watch the tiny specks and you will see them dancing about. You cannot see the air molecules but you can see that something is jostling these much bigger specks.
>
> 'Imagine that players in a football game were invisible, too small to see. But suppose a visible elephant on roller skates could be parked in the middle of the football field during a game. You would notice the elephant moving in a most irregular jumpy way, as he was pushed around by collisions with players. That is the kind of thing that we think is happening to the bits of ash you are going to watch. But first you should look at a model of molecules, the tiny particles, in a gas.'

Note to Teachers on Models

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

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

Q

Robert Boyle, who lived 300 years ago, carried out many experiments on the pressure of gases, and discovered a famous law that bears his name. He found that by halving the volume of air you double the pressure. In 1661 he read a paper to the Royal Society of London called 'Touching the Spring of Air'. He supposed that air is made up of tiny particles crowded together, touching each other and surrounded by springs – perhaps nowadays we might think of his particles as being like balls of foam-rubber or springy steel wool.

1. How, from this 'theory' (picture of gas particles), would Boyle explain the pressure of a gas, and the fact that the pressure of a gas increases as it is compressed?

Boyle did experiments and his law came straight from them, but his theory did not fit the facts very well, and now we have a different theory, which explains pressure by supposing there are many tiny particles in motion.

2. How does the particles-in-motion theory of a gas explain the fact that gases can exert pressure?

3. How does the particles-in-motion theory explain the fact that a gas exerts a bigger pressure when you squeeze it to a smaller volume?

R

Read question Q again, then describe briefly one experiment you have seen or heard about which gives support to a particles-in-motion theory of gases but not to a 'foam-rubber' particles-at-rest theory.

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

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

'let's pretend that ...' *

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

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

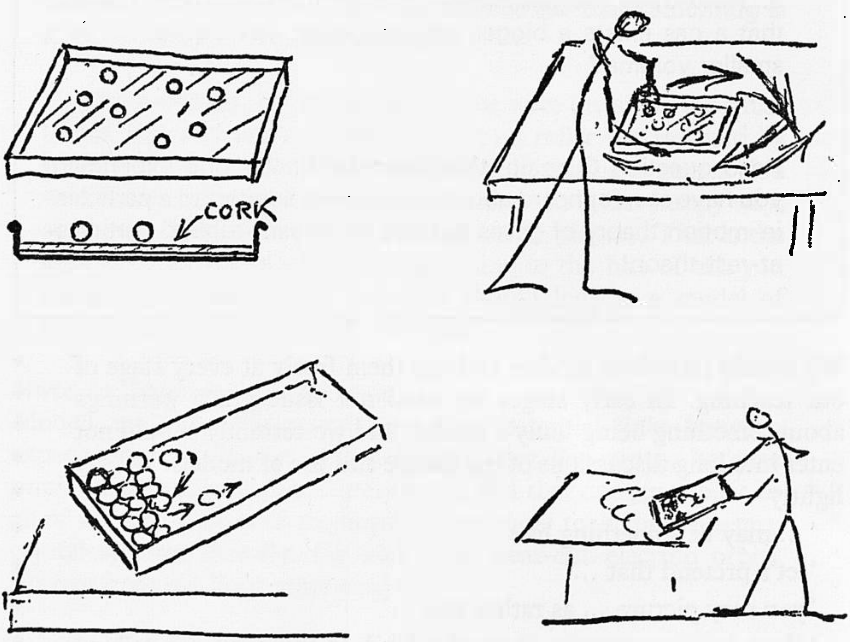
'not real ... but only a toy to help you think about it.' *

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

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

Model of Gas Molecules in Motion§

As a class experiment, give each pair or quartette of children a tray of marbles which they keep in constant agitation by pushing the tray about irregularly on the table by hand. C49



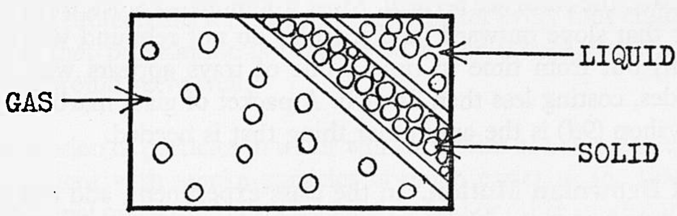
§ 'This simple experiment is extremely effective. My boys found it interesting and afterwards told me most of the kinetic theory principles – although I didn't mention it by name.'

Although it is only a two-dimensional model, this simulates the behaviour of gas molecules more closely than some three-dimensional ones. The tray should be of metal (or glass) with massive *vertical* edges, with two dozen ordinary glass marbles in it. The pupil operating it keeps the tray on the table and moves it with a rapid, jerky, vibrating motion. A circular motion will do if it is interrupted by frequent changes. The noise is reduced if a thin sheet of cork is placed in the tray as a carpet; and then pupils can hear the individual collisions of 'molecules' with walls and with each other; and can distinguish between those two kinds of collision by ear.§

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

Pupils may ask why we have to keep agitating the tray, when a real gas does not require a continual supply of energy to the walls of its container; and when that question arises we should say that the walls of all containers are, on a molecular scale, themselves in constant agitation. If pupils distinguish by ear impacts on the sides of

§ 'The slower class seemed to get far more out of this model. One group were very excited with their own intelligence when they showed this arrangement:



'"Look: if we shake this tray we can see how solid, liquid, and gas molecules move."

'With this class I had ten minutes more for the lesson so I told the children to count how many times one of the small marbles bumped into the others in one minute. They wrote the answers on the blackboard and found they had results ranging from 40–120. I asked "what factors would affect the number?" Answer "number of marbles. Energy put into shaking." They arrived at the ideas of increased pressure with smaller volume and pressure depending on number of collisions.'

the tray from collisions between one marble and another, they can listen to the pressure increasing as the sound of the former grows.

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

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

At present, we simply give a tray and marbles to each group of C49
children and ask them to agitate the tray and watch what happens.

They may also listen to the noise. If they distinguish between the sound of marbles hitting the sides of the tray and the sound of collisions between marbles, they may even take the former sound as a rough indication of 'pressure'. Teachers in trials report that listening to this experiment is valuable and popular.

This is such a simple but powerful model that we hope some children will make their own version at home. They need a tray whose edges will bounce a marble back easily. A bright 'tin' baking tray, about 12 inches × 8 inches with edges $\frac{1}{2}$ inch to $\frac{3}{4}$ inch high, does well, provided the sides are *vertical*. Most ironmongers stock trays with sides that slope outward (and marbles do not rebound well from them) but from time to time a line of trays appears with vertical sides, costing less than 2*s* each. A packet of glass marbles from a toyshop (9*d*) is the only other thing that is needed.

Model of Brownian Motion. In the class experiment, add one C50
or two much larger marbles to each tray, among the ordinary marbles, and ask children to watch them, pretending that those are the smoke-ash specks that they are going to see in air. This model should probably be shown both before and after the real particles-in-motion experiment.

Demonstration Model of Gas Molecules. Also show a three- D51
dimensional model; small balls kept in motion by a vibrating piston at the bottom of a tall transparent tube. The distribution of

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

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

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

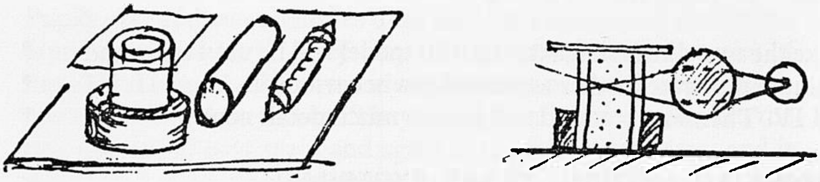
BROWNIAN MOTION: CLASS EXPERIMENT

This is one of the most important 'atomic' experiments in the whole course: it is one of the few that show the 'graininess' of nature – molecules, atoms, electron charges, quanta of energy. The children should have plenty of time to see it, and a good chance to see it again if they wish. The microscopes that were needed for the early class experiment C 11 should be brought out again so that children can see the real Brownian motion for themselves. As we explained in discussing that earlier use of microscopes, many biology departments feel that they should not lend their best microscopes for class use with these young pupils. And in that case it is essential for a school following our programme to buy enough microscopes (simple models but with large enough aperture) for that general use, and for this use for the Brownian motion. There should be one microscope for every four pupils. (The Nuffield Biology project asks for microscopes – one for every four children – and if that programme is being used in the school, those microscopes would serve well.) C 52

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

The smoke should be in a small cell under the microscope with bright light from an electric lamp focused in a central region which is observed with the microscope.

In our trials, we found that young pupils cannot manage a microscope with a smoke cell which has a separate lamp that can be shifted. It is necessary to have the lamp firmly attached to the smoke box. Of all the available forms of smoke cell, for looking at the Brownian motion under a microscope, the very simple Whitley Bay form is much the best.‡ Young pupils can insert the smoke themselves and look at it by the light of a small built-in lamp and see the Brownian motion for themselves.§



WHITLEY BAY SMOKE CELL

The sketch shows the general arrangements: the smoke is put in a small vertical glass tube, closed at the bottom, with the bottom blackened. Light is concentrated into a narrow line across the tube by a cylindrical lens. The light source is a horizontal festoon lamp and the lens is a horizontal glass rod arranged to produce a line-image of the filament in the middle of the glass tube of smoke. In order to minimize convection, the lamp is placed *below* the level of the glass rod so that the image in the tube is *very nearly at the top*.

For proper imaging (necessary to make the cell work well), the lamp, rod and cell must be spaced as follows: from filament to surface of rod, one rod-diameter; from surface of rod to centre of cell, one rod-diameter. If teachers make their own smoke cells they should follow this geometry carefully because preliminary trials have shown that deviations from that produce much poorer results.

Pupils put smoke in the cell and cover it with a microscope cover glass before they look at the smoke.

The smoke may be provided by a smouldering milk straw, or a smouldering piece of sash cord, or a cigarette. The milk straw is

‡ This design was evolved during the trials of Nuffield physics materials and has since been made available to all suppliers of apparatus.

§ 'This experiment and equipment are excellent. The bottom stream in this secondary modern school can all perform this experiment unaided.
'It provides the right amount of technique to grip the interest of the class.'

held almost vertical and lit at the *top* end, so that smoke pours down through the straw into the cell at the lower end. The sash cord is lit and then held just over the mouth of the cell; but pupils must be warned not to leave it smouldering. (More elaborate schemes have been suggested, in which smoke is picked up in a small eye-dropper and squirted into the cell. That is an unnecessary complication, and it does not work so well after some use.)

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

Again show the models of gas molecules, with a large 'particle' D53
added to simulate Brownian motion. (The three-dimensional model D 51 and the tray with marbles, C 49 and 50.) Point out that molecules of air must be much smaller than the smoke particles. Again raise the question of the size of molecules. We shall ask pupils to do an experiment to estimate the size of a molecule. (See Experiment C 68.)

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

Therefore it is important to have smoke cells with an illumination arrangement that shows the particles brightly, even with a small microscope, and does not give too much convection. The lamp must be attached to the microscope so that when a child moves the microscope the illumination is not cut off. The position of the lamp and the focusing of the microscope must be arranged so that the smoke that is viewed is almost at the top of the cell, so that convection is less pronounced.

(When children look at smoke specks in the small cell there are two difficulties: (1) There may be convection currents. There will always be slow drifting; but if there are strong convection currents so that the whole collection of smoke specks sweeps across the field of view, something is wrong, either with the illumination or with the box, which *must be tightly closed.* Those currents will confuse the story for the children badly and we must stop them. (2) There will always be some specks out of focus, and others which are in focus at one instant will dance out of focus the next. Specks which are out of focus appear as round patches of light; and children need to be warned of this. The working of the smoke cell takes some apprenticeship and many a teacher uses it for some time without knowing its full possibilities. It is a thing to play with carefully beforehand and it needs watching while pupils are using it.)

Brownian Motion in Liquids (optional extra)

We regard the Brownian motion as strong evidence that gas molecules are a constant motion. Ask whether molecules and atoms in liquids and solids are also moving. If convenient show Brownian motion of carbon particles in water – and in that case make it very clear that this is in a liquid and that any difficulties of seeing these are nothing to do with the story of gases. To make a suitable suspension of very small particles, dilute a drop of Indian ink, or mix a little aquadag with water. The microscope should have an objective of much higher power than for the smoke cell, say $\frac{1}{6}$ inch. To gain more light, it is preferable to use the objective, informally, as a water immersion lens. Leave the drop of liquid on the slide without a cover and let the lens make contact with the liquid.

OPT. D54

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

S

(Not very serious – just for amusement.) This is to find out what being a gas molecule feels like. Go out of your front door, taking a penny with you. Toss the penny; if it is heads, turn right; if tails, turn left. When you get to a place where there is a choice of paths, toss the coin again to decide which to take. If there are more than two alternative paths, at a crossroads, for example, you will have to toss the coin twice in order to make a decision.

Notice how you get further from home, but not so far as you would if you walked in a straight line. You are behaving rather like a molecule: each street corner corresponds to a collision with another molecule which may change your direction. The varying distances between one street corner and the next correspond to varying distances travelled by one molecule between collisions with other molecules.
Note: to make a better comparison you ought to include, at each road junction, the possibility of returning the way you came – but this makes it too boring! You may decide that being a molecule is not very interesting anyhow. If your peculiar behaviour leads to your being questioned by the police, explaining that you are a molecule will not help you much!

MOLECULES AND MODELS

Talk about motion of molecules in liquids and vibration of atoms in solids to give a survey of our knowledge to date. T

Bring out the two-dimensional gas model of marbles in a tray and fill it with a crowd of marbles, leaving just enough space for the crowd to move like a liquid when the tray is tilted. Agitate the tray to show molecular motion in a liquid; but warn pupils that the model is now even further from being a close model of gas molecules: in a liquid, molecules are close enough to attract each other most of the time.

Show a big model of a solid crystal, consisting of massive balls joined together by weak steel springs. The springs should be relatively weak so that the model wobbles like a jelly. It is best if the model has springs from each atom to several neighbours, to illustrate the interaction between atoms. A tight model, that vibrates as a whole, is in some ways closer to a single crystal; but it will not give our pupils a good feeling for atoms in solids. Here, our model should have atoms represented by massive balls such as golf balls, connected by weak springs like the ones used for our spring experiments in this Year. Most commercial models have springs that are much too tight; so it may be advisable for the teacher to make his own. D 55

Diffusion

Some teachers will want to show diffusion of gases here and diffusion of salts, etc., in liquids. For many classes it may be better to postpone these demonstrations to the next round of Kinetic D 56

Theory in Year III, unless we have them in simple form which these young pupils can understand. We advise teachers to postpone them. If we have simple demonstrations we could use them now – but we must remember that there is no sign in our discussion so far of the differences among molecular speeds that are coupled with differences of molecular masses. So all we are showing is that gases do mix and do diffuse through walls at different speeds.

With visible materials, we can show the diffusion of nitrogen peroxide into air – that certainly shows gas molecules making progress – copper sulphate in water, potassium chromate in a mixture of water and gelatin. D 57 D 58a D 58b

There should be an exhibit of copper sulphate crystals in a tall jar of water, that is left standing for several weeks.§ D 59

Bromine diffusing in air does not show the great speed we would expect for the brown bromine molecules (Kinetic Theory suggests over 200 metres per second). We can show it but children will be puzzled. In a later Year they will give the explanation at once 'air molecules get in the way'. And at a still later stage (Year IV) we can put the speed of diffusion to good use to obtain an estimate of gas-molecule size. From experience in trials we find the bromine experiment is appreciated at this age, particularly if repeated with a vacuum. D 60

Bromine diffusing into a vacuum is a startling sight, an experiment well worth doing despite the difficulty. However, this is needed in Year IV as a very important demonstration to illustrate the high speed of gas molecules when we have estimated it by calculation with kinetic theory. And that is followed by a *measurement* of the diffusion, needed for an estimate of the size of a molecule, so this experiment must be shown then. Some teachers will prefer to leave this experiment until Year IV so as to avoid losing its startling effect when it is shown in the middle of a rather long, dull, difficult part of that year. But other teachers, following the advice of teachers who have tried this in Year I, will show both the bromine diffusion experiments now. Teachers who have done that consider that it will not spoil the delight when pupils meet it again in Year IV. D 61

§ 'We spent a double period talking, discussing and showing a few diffusion demonstrations (and how to make gelatin at home!).
'Brownian motion was thoroughly discussed in terms of marbles, elephants on skates and smoke particles. All in all, a good opportunity to show how things fitted into the overall scheme.'

For those who wish to show it now, details are given. Bromine is dangerous material and needs special handling to make the demonstration safe. (See special instructions. Always have ammonia solution at hand.)

We release about 1 cm^3 of bromine at the bottom of a tall tube 2 inches wide $\times$ 1 ft high, which has previously been pumped out. The bromine must be released suddenly by breaking a small glass capsule. Then the vapour fills the tube instantaneously.

How Small are Atoms?

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

This is a first chance to give the idea of 'order of magnitude', not by that name, but by asking children whether they think the length of a postcard would contain 100 atoms in line; or 1,000; or 10,000; or 100,000; or ... and point out the good sense of skipping up by a factor of 10 each time and not bothering for greater precision until we get some idea of which county we are in. * * * * * *

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

'For example, in chemistry we sort out all the materials we know into atoms of one kind and atoms of another kind and so on. We say that atoms all-of-one-kind belong to an "element". If there were 10,000 different elements making up this world, chemistry would be so complicated that we should never have sorted it out, even yet. If there were only 10 kinds of atom, only 10 elements, chemistry would be far simpler than it really is. There are in fact about 100 elements. But from the point of view of knowing whether chemistry is going to be very difficult or not, all we need to know is whether there are 10 elements, 100 elements, or 1,000 elements.'

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

Some parts of Problem C (p. 292), set for homework, will be useful T
here.

> 'Although a rough guess would be sensible for the question about atoms along a postcard, you still need to know something about the size of atoms before you can make any estimate. You can tell that atoms must be very small by using common sense.
>
> 'Suppose atoms were great big things, so that we had only a few of them in a teacup of water. If they were big enough to see you would certainly notice them; and you might even hear them. Suppose atoms were as big as these marbles; listen ...'

Pour a handful of marbles from one transparent container into D62
another; then a handful of dry peas; then a handful of sand; then a handful of water, pouring the water very smoothly.

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

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

§ The planning of a safari might be a suitable example:
If it is to be about 10 miles, all we need is stout boots.
If it is to be about 100 miles, we need some food and a tent.
If it is to be about 1000 miles, we will need porters to carry all the equipment.

Or the planning of alterations to our house:
If the alterations are going to cost about £10 we get someone to do it straight away.
If the alterations are going to cost about £100 we ask for estimates.
If the alterations are going to cost about £1000 we consider very carefully whether we can afford it at all.

This, therefore, did *not* demonstrate the existence of molecules or atoms as limiting particles of dye. It only showed that *if* molecules do exist, then they must be extremely small and therefore extremely numerous – so numerous that even in the utmost dilution there were far too many of them to show irregularities of pink patches. It was useful then in showing one must look for smaller sizes, if there are atoms. Now that we know so much about atoms, and can make good measurements, that experiment is only of historical interest – unless we can use it with very careful logic.

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

Chapter 7

MEASUREMENT OF A MOLECULE

Surface tension experiments; oil film experiment

Can we Measure Atoms?

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

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

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

Note to Teachers on the Oil Molecule Measurement. This measurement ranks very high in our experiments; and it should not be omitted or hurried or be allowed to become a demonstration.

It provides opportunity for manual skill, careful imaginative thinking – for which models and pictures will help – and also for some appreciation of orders of magnitude, degree of accuracy, and approximation.

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

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

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

Surface Tension Experiments

Some acquaintance with surface tension phenomena is needed as a preliminary; but, delightful as such experiments are for children, we should not spend long on them now, but should rather provide suggestions for more experiments that can be done at home – such as flat soap films with a loop and thread; stretching a film by pulling a thread; joining two soap bubbles together with a pipe 'to see the big bubble blow the little bubble up until they are equal', putting a drop of water on a waterproof table and spoiling it with a detergent: waterproofing a sieve, wetting a waterproof greasy rag with wetting agent so that it can be dyed,§ etc. H 63

However, we should do some experiments to illustrate surface tension: children should watch

(i) drops of water dripping from a medicine dropper, C 64a

(ii) drops of water falling on a sheet of clean glass and look at the pool that the water makes on the glass,

(iii) the same, when drops of water fall on a sheet of glass covered with paraffin wax.

Those are things for class experiments if possible. The teacher should show a demonstration of mercury on a sheet of glass. D 64b

§ We should give children small samples of 'wetting agent' to take home for this. Its effect is more striking than that of household detergents. The best material to make water spread on paraffin wax – and to cure new greasy dishcloths – is 'Manoxol OT'. A few drops of dilute solution will suffice for children's home experiments. The wetting agents supplied by photographic shops for use on films are not very good on wax.

Also if the demonstration is easily available, show aniline dripping in water. The aniline should be in a glass separating funnel with a tap. The end of the funnel should dip into a tall beaker of water for a small class to see by crowding round, or into water in a flat sided jar, of glass or plastic, in a projection lantern for a large class. Aniline is slightly denser than water; so, as the drops form at the end of the funnel, they hang, buoyed up by the water, almost 'gravity free'. D65

Then a narrow neck forms and a round drop falls, while another drop begins to start. This makes a wonderful sight, particularly if one has crude aniline or old aniline which has a dark brown colour that shows clearly. (Remember that aniline is a liver poison, that can be taken in through the skin.‡)

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

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

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

Class Experiments to prepare for Oil Film

(These experiments might be done as demonstrations to save time; C66a, b,
but as class experiments they have a much more personal impact. c, d, e
Children enjoy them, provided the cleaning process can be speeded up. If cleaning can be done beforehand, children should do all the following experiments.)

‡ A number of alternatives to aniline have been suggested, ranging from ortho-toluidine – probably no less unpleasant than aniline – to ingenious mixtures of more pleasant materials such as common oils. Aniline seems preferable and reasonably safe for a demonstration carefully done.

In each case pupils use a glass dish half full of clean water. The dish must be carefully cleaned beforehand, with a detergent, and then very carefully washed. A non-foaming detergent that does not contain free soda is most suitable, for example 'Dreft'. The dish is then filled to the brim with water, and half the water is quickly poured away, in the hope that it will carry off any residual oily film. The children should have one dish for every pair for each experiment. Some of the experiments will leave the dish fairly clean, so two or three dishes per pair will suffice.

The children powder the surface *very lightly* with waterproof powder (like lycopodium)‡ to make the surface visible; then the dish is ready for children to try adding various things which may change the surface tension.

a. Put a drop of alcohol on the powdered surface. A clean patch appears, as the powder rushes away to the edges – and then the powder returns, as the alcohol mixes with the water. (If there is no violent motion the dish was dirty.)

b. Repeat with fresh water and hold a small 'red-hot poker' very near the surface without touching it. The powdered surface rushes away from that region. This is a more difficult experiment, but it is useful because it shows a change in surface properties when we do something to its molecules without adding new material. (The 'red-hot poker' for this, a piece of wire heated in a bunsen flame, must be thick enough to remain very hot while it is being carried across to the dish but not so thick that the heating takes too long. An iron wire about $\frac{1}{16}$ inch diameter, or 18 gauge, or a knitting needle of that size, does well.)

c. Repeat that with a very small quantity of oil – on a matchstick that has been dipped in oil and wiped clean.

d. Just for fun, we should also show the effect of crumbs of camphor on a clean water surface. If the camphor seems lazy, it is a sure sign that the surface is dirty.

e. If pupils can clean their dish very well indeed so that it is quite free from oil, they will find it interesting to dip a finger in the dusted surface and see the 'grease ring' that is formed even when the owner thinks his finger is quite clean. (Moral: a little hair oil goes a very long way.)

‡ If children like to repeat these experiments at home they can use flowers of sulphur, talcum powder, face powder or even coal dust.

Illustration of Oil Spreading. As an illustration of a liquid spreading out until it is one molecule thick (like oil on water) some teachers like to show a demonstration of a handful of sand or lead shot poured on the tray, spreading to a sheet one grain thick. This is a clever illustration, but a misleading one. Pupils take it too literally and think that oil molecules are round. If they were round, the film of oil would be one molecule-*diameter* high.

And then, assuming that, it would not only give a misleading picture, but also a wrong picture. Worse still, it suggests that the oil-film measurement can tell us the volume of a single molecule, or the number of molecules in a known volume, and thence the Avogadro number when in fact it can only tell us the length of the oil molecule, so that we need further information before we can find its volume.

A much better model can be made by pouring a large number of D 67
small pieces of drinking straw into a bowl of water. Cut drinking straws into lengths about 1 inch long; load and seal one end with a small pellet of plasticine or possibly a lead shot; then close the other end by squeezing. Throw a handful of these into a bowl of water. They will float upright and will even tend to collect together in a flock. This is such a close model that it will repay the trouble of manufacturing the loaded straws.

Discussion of Surface Tension Experiments. We speak of the rise in temperature '*weakening the surface skin*, so that the stronger cold skin farther out can pull the powder away'. And we use the same description when we see a drop of oil placed on the powdered surface and spreading quickly. Yet, the real effect of the added material is much more like a surface *pressure*, pushing out in all directions along the surface; so the earlier experiments with drops and pools of liquid are only a help in drawing attention to surface effects in general.

Cleanliness. If the dish is at all dirty, with a little oil on the water surface before we start, the alcohol has much less effect. (*We* know – but we can hardly anticipate the whole business and tell children that a monomolecular layer of oil will suffice to spoil the whole experiment. That means that $\frac{1}{40}$ milligram of oil will ruin a surface six inches square. A finger that has touched the hair of one's head and taken nothing more than its natural oil can spoil a dish after the most careful washing.)

A drop of alcohol forms a good test of cleanness of a dish and its water and the surface is no worse for the test. The teacher can bring an alcohol dropper round to test dish after dish.

However, when it comes to allowing a measured drop of oil to spread on a big tray, meticulous cleaning makes too serious a demand; so we must follow Langmuir's method which is described below.

Discussion of the Main Oil-film Experiment

We use *olive oil* which is a common substance and, as a vegetable oil, has a long molecule with one end that attaches to water and the other end that is inert. (Actually, the chief constituent has a three-fingered structure but the statements we make here are essentially correct.) We tell the children they are going to make a tiny drop of oil (half a millimetre or $\frac{1}{50}$ of an inch across) and let it spread to a flat patch on clean water in a large tea tray. We then tell them the story of Rayleigh's work and of the assumption, or guess, that he made – that the oil spreads until it is a sheet one molecule thick. We try to make that assumption seem reasonable.

Then when the experiment is done we simplify the arithmetic by taking the little round drop of oil as a cube and the patch to which it spreads as a square. That will yield a smaller estimate of molecule size, two-thirds of the proper result – but never mind, simplicity is best here.

The usual instructions to use a *solution* of oil (or fatty acid) and let the solvent evaporate will lead to much too complicated arithmetic. It is *not* suitable here.

This oil-film experiment to measure a molecule length is one the children can do if we explain what it is aiming at and then give them plenty of time. The object of the experiment is to have children experience the delight of success in a real atomic measurement. We should give them encouragement, we should simplify the experiment and its calculation, but we should not do the experiment for them. Of course the teacher can do it much more quickly, and that would save a great deal of equipment, but then we should be cheating children of a personal experience of doing science, which will be of enormous value now and later.

As regards cost: this is well worth while even if it makes us economize on some more advanced apparatus. As regards time: we shall gain time in the end if children do their own experimenting now, because it will give them tremendous confidence in atomic knowledge. * *

All that the children need to know for our important oil film measuring is that the oil *does* spread, and that it goes on spreading until it makes a very thin film which does not seem to want to spread any more. We need to borrow from our chemical colleagues the assurance that oil molecules (of this kind) have one end that is attracted strongly to water and the other end that does not care for water at all, 'a waxy end'; and that these molecules attract laterally so they cling side by side. One might say: T

> 'Suppose we poured a whole school of children out on to a muddy playground in a pile. Each child has a good pair of rubber boots on that are safe in mud, but wants to keep the rest of his or her clothes clean. So there is one end of the child that likes mud, the boots, just like the oil molecule's end that likes water. Which way will the children end up, lying down, standing on their feet or standing on their head? What will the whole lot look like if we go on pouring out children till the playground is full? ... Rather like an army all upright and crowded close together; or like the hairs of a velvet carpet.'

Pupils' Preparation for Main Experiment. The main experiment with the tray needs two pieces of preparation: T

1. Children must see what happens when oil is put on clean water preferably in a small glass dish, with dusted surface. (See C 67(c)).

2. We must tell the story of Rayleigh making an estimate of molecular size, so that the children know what they are going to do with the tray and why they are doing it.

> 'Lord Rayleigh made a guess, one of the earliest good ones, by doing an experiment just like yours in which you put a little oil on clean water and watched it spread. He bought a big washtub 30 inches across, cleaned it carefully, filled it with water, and then put a tiny drop of olive oil on the water. He tried that again and again until he found the amount of oil that would just cover the whole surface of the water in the washtub.

> 'He could test whether the oil had covered the surface by something that you have seen: he put some crumbs of camphor on it. Where there was oily surface the camphor crumbs stayed dead, but where there was clean water surface they rushed about.

When he put too much on, the whole surface was covered with oil. He tried again and again till he found just the right amount to cover the whole surface.

'Lord Rayleigh knew that oil molecules are long molecules – a whole chain of atoms – and that they have one end that clings to water very strongly. The other end does not mind about water and so it is left standing up from the water. Then the oil molecules will be upright like the hairs of the pile of a velvet carpet.

'He expected the oil to spread on water until it wanted to spread no more. How thick do you think the oil patch will then be? Suppose it has spread and spread until it doesn't want to spread any more over the water surface. How thick?'

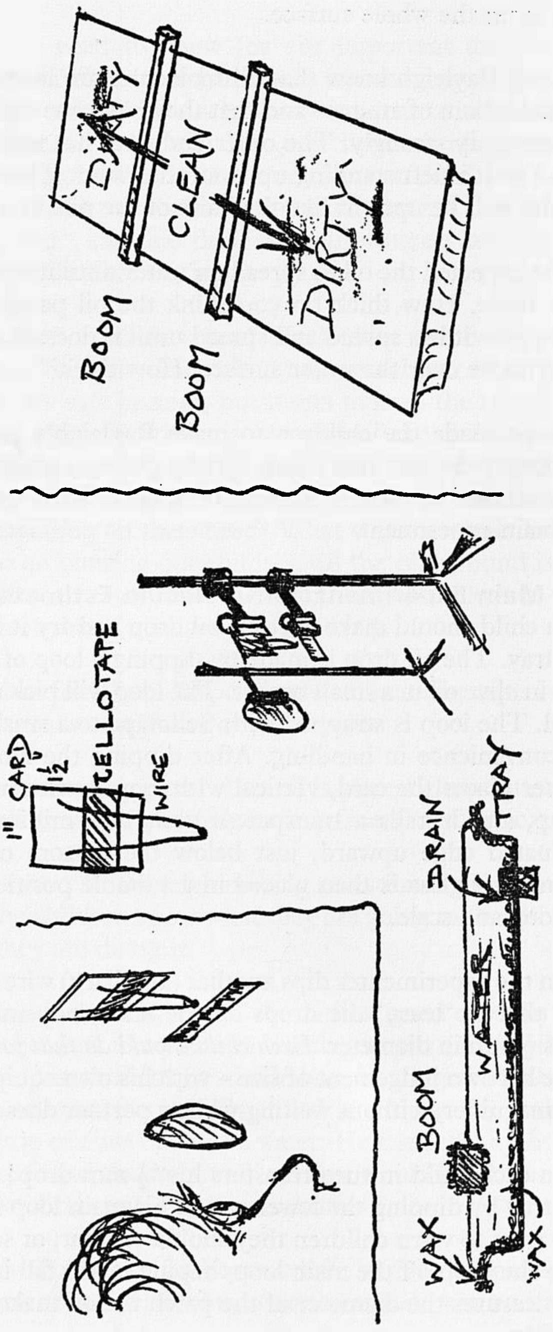
First persuade the children to make Rayleigh's guess, and then emphasize the fact that it was a risky guess, a guess that has now been verified by alternative measurements. Then we are ready for the main experiment.

The Main Experiment: Oil-molecule Estimate

Each child should make his own oil drop and try it on clean water C68 in a tray. The oil drop is made by dipping a loop of very fine steel wire in olive oil in a small beaker. The loop will pick up small drops of oil. The loop is strapped with Sellotape to a small piece of card for convenience in handling. After dipping the loop, the experimenter places the card, vertical with loop downward, in a clip or clamp, and installs a transparent scale of $\frac{1}{2}$ millimetres, with its graduated edge upward, just below the bottom of the loop. A magnifying glass is then placed in a suitable position for viewing the loop and scale.

Then the experimenter dips another (auxiliary) wire loop in oil and uses that to 'tease' the drops on the main loop into a drop that looks $\frac{1}{2}$ mm in diameter. *Each child should do that for himself* – and make his own judgement of size – with his own equipment of loops and magnifier, without waiting while a partner does it.

Then each child in turn transfers his '$\frac{1}{2}$ mm drop' to clean water in a tray by dipping the lower end of his main loop into the water. (We need to warn children they should do that; or some will try to tease the drop off the main loop, hoping it will fall into the water.) He measures the diameter of the patch the oil makes, quickly and roughly.


BOOM
BOOM
DIRTY
CLEAN
DIRTY
1" CARD
1½
SELLOTAPE
WIRE
DRAIN
TRAY
WAX
BOOM
WATER
WAX

The tray is waterproofed and filled to over-brimming with water. The water surface is swept clean, just before each child places his oil drop on it, by moving two waterproof waxed metal booms out from the centre to the ends. After this clearing, a little lycopodium is sprinkled on the surface and the oil drop placed on it. The child should dip his wire into the water.

(It is easy to use too much lycopodium. It is only a marker, and unless one is sparing the oil will crowd it into a denser sheet than is good.)

The tray of water can be used for several oil drops in succession, if the surface is cleaned by sliding booms after each. After four or five oil drops, the tray will probably need washing. So will the booms.

Individual Equipment. It is quite certain from our experience in C68
trials that each child needs to have a full set of equipment for making his own oil drop, undisturbed by a partner. It is for the making of the oil drop that each of these young experimenters needs time and his own apparatus. Waiting for a partner makes a serious bottleneck and does much harm to the atmosphere of the laboratory.

For children to work individually, the laboratory needs a retort stand and boss-head for every child. That requirement has already cropped up for springs; and we assure teachers that a full complement of stands is essential for our programme. A simple device must be installed on each stand to hold the magnifying glass, the scale, and the loop of wire on which the drop will hang. Although such a holder will be needed for each child, the expense will not be great, because a simple arrangement has been designed – see below. The use of the tray does not take long, so one tray may be shared by four children – but not more, because too many oil drops in succession will lead to cleaning troubles.

A First Rough Try. Children should try the experiment first quickly, to see what it is going to look like and to be prepared for measuring the circular patch. G. K. Chesterton's aphorism is a wise one for research in science, 'a thing that is worth doing is worth doing badly'. A first rough experiment with any tiny drop to find out what one is up against, or to establish that the experiment *can* be done, is as well worth doing here as it is in professional research. That will show that only a very light powdering with lycopodium is necessary.

For the first trial with a tray, show children how to clear the surface of the water, then powder the surface with lycopodium and let them place any very small drop of olive oil on it. Then say: C68

'Now, if only you knew just how much oil you have put on the surface, you could calculate how tall the molecules are when they are spread into that velvet patch.

'Here is a small loop of very thin wire that you can catch a tiny drop of oil on. Take your magnifying glass, and see whether you can catch an oil drop that looks to you just half a millimetre in diameter. That is difficult, but if everyone tries, some people will be successful and we can average out the results we get.

'You have a small dish of olive oil. Dip your loop of wire in the oil until you catch a tiny drop on it. Then take a second loop of wire which has been dipped in oil and tease the drop on the first wire until it looks just the right size.'

This experiment is so important that children need two to four class periods for it, after earlier classes of preparation. It is their first atomic measurement. * * *

(Teachers will find it well worth while to practise the whole business privately beforehand, so that they know the symptoms of trouble and can help children to get the right size of drop, and can advise when a tray of water is obviously not clean.) * * * *

The result of careful measurements is about $\frac{15}{10{,}000{,}000{,}000}$ of a metre; and children's measurements will range by a factor as big as three in either direction – yet they will still be within the right order of magnitude. The drop looks oblong so some average diameter must be guessed at. C68

The teacher will be called in to give advice on the size of the drop; and he should not give any, except to an experimenter who is very discouraged. When he has seen many drops spread, he will know the look of a drop that will 'give the right answer'. He should then be very careful never to judge drops for pupils by using that knowledge. C68

Calculation of Oil Molecule Estimate. The measurements are obviously rough but worth having. The arithmetic to estimate the C68 molecule length will be difficult enough to spoil the game, by dragging in $(4/3)\pi r^3$, unless we provide a simplifying trick.

Therefore, teachers should suggest that children treat the oil drop as a cube, or width equal to the diameter of the sphere, half a millimetre here. And they should treat the oil patch as a square instead of a circle – a square of width equal to the diameter of the circle. That will yield a smaller estimate of molecule-height, two-thirds of the proper result – but never mind, simplicity is best here.

> 'Remember that, like Lord Rayleigh, you and I are desperate to know something about the size of a molecule because from that we could even make a guess how big atoms are. Any rough measurements would be a tremendous scientific achievement for us. This is a tremendously important measurement that you will remember all your lives. If you want to, you can even take the apparatus home and show the experiment to people at home.'

Then each should work out his own result, and post it on the blackboard.

The Result agrees with Alternative Methods. When the children have arrived at some estimate of molecule length, we should tell them that there are other ways of making that estimate (e.g. X-ray reflections from molecule layers in crystals – which they will meet in Nuffield chemistry. Those agree very well with this estimate, done carefully).

Proceeding to an Estimate of Atoms. We want to arrive at a guess of the size of a single atom. For that we need the chemical knowledge that an olive oil molecule is about a dozen atoms long.§ (The simpler fatty acid molecules, which are long chains, range from a dozen to two dozen or more atoms long, adding a standard amount of about 1·3 A.U. for each carbon atom added to the chain.) That increment gives us one way of estimating the size of an atom, or at least of a space taken by a carbon atom, provided we are sure that we have added only one more. One might, in theory at least, also make an estimate of the number of atoms in a whole chain by studying the compounds formed when hydrogen atoms in the chain are replaced by, say, chlorine. As a direct test, that could hardly be done; but indirectly, that is what a skilful chemist can do, in organic analysis. We cannot explain all this to children but we might give a simple story like the following:

§ 'They did not like having to accept this!'

'That is a good guess at the length of an oil molecule. Can we jump from that to a guess at the size of a single atom? Chemists can find out how the atoms are arranged in the big molecule and they tell us its chain is about a dozen atoms long. They can find out how many atoms long each of those molecules is without ever knowing how big a single molecule is or how big an atom is. T

'In a cold winter you could find out how many children there are in a family without ever seeing the family if the shops will tell you how many pairs of gloves they supplied to that family. Chemists do something rather like that with atoms. They don't fit gloves on to the atoms of the long oil molecule; but they can do something rather like taking gloves off each atom all the way along the chain and putting mittens on instead.'

We need not give children that story, or any detailed story. We simply have to assure them that if only we can measure the length of an oil molecule we can borrow some information from chemistry about the number of atoms in the length of the chain to see how big a single atom would be.

Suggest dividing by 12 though 10 or 20 would be near enough here.

Data for Teachers. (Atoms range from about 1 to 4 Ångström Units in diameter. One A.U. is 10^{-10} metres – easy to remember by its old name, 'tenth-metre', and convenient for use in atomic measurements. Olive oil molecules seem to be about 15×10^{-10} metres long. Fatty acids such as stearic acid range from 20 to 30 A.U. long, adding 1·3 A.U. for every carbon atom added in the chain of —CH_2— groups. Since the length from carbon to carbon is about 1·3 A.U., we may regard that as a rough diameter for a carbon atom, although the actual chain is a zigzag one.) *

How many Molecules along a Postcard? When that is done, return to the original question: How many atoms along the length of a postcard? The postcard is about 15 centimetres long. If we take an oil molecule to be 15/10,000,000,000 of a metre long that is 15/100,000,000 of a centimetre; so 100,000,000 molecules in line would take 15 centimetres, one postcard. If our number from the chemists is right – a dozen atoms in the molecule chain – there would be twelve times as many atoms in the postcard length, 12 hundred million atoms. T

What Does Measuring Atoms Mean?

In commenting to children on the size of atoms we should keep in *
mind the close interaction between the measurements and Nature. *
The estimates we get here are for molecules or atoms lying side by *
side or loosely attached to other atoms, or making mild collisions *
like those between air molecules. *

Point out that a tailor can measure the 'diameter' of a man's waist D69
by encircling him with a tape-measure, undoing it, and dividing by π and demonstrate that on a pupil. But a demoniac tailor could use a steel wire like a cheese-cutter and pull tighter and tighter, till he is ready to measure the diameter of his poor victim's spine.

That is true of atoms: with sufficiently violent collisions, one atom *
moves right in through the electron structure of another; we lose *
track of the 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. *

Notes to Teachers on Apparatus for Oil Film Methods. In our preliminary trials, the recommended trays were C68
not always available and this experiment was carried out with a great variety of techniques and apparatus, ranging from a traditional dilution method to individual experiments with carefully scrubbed trays. All of these succeeded, thanks to determined work by teachers; and all of them will succeed – sometimes. However, to be sure of success when the experiment is repeated, and to give children a simple procedure that they can operate themselves, we urge all teachers to use the method described here.

Trays. The tray should be a large, enamelled metal tea tray, painted C68
beforehand with molten paraffin wax to make it waterproof. The tray must have a waterproof rim so that it can be filled over-full without the water overflowing, because then the surface can be cleaned by sliding booms. To make the clear patch of oil easily visible, the tray should be a very dark colour. Unless its enamel is already very dark, it should be painted black. That is done by mixing a little vegetable black in the paraffin wax that is used to waterproof the tray.

To paint a tray, heat $\frac{1}{2}$ lb of clean new paraffin wax in a metal beaker until it is far above melting point, almost smoking. Add $\frac{1}{4}$

ounce of vegetable black (from a paint shop) and stir, keeping the molten wax very hot.§ Use a clean, new, cheap paintbrush (1 in to 2 in wide) to paint the tray in quick strokes with this molten wax. The coating need not be even except on the rim where it is important to have a smooth waxed surface for the water and for the booms. Warming the tray with a bunsen flame may make it warp, and might deposit undesirable greasy substances; it is far better to use a brush with hot molten wax. Heating in an oven is not advised either.

Cleaning the Trays. Instead of relying on scrupulous cleaning of trays before use, we produce a clean water surface simply by moving two waterproof booms out from the centre across the brimming water surface just before a drop of oil is placed on it. C68

Repeated clearing by booms allows several children to use the same tray in turn. If there is one tray for every four pupils, each child will be able to make his own oil drop and put it on a tray without delay; and the trays will not have to be emptied, washed and refilled during the class period.

Setting up the Trays. Filling a tray with water, levelling it so that it can be filled brimful, and adding water until it stands above the rim of the tray all round, needs care and if children try to do it, will take considerable time. If possible, the teacher should set up the trays and fill them. That makes a considerable demand, if 8 trays, for a class of 32, are to be filled and levelled. Yet, for this very important experiment, adult help would be welcome in this part of the preparation, in contrast with the main experiment which we hope children will do entirely on their own. C68

Whether the filling and adjusting is done by teacher or children, each tray should have a cheap plastic bucket ready to receive water that is spilled or emptied from the tray. There should also be one large plastic sponge with each tray. The buckets will receive a certain amount of oil from the trays, and probably dirt from the floor. Therefore they should not be used for the clean water to fill the trays. A few extra buckets should be reserved specially for that.

Using the Tray. The tray when painted with wax is waterproof, so it can be filled *over-brimming*. Then we use Langmuir's method C68

§ 'The main experiment went very well, with very sensible results obtained by 95 per cent of the pupils. I cursed when painting the trays but this does help when performing the experiment, making it very convenient to repeat.'

of clearing the surface by moving waxed booms along it to sweep away all the dirt and oil just before doing the experiment. This works easily and well; and the experiment is so important that we consider it justifies the cost of buying trays specially for it, to provide one tray for every four children.

It is worth while to invest money in a strong tray that will maintain a level rim. And the tray must be large enough to accommodate a big patch when the oil spreads. A drop of olive oil half a millimetre in diameter will spread on clean water to a patch about 9 inches in diameter, and a tray 12 inches wide would suffice for that. However, it is easy to be wrong by 25 per cent in judging the oil drop. An oil drop 25 per cent more than $\frac{1}{2}$ mm in diameter will spread to a patch nearly 13 inches across. So one needs a tray at least 15 inches wide or, better, 18 inches; and somewhat longer than that, to leave room for the booms to do their clearing.

Skilful teachers can make sure that *they* will not need a tray more than 12 inches wide and they may be tempted to economize by buying small trays. That would be most unfair to their children who need much more latitude, as they experiment on their own. The tray should not be of porous wood or plastic that might retain oil and spoil its use in future. Baking trays of tinned iron are much cheaper but they have a crack at each corner where oil may reside; so they are risky. It is worth the cost to buy good enamelled tea trays. *They must have a broad flat or rounded rim.* These will cost about £1 each retail.

Since the tray must be filled brimful for this method of clearing the surface, emptying it is a serious problem. There must be a drain-hole in one corner, then the tray is placed on the table with that corner overlapping the edge, with a rubber stopper in the hole. The stopper must be inserted from underneath, so that it does not upset the water surface. Otherwise it is necessary to use large sponges or a slow siphoning process; and even then some experts advise a barrage of newspaper around the tray. Even with careful organization, water will be spilt in the course of filling and emptying these trays – and the plastic buckets and sponge will prove their worth.

(After use the trays should be washed with a detergent, then wrapped in a dust-proof protector of thin polythene sheeting, and kept for next Year. It would not be wise to use the trays for other things meanwhile, because dirt is a nuisance and chipping or bending may be fatal.)

Booms. The booms should be strips of metal of rectangular cross-section, and should be a few inches longer than the width of the tray. When the tray is painted, the booms must be painted also with molten wax. C68

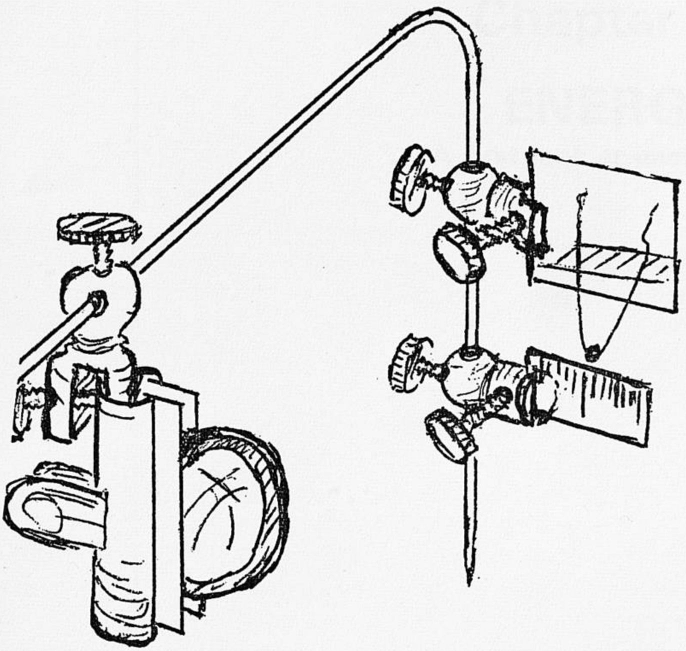
Loops for Oil Drops. The experiment will lose much of its point if we do not ensure that each child makes and uses his own half-millimetre oil drop. Therefore we must be sure to provide *each child* with two wire loops each mounted on a card and a glass half-millimetre scale and a magnifying glass. The experimenter needs one hand to hold the teasing loop and may need the other hand to steady it or to adjust things. So *each child* must have a stand and clamps or clips to hold the main wire loop hanging down vertically, the scale with its graduated edge upward just under the bottom of the loop, and the magnifying glass in a suitable adjustable position. As explained above, providing enough large stands and clamps for that may be expensive, but we are sure it is worth the cost. It is not fair to young children trying to do this difficult important experiment to expect them to hold the apparatus in their hands or look at it in an uncomfortable position or share it with a partner. C68

Holders for Oil Drops, etc. A retort stand for every pupil is a general necessity. The holder for the oil drop, scale, and magnifying glass is a special device for this single experiment – it should be made as cheaply as possible provided it is robust. C68

Here is a simple design which does work. The boss-head on the retort stand carries a horizontal, metal, knitting needle, say size 10. The head should point forward so that the knob protects the pupil's face. The 8 inch needle is bent at right angles about half-way, so that the farther half points vertically down. Each of the three things to be supported is held by a small brass 'battery clamp' terminal with a thumbscrew and hole (to fit on the needle) and a thumbscrew and slot to hold the scale, the card carrying the loop of wire, and a large bulldog clip to hold the magnifying glass.

As the slot is parallel to the hole in these terminals (which are standard items, still available), the bulldog clip must be inserted as an intermediate device to hold the magnifying glass. Some forms of magnifying glass in a holder will fit in the slot of the terminal, but that would carry the lens at right angles to the desired position.

It is *essential* that the magnifying glass should move freely along the knitting needle, so that its distance can be adjusted for com-



fortable vision; and then it must be clamped firmly. It is essential that the ½ mm scale and the card with the wire loop should each have it own clamp, so that they can be moved independently of each other to bring the wire loop very close to the scale and to bring it into the same plane as the scale, even if the loop is warped, as it often is. That is why two terminals are needed there. The bulldog clip is held by inserting its arched back in the slot of its terminal.

This is by no means the only inexpensive design of holder but it does give the full freedom of adjustment that is *essential*; and its chief cost lies in the three terminals, which could be produced very cheaply, perhaps in still simpler shape, if needed in quantity. 'Essential' is written here and just above because we must make success easy for these young pupils or else leave out the experiment altogether, losing a very valuable class experiment. The arrangement suggested here does enable pupils (even younger than those in Year I) to set up scale, wire loop and magnifying glass, adjust them and then clamp them, without difficulty.

Chapter 8

ENERGY

A first look at energy

ENERGY AND ENERGY CHANGES

In this Year, children should take a first informal look at 'energy' – or, rather, 'energy changes' since those are usually the most important aspects of energy for us. This should be a *very brief*§ look *to be renewed and discussed in Year II.* At this point, teachers should consider the time available and plan if possible to get to the end of this Year's suggested programme, including without fail the spark counter and both forms of cloud chamber, even if those are at the expense of making the introduction to energy and its forms very hasty and superficial.‡

Unlike other sections of this course, where we hope that what is done will be done thoroughly so that children gain a good sense of understanding, this introduction to energy is only the beginning of a serial treatment that we shall take up each Year for the next four Years. This is intended to be literally an introduction, to meet the word 'energy' and shake hands. Acquaintance will come next Year, and knowledge and understanding in later Years still. Even if we spend considerable time on this introduction, we must not expect children to emerge at the end of this Year ready to give clear definitions or carry out successful calculations or even to describe changes of energy competently.

To change the metaphor, we shall have taken our pupils to look at a strange country in the intellectual world; viewing it from one hill after another, each time seeing quite a different landscape, each time not knowing what to look for; knowing that the trip is important, yet not knowing quite why. Such a trip could be a pleasure and leave useful memories, or it could be a painful rush, spoiled by demands that are too heavy.

By the end of this Year we do not expect pupils to understand energy or even to be able to describe energy changes in the right words; but we do hope that they will have seen and learnt some interesting experiments concerned with energy changes, which will prepare the ground for fuller discussion in Year II. Teachers would be wise to look at the suggestions for teaching energy in Year II and its important continuation in Year IV before embarking on the present introduction.

§ 'In spite of trying to cover the topic briefly, as suggested, to give a nodding acquaintance, even a good form becomes a little restless with too much discussion.'

‡ Esso Petroleum issue a good wall chart on energy conversion: 'Energy – Key to all activity.'

We must be careful not to build up for energy a reputation as a *
magic word that will answer any question about why things hap- *
pen. Yet children know a lot about food and what it does for *
them and are interested in climbing hills, hauling up loads, shoving *
things along; and in engines and what they will do. We can make *
an informal approach to energy by linking children's natural know- *
ledge of food and fuels with their interest in those activities. *
Children recognize those jobs for which fuel is needed in one form *
or another; so this is a good point with which to start. *

Food. We start by asking, 'What does your food enable you to do, T
besides keeping warm and breathing and generally living?' We encourage as many answers as possible, and ask again and again 'Do you have to have food for that?' and sometimes we ask 'Could an engine that uses petrol do that for you instead; or an electric motor that draws on the electric supply?' Now or soon we should do some experiments to promote discussion of jobs. Suggestions are listed under Experiment 70 below. Teachers in preliminary trials advise showing experiments early and doing the talking afterwards.

Jobs that need Fuel

We rule out some jobs that people have to do as not necessitating T
food or fuel: 'Yes, I know you get tired if you hold four bricks up above your head with your hands, but you *could* just put them on a shelf, and you wouldn't have to give the shelf any food or petrol, or pay for an electric motor to hold the shelf up.'

'Yes, you can use some of your food to clench your fist and pinch your brother's ear, and you can go on pinching it while he goes on complaining, as long as you like. But food is not really needed to keep up the job of pinching; you do not need an electric motor with a pinching device on it to go on pinching. You could do the pinching by tightening up a small screw clamp and leaving it on his ear. That would go on hurting him, free of charge, as long as it stayed there.'

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

T

Energy. Here is a list of ten 'jobs' done by living and non-living things. Which of these is a 'fuel-using' job, and which requires no fuel ?‡

a. A man hoisting a sack of potatoes off the ground on to his back.
b. Pillars holding up a roof.
c. Air molecules in motion in this room.
d. A piston moving in and compressing air.
e. A man winding a clock spring.
f. A clamp tightly holding a piece of wood.
g. A refrigerator keeping things cold on a hot day.
h. Water keeping a boat afloat.
i. A bus moving along a horizontal road on a windy day.
j. A man or a computer doing sums.

‡ *Note to Teachers.* These questions are meant to promote discussion. If differences of opinion arise, all the better, even if they cannot be settled, in the present state of pupils' knowledge. In some cases the best answer depends on the way the question itself is read – and the questions are left vague with that in mind. For example, in (*c*) air molecules require no fuel, *once they have been warmed up to their present temperature*, and *provided the room temperature stays constant.*
In (*g*) the answer depends on the kind of refrigerator being used, perhaps; and we hope teachers will not be offended by finding these questions here in Year I. It really raises important questions of thermodynamics, but of course we do not have them in mind here. Yet there is no harm in letting pupils discuss this case. Many will know that an electric refrigerator takes something from the supply, and increases the electricity bill.

We try to distinguish in this discussion between jobs that *essentially continue to use fuel* or make demands on our food supply, from those which, perhaps after some initial demand, do not involve further energy transfers.

The Name 'Energy'. Then we begin to use the name 'energy' saying: T

> 'Your food provides some heat to keep you warm, but it also provides something stored up in chemicals in your muscles that makes you able to raise loads, shove things along a rough floor, and do various jobs like that. We say you have got *energy* stored up in your muscles, "chemical energy" as we call it.

'What else has a store of energy like that in it? ... Yes, petrol, coal ... any others?'

We try to elicit suggestions such as fireworks, waterfalls, oats for horses, the electric supply mains.

If someone mentions sunshine, we say 'Ah ... we shall come back *
to that.' We do not try, just yet, to trace our fuel energy back to *
sunshine or any other 'original source'. Though that would give *
interesting stories, it would involve us in too many assumptions or *
assertions in a hurry. We want first to make children form some *
idea of the jobs that energy-transfers provide for; to give them *
some idea of the forms of energy involved, with common names *
for them; and a general feeling – given by taking conservation for *
granted, without discussion – at this early stage – that energy is *
something that shifts from form to form without getting made or *
lost.‡ *

Experiments and Discussion: Jobs that need Fuel. As a simple class experiment we ask children to do certain things, and to say for each whether they think it makes demands on their food. C70

'If you had to do that again and again all day, do you think you'd be more hungry? Do you think you'd need extra food if you had to keep it up week after week?'

Ask children to:

a. Blow up a balloon.
b. Put a blown-up balloon on the table and sit and watch it.
c. Hold a steel spiral spring or rubber band between your hands and stretch the spring by pulling its ends further apart; let go; repeat.
d. Tie a string to a brick and raise the brick from the floor to the table by pulling the string.
e. Attach a pulley wheel to the edge of your table and run the string from the brick on the floor up to the pulley, over it, and

‡ In the course of this discussion, some pupils will raise questions about 'getting tired when just holding a load, or when carrying a load along on level ground'. We do draw on food energy in doing something like that and we may even feel more tired than the actual energy transfer would justify. For a discussion of this difficult question, see the Note in the General Introduction. In early discussions we should avoid spending long on these particular jobs, and just point out that a load can be held high up by a shelf, which would not need food; and a load can be transported along the level on almost frictionless rollers, without needing much energy.

along the top of the table horizontally. Raise the brick by pulling the string.

'Here are some more jobs to do *in your imagination*': T

f. Bicycle uphill.
g. Climb a mountain.
h. Go on stirring a large thick pudding.
i. Put a neighbour on roller skates and give him a push to get him going: after that, as he skates along the floor, does he need extra food because he is moving along?
j. You have a torch lamp that is lit by a battery. Suppose you turn on the torch and leave the lamp running all day and all night.
k. You have electric light in your house in the country but there is no main supply there. Instead of that there is a small dynamo which runs the electric lights. Suppose that the engine that drives the dynamo breaks down and you run the dynamo by turning it by hand all evening. (This is too difficult a question to raise unless it can be demonstrated at once, with a dynamo that gives a difference of force that can be felt, when a load is turned on.)

With the same story about the dynamo above, would there be any difference between having all the lights on while you are turning it by hand and having no lights on?

Useful Jobs need Energy-Transfer. The teacher should point out that in all those changes where something has to be provided for a 'useful job', like lifting up a load to the top of a building, there is something that seems to shift from one kind to another. Something that was in our muscles that shifts to something in a stretched spring or a raised load or a lighted lamp. We call that something 'energy', saying 'Energy is something which we get from stored up form in fuels, which, in moving across to some other form, does useful jobs for us.'§ T

We make a joke, saying 'If you want to know what a "useful job" is in this description of energy, I can tell you: it is one of those jobs which needs some energy supplied from some fuel!' This circular description is not as stupid as it sounds, because in dealing with it we can build up considerable familiarity with energy and with 'useful jobs'.

§ 'Finally I asked, "What does it mean when we say that somebody has energy?" Unhesitatingly "He can do things."'

Energy only Shifts. We shall suggest that in shifting from one form to another, energy is never lost but keeps the same total, just like money that circulates in a town. T

Feeling Forces

It is clear that many energy-shifts in useful jobs involve a force, pulling or pushing, moving along a certain distance. If we have not given pupils the simple class experiment of C 2(c, d), feeling forces, we must do that now. We give them rubber bands, springs and strings, with which to feel pulls – and suggest stretching two rubber bands in parallel for double pull. Then we provide magnets so that pupils can feel repulsions as well as attractions – but we offer no iron filings and say nothing about poles at this stage. We say that all these pushes and pulls are 'forces'. C2c,d

Stores of Energy

Food Energy. We have introduced energy with the idea that fuels contain stores of energy that can be transferred usefully. And we have included food among fuels. From now on, we might post up a chart of the energy-intake in daily food of a man, a woman, and a child; and then some measured rates of drawing on food energy for various activities. The energy-units in such a chart, kilocalories, will raise questions, but we may be wise to postpone discussion and simply say the numbers give comparative amounts and rates. T D71

Strain Energy (P.E. of Spring). We point to a stretched spring and say that the spring also has 'something like the energy that fuel holds stored', because, instead of using fuel to drive an engine or using food to keep a man going, we could use a stretched spring to pull on a string and haul a load up or do some other useful job. So a stretched spring or a wound-up clock spring has a store of 'springs energy'. T

Heat

We speak briefly of heat, *without defining it or measuring it*, yet suggest that it plays an important part in the energy story; because, as we know, heat can drive an engine to haul up a load for us or do other useful jobs. T

This suggestion should be very brief and light. It would be better to omit it altogether than to expand it into statements that would upset later teaching. Teachers are advised to look at the treatment suggested for Heat and Mechanical Energy in Year IV.

Introduction to Potential Energy and Kinetic Energy

Two forms of energy with which we usually start our teaching in mechanics, potential energy and kinetic energy, need a very careful introduction here: to children they are not familiar or obvious like heat or the energy stored in a spring. For our simple introduction in this Year and the continuation in Year II, we suggest using some informal names for several forms of the common forms of energy. 'Gravitational potential energy' is a clear descriptive name for scientists, but it would spoil the beginning with young pupils. So we suggest the names listed below. At first glance, teachers may feel that those names are too informal, undignified, not likely to be acceptable to children. It is true that children beginning science do like to learn long names – they feel they are making advances into a new technical region of the adult vocabulary. There is no harm in that, as long as learning long names does not become an end in itself, or a substitute for understanding science. Names of technical instruments, or full names of plants or animals, are harmless and grand. But here where we are embarking on difficult new ideas, we shall gain greatly by using very simple names, temporarily. We suggest '*motion energy*' for *kinetic energy*. In our treatment below, we shall use this informal name when we are suggesting discussion with pupils. But we shall, of course, refer to it as kinetic energy or just K.E., when we are discussing policy or methods with teachers.

'*Uphill energy*' instead of *gravitational potential energy*. Again, we shall use this informal name in our suggestions for teaching, but we shall of course call it P.E. in our own discussions as physicists.

'*Springs energy*' instead of *strain energy* of a wound-up clock spring or a stretched wire, or a bent beam. This wording may sound uncouth, but we believe it will help in teaching at this stage, by conveying the feeling of springy material holding some stored-up energy. However, when strain energy is involved in some machinery which is transferring energy from, say, steam in a cylinder to, say, spin energy of a flywheel, we shall evade some difficult distinctions by calling that '*mechanical energy*'.

(In fact, when ropes, pistons, levers, etc., transfer energy from one place to another or transform it from one kind to another, the energy does go through some form which we should call strain energy, essentially travelling in some form of waves. This raises considerable difficulties even to ourselves, both in picturing the location and behaviour of that energy and in explaining its transport. Therefore this part of any discussion of energy-transfer should be avoided in elementary teaching.)

'*Light energy*' instead of '*radiation energy*' or any other name for the energy of electromagnetic waves. At this early stage, the word 'radiation' will not make things clear to our pupils – particularly since our class experiments on radiation are yet to come – and we should be teaching in a mistaken order if we started referring to waves at this stage. It is of course unfortunate to restrict our naming by using a word that usually refers to the visible spectrum alone. We must at once explain to pupils that we are thinking of light itself – all the colours, red, orange, etc. – *and* some 'invisible light' which our eyes do not notice, such as ultra-violet light and some other kinds beyond the red. As a safeguard, we then put the word 'light' in inverted commas as long as we are using it for this purpose. After pupils have done the class experiments of the 'radiation circus' we might wisely change to 'radiation energy'. At the moment, however, we want to keep the naming simple when we are trying to deal with this important and difficult concept.

We suggest some simple demonstrations to start discussions. These T
are described in Experiments 72 and 73 below. They should be done briskly and not laboured. Pupils need to feel that this material is obvious.

Place a brick on the bench and ask for a description of it. The D 72a
pupils will probably give many details but no mention of its position. Move the brick to the floor and ask for a description of it. Lead the pupils to realize that the brick higher up can 'do a job for
you'. Show examples of such jobs being done, to illustrate this: D 72b
Let the brick: (1) accelerate; (2) lift another load; (3) stretch a spring; (4) pull down a string that is wrapped round the axle of a dynamo that lights a lamp. (Teachers are likely to add others.)

'Uphill-energy' (Gravitational P.E.). Point out that we have T
not given a full description of an object unless we say something about its position. This leads to the idea of (gravitational) potential energy; but there should be no definite formula at this stage and its formal name should not be given yet. For first acquaintance we might call it 'high-up energy' – soon we should change to 'uphill-energy' for general use this year.§

§ 'Several boys invented the term "UPHILL ENERGY" for energy of position (P.E.). I thought this rather good at this stage.'

Then place a strip of hardboard across two bricks or stools to make a bridge. Place another brick on the bridge and ask for a description of it. Of course, this time its position will be mentioned; but nothing will be said about its speed because it is not moving yet. Then raise the brick several feet and let it fall to the floor. Ask for a description, in detail, of the brick just before it hits the floor. D72c

Let the brick fall on the hardboard and break it. Now the description will include motion; and we can point out that because of that motion the brick may be able to 'do a useful job'. Give examples:

a. car accidents; *b.* coasting uphill; *c.* switchback;
d. piledriver and common hammer.

From this, we can suggest a form of energy which belongs to moving things. Of course we shall give this the name 'kinetic energy' later but at the moment we shall call it 'energy-connected-with-motion' or just 'motion-energy'. T

At this point ask about both those forms of uphill energy and motion energy – whether a large package of bricks has the same energy as a single brick. Children will probably say that two bricks have twice as much energy as one and three bricks three times as much energy.

Masses are Additive: so are Energies

This is also a beginning of discussing mass by counting. We let it be taken for granted that 2 lb of stuff plus 3 lb of stuff make 5 lb of stuff (and the corresponding thing for kilograms). We do not even raise a question about conservation of mass. And we encourage children to assume that these forms of energy are additive: that two bricks side by side gain twice as much energy as one brick, when raised by the same height, or given the same velocity. * * * * * * *

That may seem obvious to us as adult scientists, yet it is a basic property at the root of all ideas of conservation of energy. * *

We are assuming that when the two masses are placed side by side, one does not affect the amount of energy needed by the other for a certain change. We assume that the two masses do not 'interact'. * * *

So we have three characteristics used in specifying mechanical energy: T

position (height above the ground),
speed (for energy connected with motion)
mass (the number of bricks).

Food and Fuel

'I raise this 2 pound load from the bench up to here, 3 feet higher – which I will call the "top" of the building. That is just like the job of raising a load of bricks from the bottom to top of a building, or like a job of hauling up a lift that is going up, full of people. You could use an electric motor for either of those jobs; and you would have to pay for the fuel that the power station uses. In the old days, a horse hauled bricks to the top of the building; and the horse had to be given food, extra food if it had to do a load raising. D73a

'In hauling up this model of a lift, do I use fuel? I certainly don't take in petrol or coal, but I do eat food, just as the horse does. If I had a great deal of hauling to do I should get very hungry and should have to eat more. D73b

'The food you eat goes to provide many things that you need: some heat to keep you warm, some materials for repair work and building, and some chemicals which are fed to your muscles as "fuel" to run your muscles as an engine. When you haul up a load or climb up a stairway or push something along, your muscles "burn" some of those chemicals, producing some waste heat and something which is useful because it gets the load hauled up or the cart shoved along. When energy comes from your muscles to some other useful form you are drawing upon fuel, chemicals in your muscles which came from your food. In that way, your food is a fuel just as oats and hay are fuel for the horse and petrol is fuel for a car and coal is fuel for a steam engine or a power station.' T

Note on Food and Energy

We should not give pupils details of diet and energy now. (That is *
discussed in detail in the Nuffield Biology Programme.) We should *
ourselves remember that an average adult will take in food that *
provides 3,000 or more kilocalories per day. Athletes, manual *
workers, and others who do other heavy physical work have to do *
much more. At the extreme, a lumberjack in cold weather may *
eat food that will yield 9,000 kilocalories per day. *

Over 1,800 kilocalories are used by an adult man for basic living, to keep the body warm and lungs, heart, etc., going. So, in those regions of the world where a man's food yields less than 2,000 kilocalories per day, one cannot possibly expect a man to do much lifting, hauling or other manual work. That is something which, as a result of our teaching of energy in all the sciences together, our pupils should come to understand. * * * * * * *

Measuring an Energy Change

'I am going to use just a little of my "fuel" – my "breakfast energy" – to haul this load up to the top. I haul it like that. (Raise 2 pounds 3 feet.) And now, though I don't even notice it, I am a little tired and shall need a little more food. Presently I shall eat one extra grain of sugar. (The grain I need is about a ½ millimetre cube – like your oil drop.) D73a again

'Suppose I do half the job first: one pound from table to top, and then the other pound from table to top. Will that cost me the same amount of food energy in the end? People have tried experiments with that and find it does take the same. You need just as much extra food if you do it in two stages.'§ D73c

(Note to Teacher: In fact the job done in two stages takes more food, because we waste a little energy going back for the second trip; but we could avoid that by using a simple pulley arrangement. It may help our teaching to suggest that, because we can pull hand-over-hand in many short pulls, with our arms always in much the same position, so that it is obvious that the pulling remains equally difficult all through. If we picture someone reaching up and then pulling a great length of rope down bending as he does, the pulling operation will seem to pupils more difficult in the later stages so we should avoid that.) * * * * * * * * *

'I could do each of those half-jobs in three stages, one pound one foot, and then one foot and then one foot,‡ and the other pound one foot and one foot and one foot. I'm going to call each of those

§ 'The idea of "measuring" energy came very easily after 73(c). When asked for ideas one girl suggested measuring it in "foots of energy"! A boy said this was no use because you used up more food energy when you lifted a weight, so it would be much better if you multiplied the pounds by the feet.'

‡ To some beginners it is *not* obvious that these three unit-jobs are equal. We need to discuss that carefully, perhaps with the help of an imaginary rope and pulley. Even in imagining that, we must describe the person as pulling hand-over-hand with short motions.

six jobs of one-pound-hauled-up-a-foot one foot.pound. That tells me how much energy I take *from* my breakfast supply, *from* the chemical energy inside me, across *to* some energy stored up here where I raised the weight. I do not know whether the weight itself holds this new store of energy or whether it is somehow stored up here in the region round it but it is no longer in me. And I say that I have transferred 6 foot.pounds – either separately or all in one go – *from* stored up chemical energy in me *to* some energy stored up by this lifted load.

'Instead of lifting a load from table to top, I can use my muscles (drawing on food energy) to stretch a spring like this. Then you can see quite clearly where the energy has gone to. It has gone into the stretching spring and I can use the stretched spring to pull something else up for me and do another job in turn.' D73d

Then demonstrate a stretched spring doing a job by lifting a load.

(We should not say dogmatically that we cannot get jobs done without fuel; but we give a strong impression that we think it is very unlikely.)

We talk of energy stored by the lifted load, or in the stretched spring. In each case it is a store of this marvellous thing which can enable us to do other jobs. If pupils say 'But stored up energy sounds just like the energy you said fuels have', praise that as excellent and say:§ T

'Yes, that's true. In fact fuels are chemical stores of energy. The energy is stored somewhere in the spaces among the atoms and molecules instead of being stored up in this wide space between the Earth and the raised load. When we stretch the spring, the energy we gave it was stored up all the way along the spring.

'For the raised load you might *imagine* that there is a spring attaching the Earth to the load as I raise it up like this from table to top. All those have stored up energy.'

See later discussion and suggested experiment (C 76).

§ 'There seems to be a lot of talking and not much doing in this section of energy. We did it quickly but I found that the children asked some very interesting questions and seemed to enjoy the discussion.'

'When we move some energy across from chemical energy in muscles (breakfast energy) to uphill energy with a raised load or to springs energy stored up in a spring, we can calculate how much energy we move across. We could calculate that in foot.pounds. We call that calculating the *work*. T

'If I raise one pound one foot higher, I call that "one foot.pound" of "transfer of energy". That shows how much I have shifted from chemical energy to another form. We calculate the amount of the shift or transfer which we call *work* by multiplying (force) by (distance moved). That is (how hard you shove) multiplied by (how far you shove along); or (how hard you pull) multiplied by (how far you pull, along or upward or in whatever direction the force goes).

'I warn you that *work* is going to be used in science in a special way, not just like the work you do for school or work in a garden. It means a definite number, a clear statement of how much energy has been transferred.

'We think energy is never lost but only shifted from one place to another, and sometimes from one form to another. The useful thing we get from fuels is the shift *from* stored up chemical energy *to* uphill energy, or to some other form. When we calculate some work, by multiplying (force) by (distance), we must always say clearly what the two kinds of energy are, what kind of energy we are taking away and what kind of energy we are adding to, like this: "When I raise this load, the work is 6 foot.pounds, transfer of energy *from* chemical energy *to* uphill energy."

'You will meet many examples of energy-transfer and in each case you should say "*From* such and such a kind *to* such and such another kind." That is rather like saying of a bank cheque that it is a cheque for £5 *from* Jones *to* Brown.

'Watch again while I raise two pounds three feet. Two pounds raised three feet could be done in stages: six lots of one foot.pound, so I say the transfer of energy from my breakfast energy to uphill energy is six foot.pounds. You can calculate that *work* by saying it is (a pull of two pounds) multiplied by (three feet). That is (force) multiplied by (distance) makes six foot.pounds. D73a again

'We do not call that work +6 foot.pounds or −6 foot.pounds because it shows energy that I have lost but something else has gained. You do not call a 5*s* postal order +5 shillings or −5 shillings because if it is given by Jones to Brown it is −5 for Jones but +5 for Brown. Nor do you call a coin + or −. If I give you a half-crown it is +2*s* 6*d* for you and −2*s* 6*d* for me. And so with work, we do not say plus or minus but always say where the energy comes from and where it goes to.'

ENERGY CHANGES: EXPERIMENTS

The teacher should show experiments that illustrate or involve changes of energy. (He should mention names of forms of energy concerned; but children should take no notes and should not be asked to learn the formal names.) Some suggestions follow below. These experiments are more for the fun of seeing the changes and hearing talk about energy – names and details for discussion of changes can wait till Year II. D/C74

a. Let a brick fall (from Uphill Energy to Motion Energy). D74a

b. Brick falling fast stops at floor. What has happened to the brick's Motion Energy? Some children may dutifully suggest heat; but the teacher should ask whether they can feel the heat in the brick which has landed – let us avoid pious obedience to hearsay. D74b

c. (May be postponed to Year II.) Moving hammer stops when it hits a small chunk of lead resting on the floor.‡ Ask the same questions as in (*b*). This is a much more useful experiment than it sounds (Motion Energy to heat. A more complete answer would be from chemical energy 'breakfast energy' (in muscles) to Motion Energy to heat). C74c

‡ The lead should be a small piece of sheet, one or two square inches by, say, $\frac{1}{16}$ inch, or thinner. It must not be more massive than that or the temperature-rise will not be sufficiently noticeable. (A piece of lead pipe should not be used because it will be too thick.) The small piece of lead sheet should be wrapped round a piece of thin iron wire, say 20-gauge, which will serve as a handle. The child holds the other end of the wire, say 6 inches from the lead, and places the lead on an anvil on the floor. An iron kilogram weight will serve as an anvil. If necessary, a pad of felt or newspaper can be placed under the iron anvil. Then the child hits the lead several times in rapid succession with a hammer, as violently as he can.

(In preliminary trials, some schools used a heavy piece of lead pipe on an iron rod. This gave much too small a temperature-rise – the kinetic energy of the hammer was distributed in far too much metal. Also it caused a great deal of unnecessary noise. The smaller the piece of lead the better for temperature-rise, provided it is not so thin that the first blow of the hammer squashes it off the holder. It is better to regard these scraps of lead as expendable than to use heavier ones which will last. With small scraps, the temperature-rise is surprising, and the noise is not excessive.

Let the children try this as a class experiment and feel the lead.

The child should hold the lead against his cheek to feel its temperature before and after hammering.

d. Throw a brick out of the window, or throw a block of wood across the room, concentrating on the energy change in the throwing (from chemical energy provided by breakfast to motion energy). D74d

e. Haul up a load of bricks with some pulleys. If possible let children do that as a class experiment, and ask them what the energy changes are from my breakfast energy to some energy that travels through the stretched strings to a store of uphill energy. C74e

f. Light a firework rocket (from chemical energy in the firework to heat, etc.). D74f

The following experiments might be shown by the teacher as a series of demonstrations; but experience in trials shows that such a series can be surprisingly disappointing. Even a toy steam engine can fail to excite enthusiasm when it has to be viewed by a seated class. When, instead of that, the demonstrations were arranged round the room with pupils as demonstrators for different experiments, that 'circus' class experiment was a great success. Therefore we suggest these experiments should be Pupil-Demonstrations, even though it demands considerable preparation. * * * * * * * * *

g. Battery lights lamp – chemical energy stored up in battery to some electrical form of energy, to heat and something else which much later we shall call radiation, which comes out from the lamp in the form of light, etc. P–D 74g

h. Bunsen burner runs toy steam engine (from chemical energy of the gas and the air combined to some mechanical energy from the engine ... this story is unfinished: see items (*i*) and (*j*) below). P–D 74h

i. Toy steam engine hauls up a small load (from chemical energy in fuel to stored up uphill energy). P–D 74i

j. Toy steam engine drives toy dynamo which lights lamp (from chemical energy of fuel to electrical energy to heat, etc.). P–D 74j

k. Water jet drives turbine which does some other job (from P–D 74k energy connected with motion of water to ...). (Not available in apparatus supply at present.) OPT.

l. Moving trolley hits an equal stationary one, elastically (from K.E. to K.E.). P–D 74l

Pendulum Experiments

The following give clear, important examples of energy changes. Pupils should see them, or do them, in Year I *or* Year II; and they should return to them in Year IV. * * *

Simple Pendulum. Watch a simple pendulum (without any attempt to do any timing, or reference to its isochronous property). We want the children to look at changes of energy, from a store of uphill energy to motion energy and back again. (Some teachers prefer to show a ball rolling in a bowl or on a curved curtain rail.) C/D 75a

The teacher should point out that at the lowest point of the swing the bob is moving fast so it must have considerable energy-connected-with-motion. As it swings to its highest point, that energy decreases and disappears but the bob regains it all by the time it gets back to the lowest point. Can we imagine some storage-system so that the energy of the moving bob is not really lost as the bob climbs upward, but goes into an invisible, stored-up form? T

This is probably the best way of all to introduce potential energy. We devise the idea of an invisible store of energy, to fit with our observation (that the bob repeatedly regains its full K.E.) and to fit with our hope that here again we can find something in Nature that stays constant. (See Note on 'Constant' in General Introduction.) In other words, we suggest that the visible changes of energy-connected-with-motion are really only *exchanges*. * * * * * * *

We should not say, at this stage, that the behaviour of the pendulum *proves* that the total (K.E.+P.E.) remains constant. We should rather put this as an idea that the pendulum illustrates. T

Then the question will arise 'What happens to the energy when the pendulum's swing grows smaller and smaller?' We should ask for suggestions about that. It would be wise not to give any answer now, but to leave that question as an interesting one for a later Year.

If we offer a pendulum for a class experiment it should be used only as something to watch while it makes energy changes. To start * * timing the pendulums at this stage will lead to an interested, obedient, careful class with their thoughts narrowed down to getting the right measurements when we are trying to explore a very important concept. * * * *

Pin and Pendulum Experiment. With a *very* fast group the teacher might show Galileo's great 'pin-and-pendulum'; but from experience in trials we advise postponing this. (If it is shown, the supports must be very firm and massive or the demonstration will, essentially, fail. See the discussion in Year III.) * * * * *

Coupled Pendulum. We may show pendulums hung side by side and connected by a loose thread. Children will enjoy watching energy feed to and fro from one pendulum to the other; but we can give little explanation at this stage; so we must hope for wonder rather than questions. This experiment could lead on to a discussion of resonance; but that is better left to a much later Year. D 75b

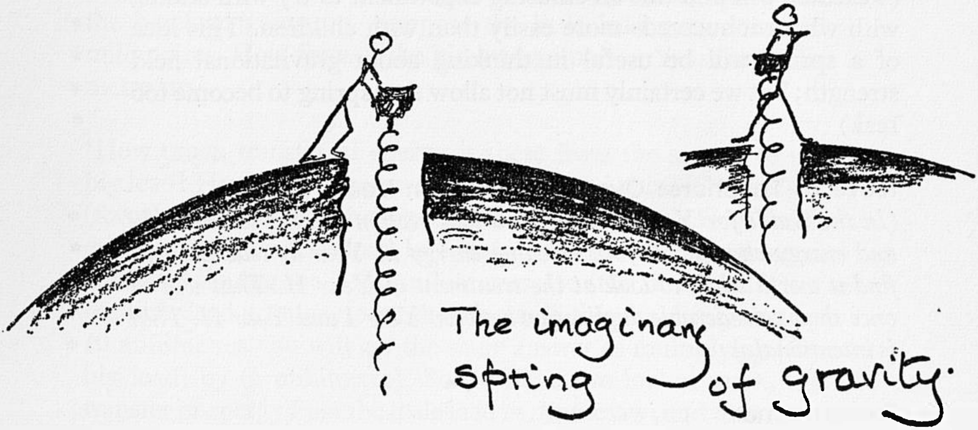
Feeling for Gravitational Potential Energy

In discussing examples where potential energy is involved, questions about what it really is, and where it really resides, may arise. We can help pupils to think of uphill energy stored up in the gravitational field that connects the Earth with the raised load if we tell them an artificial story:‡ * * * * *

> 'Imagine a spring connected between the load you raise and the centre of the Earth. There is no real spring but the pull of that stretched spring is just an imaginary idea to help you think about the way the Earth pulls on the load. T
>
> If the spring is *very long* as it is in this case, stretching all the way from the centre of the Earth to you, you will not stretch it much when you pull the load up a few feet. You will not change its length much; only from 4,000 miles to 4,000 miles plus one foot. So you will not change its pull very much however tightly stretched it already is. Even if there were a real spring you would not expect to feel its pull growing stronger when you raised the load higher. And in the case of the pull of the Earth, gravity, we do not notice any increase when we raise something higher up. Actually there is probably a very slight decrease but far too small

‡ Some teachers find this experiment in imagination and suggestion easy and profitable; others find it of little use. It depends on the general feeling of the class and the extent to which the teacher can call upon their imagination. We should, privately, remember that the most intelligent people are often the most suggestible.

to feel. So if you like to try this experiment of imagining you need not worry about the spring getting any stronger as you stretch it a little.



'Try the following experiment yourself: Stand with your feet apart, hold a brick in your hands and feel how heavy the brick is. Feel its weight. Feel how the Earth pulls it down. If you don't believe the Earth pulls it down, let go and see what the Earth does to the brick. C76

'Pretend to yourself that the pull of the Earth, which you can feel, is the pull of a long stretched spring that is attached to your brick and runs down through a hole in the ground to the centre of the Earth. You will find it difficult to imagine that spring if you keep your eyes open and can see that there is no spring there. So now shut your eyes and think about that spring and raise the brick up, holding it with your two hands. As you haul the brick up, you can feel that spring s-t-r-e-t-c-h-i-n-g. Keep your eyes shut, lower the brick, and let the spring contract a little. Now pull the brick up and stretch the spring. Did some of you manage to imagine the spring?'

If children visualize this long spring being stretched, some will bring in their knowledge of springs and expect gravity to increase with height above the earth – the 'spring' growing stronger as it stretches. If so, the teacher needs to explain again that this imaginary spring, all the way to the centre of the Earth, is so long that any ordinary stretches would not make it change its strength. Then, to avoid the story being misleading, he should add a warning that the real gravitational 'spring pull' of the Earth gets weaker as one goes farther out. But this is not the moment to go into any inverse-square story.

(Teachers will find this an amusing experiment to try with adults, *
with whom it succeeds more easily than with children. This idea *
of a spring will be useful in thinking about gravitational field *
strength; but we certainly must not allow that spring to become too *
real.) *

Note to Teachers: Overlaps between Years I and II

(_In the Guide for Year II, there is a long section dealing with energy_ *
and energy-changes. Before teaching energy in Year I, teachers will *
find it worth while to look at the treatment in Year II. That will at *
once show considerable duplication between Year I and Year II. That *
is intentional. *

Programme

The following section on energy and machines may be postponed to *
Year II. If there is plenty of time at this stage in the year, it is *
probably better to give some discussion of machines as 'energy- *
transmitters' that deliver, at best, only as much energy as is put in. *
Then pupils will be ready for further discussion in Year II. *

If this section on energy and machines is postponed, teachers proceed *
straight to the section on atomic energy. It would be unwise to post- *
pone that because it is intended to provide a very early glimpse of the *
new form of energy, really nuclear energy. Pupils cannot help hearing *
about atomic energy in ordinary conversation, and they read about it *
in the public press. We should certainly include it, therefore, in our *
present survey of energy.

ENERGY AND MACHINES: CAN MACHINES MULTIPLY ENERGY?

Discussion of Seesaw. We go back to the balancing board and D 77
remind pupils that, as a lever, it is a 'force multiplier': it will give us a big force for a small one, if we choose unequal distances. Then we ask if this 'machine' will also multiply energy for us. Can we get more energy out of it than we put in – if so, we should be rich indeed. (We should discuss this example; also a set of pulleys, in this matter; but we should not raise the question of perpetual motion, even if children ask about it. At this stage, our discussion would not be convincing and might even lead to confusion. When we consider how many people in the world are still gullible concerning this, we realize that we must go carefully.) See Note on 'Perpetual Motion'.

'Suppose we balance the seesaw with a big load here one space out and a much smaller load over here ten spaces out. How big must the small load be to balance? One-tenth of the big load. Now suppose the seesaw swings, the little load going down and the big load going up. Suppose the little load goes down 10 millimetres. How far will the big load go up? ... Yes, one millimetre up.

'How much transfer of energy is there from the seesaw to the big load? How much energy does the big load gain? The work is (force) × (distance), (the big load) × (1 millimetre). How much energy does the little load lose and give to the seesaw to send across to the big load? (10 millimetres) × (the little load). But the little load is only one-tenth as big and if you multiply that by 10 millimetres you will get the same answer as multiplying (the big load) by (1 millimetre). So we have two lots of work, the transfer of energy *from* the little load *to* the seesaw; and the transfer *from* the seesaw *to* the big load and those two are just equal. The big load gets as much as the little load loses. This seesaw does not manufacture energy. It is not an energy multiplier.'

(For beginners, it is easier to stick to feet and pounds; but in that case the seesaw had better be a huge imaginary one about 20 feet long.)

Pulleys

Pulleys: Ideal Mechanical Advantage. The children should try a set of pulleys. We shall not study pulleys in detail in this course. One set of pulleys should suffice as an example. We suggest a block and tackle giving a theoretical mechanical advantage of 3. For our present purpose we do not want to show the practical mechanical advantage but should encourage children to find the theoretical mechanical advantage by finding the pulls needed to keep 3 pounds load moving steadily up and down: and averaging them. It is probably best to make those measurements with a spring balance. We say this is how much the pulleys 'multiply force'. C 78

Pulleys: Energy Changes. Then when the mechanical advantage is clearly seen, hold a general discussion on energy changes. If the 'effort' is my hand, I must say that the input work is 'energy transfer *from* my chemical energy *to* the pulley system'. (The transmission from the man to ultimate load occurs by strain energy travelling through the pulley system; but it is exceedingly difficult T to see the full mechanism.) And the output energy-transfer is *from* the pulley system *to* the potential energy of the load. We argue these energy changes through and show that the pulleys do *not* multiply energy.

Other Machines. A fast group may go on to other 'machines' but this should not develop into a formal study of machines with mechanical advantage, efficiency, etc., being worked out for a whole string of machines. For example, the traditional wheel and axle seems to belong more in mathematics or engineering laboratories than in our present work.

Note to Teachers: Machines

There are two important things to learn about machines:

Force Multiplication: the use of the machine as a force-multiplier, the advantage it gives us and how its mechanism produces that advantage. Children enjoy learning such descriptions and explanations of various machines; and they feel they are becoming knowledgeable engineers. Such teaching establishes links between physics and the ordinary world as well as engineering. We should certainly promote those links, particularly with slower pupils who will feel that practical applications make their science much more genuine. But with faster groups we should not expand our teaching into a comprehensive study of machines, even if excellent equipment tempts us in that direction.

Energy Conservation: the essential demonstration, with machine after machine, that the 'output work' is never greater than the 'input work'. As we lessen friction, we approach the ideal case where the two lots of work are equal. This is the denial of perpetual motion – every machine that attempts to put out more energy than it takes in fails to do so. This builds our belief in the conservation of mechanical energy. As we increase friction, the 'output work' falls farther below the 'input work' and we find the machine developing waste heat (which will, upon measurement, be found to account for the difference). This begins the extension of conservation of energy to include heat.

We should not start formal discussions of energy conservation in Year I; but we can point out, with each machine that we study, its failure to manufacture energy: its success at best in giving us just as much as we put in. See General Note 'Perpetual Motion', in Introduction.

Note to Teachers: Heat and Conservation of Energy

Teachers will note that we have done very little about heat as a form of energy in this Year. If we continued to say emphatically that heat is a form of energy without showing any connection between heat and the measurements of work that we make, we should build up some 'modern knowledge' but we should also store up great trouble for pupils in understanding the meaning of Conservation of Energy. That great Principle has experimental supports which link it to the real world. For mechanical energy, the experiments are those which show the failure of perpetual motion and those which show that Newton's Laws of Motion are consistent with the behaviour of things in the real world, are good descriptions of Nature.

When the principle of Conservation of Energy is extended to other forms, a very complex and convincing set of experimental measurements carried out by Joule and others in the last century provide strong support. Those were not all direct measurements of conversion of mechanical energy into heat: there were other changes, involving electrical energy and chemical energy as well so that a failure of Conservation to cover all those forms of energy would have been revealed by inconsistency in the results of measurements. We want our pupils to sit as judge and jury on that evidence for Conservation, in a later Year; so we must not prejudice the Court by what we say now.

In this century we have found the Principle so powerful and valuable that we are now prepared to preserve it by artificial additions of new forms of energy if necessary. Since we do that with our eyes open, the extended Principle is still part of science, though no longer entirely a summary of experimental knowledge.

When we have developed the kinetic theory of gases further, we shall relate heat closely to our molecular picture; and we may take the average kinetic energy of motion of a gas molecule as a measure of its temperature. But that, too, will need to wait for experiments and discussion, and we should not rush into it now with assertion.

With all this in mind, we should be careful to keep a warning flag flying all the time we are talking about heat and energy in the earlier Years. We cannot say 'You do not know yet; you must wait', but we should not say 'You do know. You know that heat is a form of energy that must be measured in joules like everything else', or when pupils come to discuss the evidence for conservation in a later Year it will seem silly and dead to them. As a compromise, we shall say 'Yes, heat is connected with energy, it is a form of energy, but we shall treat it separately and measure it in calories until we are ready for the great discussion.'

Note to Teachers: Sunshine

We have done little about the Sun as the great provider of our energy. We could say a great deal, describing the changes between sunshine and useful jobs. But, for children to whom so much of this physics is new, those accounts would seem more like fables than real history. We suggest waiting till the pupils have more mature knowledge of energy forms. We can mention sunshine but should then leave the fuller discussions to later Years.

Programme

The following short section on Atomic Energy should not be postponed to a later year.

ATOMIC ENERGY

We can say, since everyone has heard of it already, that atoms have energy stored up inside them; and only very rarely can we get at any of that store of energy and release it or use it. A few common kinds of atom, the heavy radioactive ones, do not stay the same for ever, like common copper or sulphur, but suddenly unlatch a small part of their store of energy and shoot out a small bullet from the very centre of the atom. T

> 'Would you like to see that happening? Of course you will not see it directly because, for all we know now, atoms are much too small to see, but we can show you experiments that show the effects of radioactive atoms blowing up and shooting out bullets.'

Cloud-Chamber

Then show a cloud-chamber, preferably the expansion type for a first look. That is new and mysterious; but it is not possible at this stage to talk about ions and about supersaturated vapour and condensation. However, if the cloud-chamber experiment is to 'make sense' and give the feeling that it is really telling us about radioactive atoms, we must prepare the ground with ordinary cases of cloud formation. D81

Cloud Forming. To throw some light on the cloud-chamber before children have a second look at it, give the following demonstrations. D79a,b *a.* Show a jet of steam from a boiling flask. A shadow cast by a compact light source shows this clearly.

b. If an electric spark passes through the invisible vapour just outside the jet, before the cloud forms, one can see the effect of ions in promoting a dense cloud a little earlier. The boiling flask must be far away – a yard or more, or the bunsen flame will itself make enough ions to spoil the demonstration. A small induction coil or a 5 kV power pack will make a spark that shows a clear effect. The spark should pass across the mouth of the glass jet from which the steam emerges.

c. Show cloud-making by letting air expand as a demonstration, or better still as a class experiment. Raise the pressure in a big closed flask of air with a little water, by blowing through a rubber tube attached to the stopper. Remove the stopper and see the cloud. The flask should be very brightly lit from the side, with a dark background behind it. It is better to have the room half dark. D/C80

d. If you like, carry out the expansion several times, waiting each time for the cloud to settle, until the air in the bottle is relatively dust-free. Then the clouds are poorer. Throw in a lighted match, or poke a bunsen flame into the bottle for a moment, and then make a cloud that will show the great effect of providing smoke dust or ions as centres for cloud drops.

This is a good experiment to take home. H80

(Unless we feel desperate for a familiar 'analogue' we should not refer to the cloud trails made by jet aircraft, because the mechanism is different.)

Expansion Cloud-Chamber

Then children are ready to enjoy seeing alpha-particle tracks. If this is accompanied by a great sense of mystery, that does not matter at this stage, because we should at once explain: D81

> 'This is only a first look at radioactive events. We shall come back to the cloud-chamber and explain it later, when you know a lot more physics, which you will need before you understand the whole story.'

Mankind lives by such promises throughout life, from childhood to old age: it is not a silly way of teaching, it does *not* spoil things by skimming the cream: it is the way our knowledge grows. These * * * experiments are new and strange: the interpretation of what one sees is not obvious, and it is not clear to beginners what they should look for. In this case, therefore, it is wise to prepare the ground by showing the children the kind of thing to look for. So before using diffusion cloud-chambers for a class experiment, children should see a clear demonstration with a good expansion cloud-chamber. That will show tracks clearly and easily at just the expected moment; and children can see the tracks quickly by crowding round in small groups. The long alpha-particle tracks that appear at each expansion are easy to see (and agree with the usual photographs).

Expansion cloud-chambers for use in schools have hitherto been expensive pieces of apparatus and have acquired the reputation of being uncertain in their working. The expansion chambers that universities have long used to demonstrate alpha-particle tracks (to students in small groups or, by projection, to large audiences), work easily and consistently. We hope that schools will have a form that behaves well like that.

A rubber bulb (like the ones used on battery hydrometers) squeezed by hand and released, will produce the expansion more reliably than a bicycle pump. The volume of wet air should be increased by a piston directly under it, rather than by air flowing out through a tube to a pump – the latter arrangement may produce unwelcome currents, as well as looking less direct.

If the wet air is contained in a cylinder whose bottom drops as a moving piston, pupils are somewhat less likely to make the mistake of thinking that the alpha-particles are pulled out of the source by the pump! For a simple model, the moving piston should be simply a column of water. The rubber bulb is full of water and connected to that column, so that by squeezing it one can raise the column and momentarily compress the air above. The region of wet air is illuminated by an ordinary electric lamp bulb, well shielded.

Before buying one, teachers should make sure it is a model that works easily and continues to do so consistently – this is too expensive an instrument to be bought on optimistic hope. In all such cloud-chambers, it is important to avoid letting water coat the source, because even a thin film will stop alpha-particles. It is also important to remove the ions that have been formed by alpha-particles a short time before the expansion at which one wishes to see the tracks. Those ions would collect drops of water all over the field and spoil the picture. Therefore an electric field must be applied. In some models, quite a small voltage is needed – the a.c. mains with a huge safety resistance. In others, it is better to have a plastic lid to the chamber and charge that electrostatically by rubbing – but in that case the field may well fail to reach the proper region. *

Teachers may be tempted to save time and cost by omitting the expansion cloud-chamber and proceeding at once to the class experiment with diffusion cloud-chambers. We urge them very strongly not to make that economy, but to show a good expansion cloud-chamber first. *

Class Experiment

After showing the expansion cloud-chamber, distribute Taylor type cloud-chambers round the class, one for every four children. Allow them plenty of time to watch the tracks. This is something to be enjoyed and should not be hurried. They will occasionally see strange things in the chamber, which add to the fun of observing. Notice the random appearance of the disintegrations. If possible, do not point this out but offer a hint that will give children a chance to notice it. C82

In schools where several classes are following this programme, it may not be feasible to manufacture the supply of solid carbon-dioxide that is needed by using the small cylinder intended for demonstrations. It will be necessary to order a block (twenty-five pounds) of solid carbon-dioxide from the suppliers. Such blocks are easily obtainable, delivered by railway.

Descriptive Story of Radioactive Events. Explain that we shall learn more about these radioactive substances and that we shall see the vapour trails again later in the course. Resist the temptation to say too much: leave the subject as something to look forward to on its next appearance. We do have to give a little explanation at this point: we should say that T

> 'something comes out from the radioactive atoms and does a good deal of damage as it flies through the air leaving things there on which water drops can start' –

but the time is not ripe for talk of electrons being knocked off atoms and ions formed. We might give the cornfield story, said to be due to Andrade:

'Suppose a cannon ball is fired through a field of ripe wheat. If you were watching from a helicopter up above, the ball would move too fast for you to see it and you would hardly notice the track marked by broken stalks. But wait half an hour and the track would be marked by a line of blackbirds settled on the broken stalks.'

In a later Year we can give the next stage of explanation: *

'A radioactive atom suddenly spits out a small piece, from its *
innermost core. In doing that, its nucleus acts like a gun, hurling *
that small piece out with vast kinetic energy – at the expense of a *
fraction of its own store of nuclear energy. That piece is hurled *
out so fast that as it blunders through the surrounding air it *
can knock a chip off thousands of air-molecules. Those chips *
are electrons each with a negative charge. An air-molecule that *
has lost one is left with a positive charge; it is a positive "ion". *
And the electron that has been knocked off will soon be col- *
lected up by some other air-molecule nearby to make a negative *
"ion". So the path of the small particle that is hurled out by the *
radioactive atom is marked by a mess of + and – ions of air. *
Little water drops then form on those ions and mark the path. *
Of course, you never see any sign of the high-speed particle *
itself – it has flown through before the water drops start to *
collect on the ions.' *

Teachers who look at the account above will see why the time is *
not yet ripe even for that informal account. *

Cloud-Chamber Photographs. An adult physicist can glance at D 83
a cloud-chamber and see the tracks at once; but to a child these are new and strange and need watching. We must give plenty of time; then, after showing a cloud-chamber, we should post up large photographs, preferably transparencies, and leave them up for some time. (The Nuffield Physics group hopes to establish a library of such photographs on which schools can draw.) Some teachers will want to display other pictures as well as the simple sheaf of alpha-particle tracks, for example, pictures that show nuclear collisions, etc., with a fork. Those will promote keen questions and promises of future explanations. Still more complicated pictures, such as bubble-chamber photographs, merely produce confusion at this time – they are 'abstract art' in physics and need much more time and training for a sophisticated understanding of the events they reveal.

Radioactive Events with Counter

And now, at the end of the Year, we should offer another way of seeing the effects of radioactive events: some form of Geiger counter (not an electroscope being discharged, because, while it is just as mysterious, it fails to show the individual atomic events). We suggest a spark counter for this (and possibly also a spinthariscope, if time and place permit). * * * * * *

A spinthariscope (optional de luxe addition) is useful, for wonder and for teaching first ideas of radioactivity, but pupils must look at it one by one in a fairly dark room. (If critics call it old-fashioned, remind them of the importance of scintillation counters today.) D84 OPT.

Spark Counter. The spark counter shows alpha-particles as individual random events. At this stage we should not explain it but simply say: D85

> 'This is something which responds to the things which made the tracks in the cloud-chambers. By counting the sparks, you can count radioactive atoms blow up and shoot one alpha-particle each into the space behind the wires. You are counting single atoms.
>
> 'I cannot explain to you how this works yet. You will have to learn a lot more physics about moving things and electric charges and electric fields and changes of energy before you can understand this. But you will learn how it works; and you will see it again.'

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

Problem C. A Set of Questions on Orders of Magnitude, Standard Form and Rough Guesses

C. 1. *a.* How much is $10 \times 10 \times 10$? Write it in words.
b. Write $10 \times 10 \times 10$ in numbers, in two different ways that are each of them quicker to write than $10 \times 10 \times 10$.
c. Write $10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10 \times 10$ in numbers in the quickest way you know.
d. Atoms are extremely small, so small that people can hardly picture how small they are. But we can do experiments to find out how small atoms are. Then, knowing their size, we can work out how many atoms there are in some object of ordinary size that we can see. For example, a small aluminium saucepan is made up of about 10,000,000,000,000,000,000,000,000 atoms of aluminium. Write that in numbers in the quickest way you can.
e. In the question about the aluminium saucepan just above, the number you were given was only a very rough estimate. (It was not a wild guess, but was worked out roughly from real experiments.)
Explain in your own words why you think it would be silly to give a value like 12,356,419,000,000,000,000,000,000, and claim that it was more 'accurate'.
2. Some astronomers who have collected a great deal of information about the stars think that they can estimate how many atoms there are in the whole universe – the stars and the planets all put together.
Of course, that is only a very rough guess. They do not count just atoms, but electrons and the other small pieces which are thought to be inside atoms.
They say that they guess the total for the whole universe of all those little 'particles' is about 10^{80}.
a. Time yourself while you write out 10^{80} fully in ordinary figures. How many seconds did it take you?
b. Time yourself when you write 10^{80} in this short form, 10^{80}. How many seconds does that take you?
c. Suppose your clock was only marked every five seconds, and did not show separate seconds or fractions of seconds. Describe a simple way in which you could find the time taken to write 10^{80} with a rough clock.
d. How many times quicker is the short way of writing this big

number than the long way, in actual time of writing? (Remember that 'how many times' asks you to divide and not just to subtract and find how much quicker it is.)

3. The speed of light is 186,000 miles per second.

a. If the speed of light were only 100,000 miles per second, how could you write it quickly?

b. You can say 186,000 = 100,000 × [?]. What must go in the box [ ]?

c. Then to save time in writing you can say 186,000 = [?] × [?].

4. The radius of the earth, from the centre to the surface where we live, is about 6,400,000 metres. This is the same as 1,000,000 × 6·4, so we can write it $10^6 \times 6{\cdot}4$. We usually write it: $6{\cdot}4 \times 10^6$. This is the standard form used by scientists for writing big numbers. It is quicker than writing the numbers out in full and it has a special advantage. It gives the scientist an opportunity to say how accurate or how precise he thinks his measurement is.

No scientific measurement is ever perfectly accurate, except those few which are simply a matter of counting a whole number of things (like the number of peas in a pod, or the number of pigs in a litter). When we measure an electric current with an ammeter, or weigh something on a balance, there is often a tiny bit of friction which makes the pointer stick a little without our knowing it, and anyway, there are the thickness of the pointer and the thickness of the marks on the scale which make us a little uncertain.

A good scientist knows he is not perfectly accurate, but he is very careful to try to find out the dangers and errors in his experiment so that he can say whether his arrangement is nearly right or whether he thinks it may be wrong by an enormous amount. That is good science, not only to admit you may be wrong but to have a good idea of *how wrong* you are likely to be. The scientist shows his doubts by stopping at the last figure he is fairly sure of. Here we have 6·4. That means, we know the 6 is right, for measurements of the Earth; and we are just sure about the 4. We think the right value is 6·4, but we know we might be wrong in measurements and the real value might be 6·2 or 6·3.

Of course, the size of the Earth has now been measured much more carefully than that: and we know that the radius of the Earth is $6{\cdot}371 \times 10^6$ metres, with some doubt about that 1. The 1 may be a 0 or a 1 or a 2. As a matter of fact, the Earth is not quite round, with the same radius in all directions. From centre to poles is a little less than from centre to Equator: so 6·371 is only right for one direction, from centre to England: and by the time we are bothering about that 1 we have to say *which* radius of the Earth we want.

However, in many things that we want to work out – for example, some rough predictions for Earth satellites – we do not need to know the radius of the Earth so precisely. So we take it as $6{\cdot}4 \times 10^6$ and are glad to take it roughly, because that fits our use.

In scientific standard form, we always write the number in the form of a power of 10 (like the 10^6 in the Earth's radius) multiplied by another number which has one figure, just one figure, in front of the decimal point. And then we carry on as many figures as we think our accuracy deserves after the decimal point. Try doing that yourself with the following examples. If you like, use your own measurements instead of those that are given you for the imaginary person called Jones.

a. Jones is 4 feet 7 inches tall. That is the same as 1397·0 millimetres. Write down Jones's height in millimetres in standard form. (If you use your own height, you will have to turn it into millimetres by multiplying your height in inches by 25·40, because that is the number of millimetres in one inch.)

b. Say, in standard form, how far you would advise Jones to carry his statement of his height. What figure should he stop at? Give a short, clear reason for your advice.

c. Suppose today is Jones's birthday and his age is just 12 years. Write that in standard form in months. Suppose his school writes to him now and says 'Let us know how old you will be *next term*, in months.' Write down the most sensible answer for him to give in standard form in months.

d. Now turn Jones's age into days. (Reckon $365\frac{1}{4}$ days in a year.) Express his age in days in standard form. Suppose just after his birthday he writes to a friend in America and says 'When you get this letter, I shall be just "so many" days old.' Put that number 'so many' in standard form and end it where you think is sensible. Give a short reason for your choice of how far to carry the numbers in this case.

e. Choose any two out of the following things and in each case make the best quick rough guess you can – which is something a good scientist often has to do. Put your guess in standard form and carry the figures of the standard form as far as you think wise.

(i) The number of eggs a good hen lays in one year.

(ii) The number of gallons of milk an average cow gives in one year.

(iii) The number of quart milk bottles a family of two parents and two children take in one year.

(iv) The number of letters one postman delivers in one year.

(v) The number of chemist's shops in the nearest big city: Birmingham, Bristol, or whatever is nearest to you.

(vi) The number of grains of sand in a handful.

(vii) The number of hairs on your head.

(viii) The number of sewing-needles sold in Britain in one year.

(ix) The number of stars that you can see on a clear night outside your home with your eyes alone.

(x) The distance in yards between your bedroom and your Physics classroom.

(xi) The amount of potatoes in pounds that your family eats in a year.

(xii) The amount of potatoes in pounds that you are likely to eat in the first twenty years of your life.

(xiii) The number of robins in Britain.

(xiv) The number of golden eagles in Britain.

(xv) Height in inches of the tallest tree or building within one mile of your school (say where it is, and what it is).

(xvi) The number of dogs in your county (not counting puppies). (Note: you can find the answer to this if you ask the right people.)

SUBJECT INDEX

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NUFFIELD FOUNDATION
SCIENCE TEACHING PROJECT
PHYSICS SECTION

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.

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Batley High School for Boys
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Other Nuffield Physics publications

Teachers' guide II
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Teachers' guide V

Guide to experiments I
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