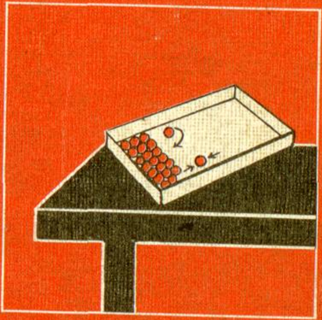
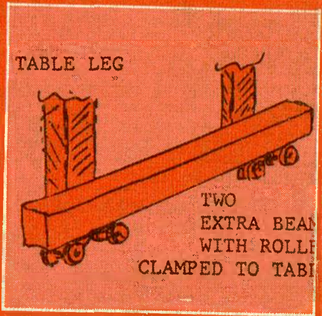
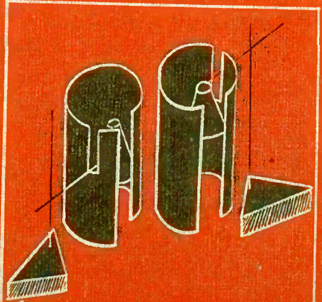
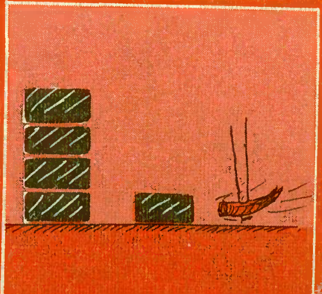
PHYSICS

Teachers' guide III









NUFFIELD PHYSICS TEACHERS' GUIDE III

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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 III

If it is assumed that a school year includes 30 weeks and that each week includes 3 physics periods, each of which lasts 40 minutes, then a very rough estimate of the number of periods suggested for each section of this Year would be:

Chapter 1	12
Chapter 2	23
Chapter 3	13
Chapter 4	10
Chapter 5	14
Chapter 6	6
Chapter 7	8
Chapter 8	4
	90

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
T = Teaching of material (lectures, discussions with pupils, etc.)
F = Film
H = Suggestions for optional experiments at home
P = Problem
* * * = Commentary (notes on, methods, aims, etc., offered to teachers)
‡ = Reference to footnote
§ = Reference to a comment made by a teacher during trials
† = In YEAR III reference to YEAR I or II material needed

(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.)

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]×[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 chemicai 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) $\times$ (distance) but (force) $\times$ (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, $I_w=K_wN_w$ where K_w is the 'irritation-constant' for whispering. And we might possibly find that $I_t=K_tN_t$ 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, $I=I_w+I_t=K_wN_w+K_tN_t$; 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_wN_t. In the latter case, with $I=K_wN_w+K_tN_t+KN_wN_t$, 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) × (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.]

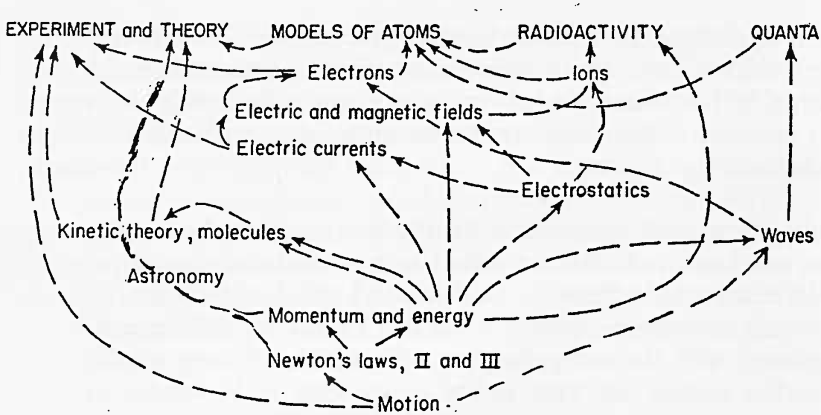
Some of our questions should be quite general ones. Though they show clearly, in a pupil's answers, whether he understands the science he has learnt, we have to mark them more loosely, with less precision – but what are we teaching for, examinability or understanding of science?

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.

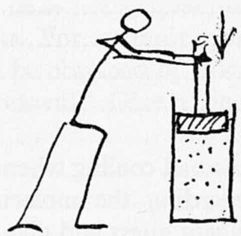
6. Tell Freddie how he can test your suggestion(s) of his mistakes.

(*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.

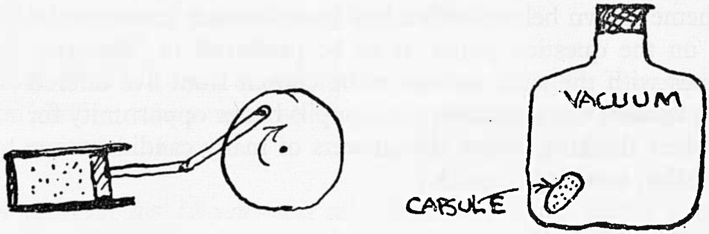
....

....

....

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.)

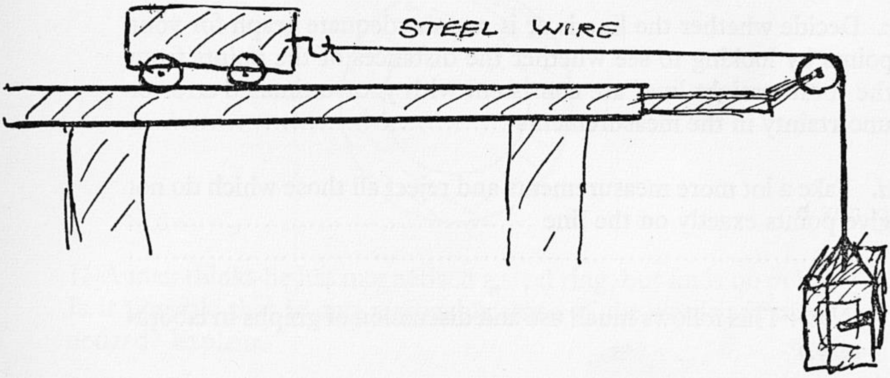
....

....

....

(*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.)

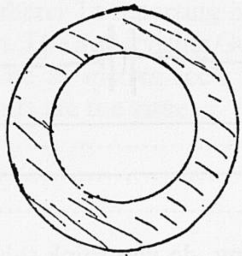
H. Describe the meaning and use of 'laws' in physical science, discussing examples such as Hooke's Law, the Law of Conservation of Momentum, etc.

(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.

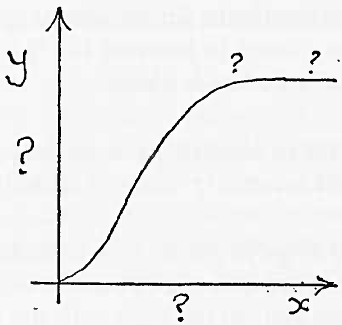


1. A man thinks he has magnetized a steel ring, but finds no poles. Is it possible that in any reasonable sense of the word it is magnetized? Explain.

....

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.

....

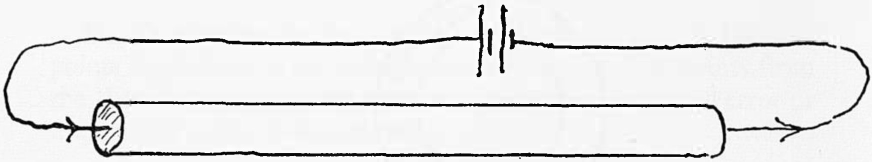
b. What is (probably) being plotted upward on this graph, that is, on the y axis?

....

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/sec^2. 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/sec^2. 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.

ERRATUM

The Publishers regret that this page from Year I has been included in error and should be ignored.

Where the children will start, and how far they will go, will depend on what they have done and heard before, in school and 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 shall 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

PREFACE TO YEAR III

This is a year of becoming a more mature scientist by trying to extract some general rules from experiments. Giving these the title 'laws' would be rather too severe: the more important thing is to let young pupils progress beyond playing with experiments and somehow enjoy extracting something common to several experiments. We may have tried that in Years I and II but the general idea probably did not seem particularly important or interesting then.

And yet since generalizing and abstracting is probably how our earliest ancestors emerged from animal life of acquaintance and instinct, we may expect this activity in children and encourage it. Some people say that language, particularly language containing abstract words and expressing abstract ideas, was the vehicle for human emergence; and that language as a vehicle for reasoning enabled simple knowledge to grow by developing towards science.

Before starting this Year, we should look at its material and ask ourselves carefully what we hope our pupils will get out of it – what they should gain as young scientists being encouraged to do some reasoning and to enjoy codifying science in laws, while they are continuing to build an increasing store of factual knowledge.

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

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

We can, later on, explain an electric spark by saying that it consists of air in which there are many ions driven so hard by an electric field that they make more ions by collision, etc. Even that, if we examine it carefully, does little more than link a spark that we have seen with a lot of other experiments on gases being bombarded, flames conducting currents, etc. If we refuse to be disappointed and claim that the explanation goes deeper than that, we find that we are linking the spark to some models of gases and things in them: a picture of molecules, a picture of an electron and a model of an electron being ripped out of the molecule; and that leads us back to explanation as a linking – this time, linking sparks through our models, to our knowledge of collisions of billiard balls and things like that. Though many of us enjoy such scientific explanations and wish to endow them with special virtues beyond mere linkage with the more familiar, we should be wise in our teaching to think of explanation as linkage. One of the best examples is the explanation of the Moon's motion round the Earth. We say the Moon is simply falling under the action of (diluted) gravity, like the cricket ball, and we feel satisfied. Yet we have there no explanation of gravity.

Sometimes, in the early stages of this Year, pupils ask, 'Why do we do physics like this?' or, 'Where are we going in this physics? What are we going to learn? What good will it do?' If we think of other subjects, outside the field of science, we can imagine cases where this request for a purpose would be disastrous. The curious thing is that in most classes, pupils do not ask but seem to take their burden for granted. In fact, where the whole purpose is questioned, we may suspect some special anxiety or doubt in pupils – or perhaps in ourselves when we are teaching. So teachers must be glad when that question does not arise over, say, Latin grammar or the more formal parts of History. However, in our science teaching, we ourselves feel that we are pursuing a very interesting study and building very valuable knowledge for life in this scientific age. We enjoy exploring nature and increasing our sense of insight.

However difficult it is for us to convey our own enjoyment and interest to questioning pupils, we should be prepared for such questions – particularly when a new programme of teaching is starting – and should try to give some general answer, such as 'You will learn about the way things go in the world of machinery and instruments and moving planets in the sky and atoms. We want you to do things for yourselves and to think things out as you go so that you understand what you learn and will remember it well later on. This is going to be part of your knowledge for all your life.'

We may feel tempted to justify our programme by a list of items, of material gains. If we can, well and good. But we should not claim that studying dynamics will make us better at bicycling; that learning kinetic theory will help our use of a thermos flask or a double boiler; or that experimenting with magnets and coils of wire will at once turn us into radio repair men. The physics that pupils learn will help them as a general basis for learning more science and for understanding applications of science; but we are probably wise to maintain a general claim rather than 'examples'.

In the case of pupils beginning Year III, there are two special reasons for doubts and questions about the purpose of the course: (1) Pupils who have not done the work of Years I and II of our programme find our use of class experiments strange. Their work in other laboratories in earlier years has probably started with much more detailed instructions and has been carried to a formal conclusion with more help from the teacher and less time for experimenting. Instead of welcoming our 'looser' class experiments, those pupils may feel uncertain or frustrated. They need encouragement and reassurance. And (2) both the work in class and the problems for homework may seem to take a different attitude from that of other science teaching, or of teaching in other subjects. Pupils used to clear definitions, limited experiments, questions in homework and examinations that ask them to repeat things learnt by heart, do find our exploration of science strange; and they worry lest examinations (of the only form they know) find them unprepared. Therefore we must give very clear assurance that the examinations will be like the homework questions, 'questions that ask for *thinking* and describing and explaining things to show that you understand them'.

Such questions about learning physics may seem disturbing when we meet them, but if they are genuine they are a sign of an interest in what we are doing and going to do which will be of great value. We hope to discourage learning that is of little lasting use, and to encourage learning that seems worth while to pupils and to us.

The syllabus for this year is concerned with waves and optics; preparatory studies of force, mass and motion; continuation of electrical experiments with electric and magnetic fields, forces on currents, motor, simple electromagnetic induction, and dynamo; and some simple kinetic theory. Each of these is already a familiar topic in school physics; yet, in each of these, we can find surprises if we think about our aims and look at the teaching in terms of them.

In waves and optics young pupils will enjoy learning how waves behave by doing their own experiments – but they would not either enjoy or profit from a formal discussion of the mechanics of waves, leading to treatment of simple harmonic motion. And they will come to optics thinking it must be science that deals with telescopes and eyes and cameras and spectacles; so we should offer such optical instruments, first as things to make for oneself and then as instruments whose working we can explain in a general way.

The desire to find the correct laws of reflection and refraction of rays, and object and image distances for lenses and mirrors, seems natural to *us* as adult scientists, but is an artificial search for young beginners. The difficulty with the Laws of Reflection does not lie in their geometry but in their irrelevance: why should man want to know the rules for rays? Our answer that the rules enable him to explain how a concave mirror works is only partially satisfying; because it really only links the concave mirror (which is so much more interesting) to the plane mirror.

If we proceed to Laws of Refraction at an early stage they appear geometrically difficult as well as not clearly relevant. We *shall* get to laws and show them as a part of the glory of science but – like advertising men building up a demand – we must prepare the ground for pupils to welcome laws as good summaries of something they already think important.

With that in mind, we should start optics with real instruments, then ask and show what the lenses of instruments do to 'rays of light'. That behaviour can very well be codified in 'image-forming properties'. We say: 'Rays of light from *this* point on an object are bent by the lens so that they all pass through *that* point; and then if your eye is in a suitable position to catch those rays from the image, you think you are looking at a real thing, not just at the image. For vision, the lens shifts the object you look at from there to here, as an image to look at here instead.'

Treating lenses as image-formers we can show that telescopes, microscopes, and of course cameras and eyes, make good sense. Then, when pupils know that the important thing is the reflection of rays by mirrors and the bending of rays by lenses so that they converge to an image point or at least diverge from one, the laws are welcome summaries of more basic knowledge. Mature physicists like to start with these laws as summaries, but then mature physicists already know how the laws help them to understand behaviour of lenses and instruments.

In dealing with motion and force we have all mankind's interest in transport and weapons and building, etc., as a driving force; but our pupils do not have clearly in mind the puzzling questions about motion that led great scientists in the past to define velocity and acceleration, to consider their measurement and relationship, and then to relate them in turn with forces.

To educated adults in 1700 an offer to clear up the relationship of force, mass and motion was a rich opportunity to throw light upon the public clash between Ptolemaic and Copernican astronomy. And when further studies of dynamics and gravitation drew the whole system of the heavens into one great explanation, Newton's work was acclaimed far and wide and taught generation after generation till the present day. But it is easy for us, when we are busy teaching Newton's Laws in school, to forget the original story of puzzling phenomena, and the magnitude of the successful explanation. Our young pupils do not have Kepler's three Laws hammering in their heads for explanation; and Newton's Laws at a first glimpse seem rather unnatural and often lead only to unreal calculations. Here we should go gently with our introduction to dynamics, doing our best to let pupils feel the problem before we offer the solution.

We cannot build up a tale of astronomical history at this stage for modern dynamics to illuminate or explain – though we hope to do so in Year V. But we can ask simple stimulating questions about Earth satellites, rockets, jet cars, the behaviour of atoms in nuclear changes. So we should think very carefully about preparing the ground for studies of motion. Essentially, we should forget traditional thoroughness and make our first treatment of Newtonian dynamics too short to be boring. Then at a later stage, even if we have not dealt with astronomy, Newton's Laws of Motion may impress older pupils as general rules which give science a sense of power.

While we are preparing to extract some rules to give strength to the main branches of physics, we should also let our young pupils continue to acquire knowledge by straightforward experiments with relatively little guidance. They should already know confidently how to connect up electric circuits and they should now continue into work with magnetic fields and forces on currents. They should make motors. And then – by their own experiments – they will find out about dynamos.

Not all our theoretical structure is built of general laws extracted from experiments in the world at large; some of it is built by a more risky, imaginative method: thinking of a model and then seeing where it would lead us. This can be fun for children – fairy-stories continued into science – and it will show them scientists as imaginative people, and yet hard-headed ones who know the risks they take. A simple kinetic theory of gases can do this for our pupils; but we must build it in stages so that the difficulties of algebra or reasoning do not pile up. This building in stages has one great danger, that the assumptions get forgotten, the model taken for granted. While we should not spoil confident progress by repeated insistence on doubts, we should maintain cautious warnings that the assumptions are there. Again and again we should emphasize the word *if* in an argument, for the sake of that caution. And we should emphasize the ensuing *then* as a reminder of our logic.

Over all, this should still be a light-hearted year of enjoying doing and thinking as an amateur scientist.

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 NOTES: YEAR III

NOTE TO TEACHERS: NEWTON'S LAWS IN YEAR III

Connection with Year IV

Year III should only prepare the ground and give a general idea of Newton's Laws. Then these can be clarified and made more precise and tested more fully, if you like, in Year IV. In fact, it is not until Years IV and V that Newton's Laws will be put to use in atomic physics, and in Year V used in astronomy.

Year IV

A year later, in Year IV, we shall test the relations between force, mass and acceleration, and we shall make measurements of momentum, looking for conservation. These will be class experiments in which pupils use tickertape (usually with a 50-cycle vibrator), and analyse the tape carefully for measurements of velocity, leading graphically to accelerations. When the mass has to be changed, that will be done by piling one or more identical trolleys on top of the original one.

Pupils will also be shown how to develop algebraic expressions relating distance travelled, time, velocity and acceleration, and they will analyse experimental tape records to see whether measurements agree with the relations for constant acceleration: in other words, they will find out experimentally whether certain motions such as free fall, or motion along a level table with a fixed force, do have constant acceleration.

We shall also have multiflash photographs: first of an object moving along a level surface with practically no friction, then of such an object colliding with another at rest, then of such an object colliding with another also in motion. Pupils will be asked to analyse these 'collisions'. That should be tried for three types of collision: (1) when the objects are ring magnets, which will repel and collide without 'contact'; (2) when the objects are similar rings of brass which collide sharply; (3) with rings with sticky surfaces (plasticine) to make inelastic collisions.

The essential flavour of those measurements should be that of a thoroughgoing investigation to give confidence in Newton's Laws of Motion and in the conservation of momentum, so that pupils feel that they have powerful weapons in their hands.

After the study of momentum, we discuss energy (introduced in Years I and II). We obtain an expression for kinetic energy and show various interchanges again using trolleys and tickertape.

As well as that, preferably after the class experiments rather than before, the teacher can give some demonstration experiments in which velocities are measured by millisecond pulses counted by the scaler. And after this work, the teacher should demonstrate some use of momentum conservation, say to measure the speed of a bullet; and there should be some qualitative talk, with cloud chamber pictures, of 'atomic' collisions.

Year III

Looking back from that busy, careful, capable Year IV we can see what we want from Year III: some familiarity with techniques, and perhaps a rough idea of relations between force, mass and motion, to set the stage for detailed studies: and above all, a clear feeling that there are interesting problems to be solved concerning force, mass and motion which concerns satellites and rockets and atoms and many other things in the modern world. We must set the stage by showing pupils there is a need, and then giving them an informal glimpse of our attack on the problem, and the nature of the answers.

This Year, pupils should do a few experiments with tickertape – enough to make an interesting beginning, but not prolonged into boring training.

Schools which are also teaching Year IV will have a camera and accessories for multiflash pictures. In that case, pupils should see a multiflash picture taken in Year III and should discuss its analysis briefly.

NOTE TO TEACHERS: TEACHING OF OPTICS

Customary Approach

In the customary approach to the teaching of geometrical optics one starts with the properties of rays of light – which are conceived of either ideally as straight lines along which light travels or, more realistically, as narrow straight pencils of light – and one states three groups of general laws, extracted from experiment:

Straight line propagation in a uniform medium

Laws of Reflection

Laws of Refraction

Then one derives from those Laws the properties of image formation by lenses and mirrors. In doing that, one defines the image of a point as that point to which rays from the object point converge, or from which they appear to diverge, after reflection, refraction, etc. The imaging is assumed to be perfect, but the restrictions which near perfection would require are seldom mentioned.

In the experimental background of that treatment, one asks pupils to trace rays to and from a plane mirror or through a glass block, and one sometimes gives demonstrations of angle relations with a Hartl disc.

Then pupils test the predicted object-and-image relationships by experiment. To many a pupil, however, these experiments do not appear as tests of a relationship but are simply measurements of 'the focal length'. The general action of a lens becomes lost in worship of a particular image point, the focus.

Pupils who find the algebra or arithmetic of formulae too hard are offered a simple construction, using 'undeviated rays' and the property of 'parallel rays passing through the focus'.

Only after all that do pupils meet optical instruments, although those should seem to most school children the essential matter of optics.

In the hands of skilful teachers that programme of teaching optics works well, though it often produces only a rather artificial skill in constructing 'cat's-cradle' diagrams – and many pupils draw those diagrams with rays that make a sudden change of direction at each image, which is optically quite misleading. When those pupils, armed with skill in calculating image positions or drawing construction-diagrams, come to optical instruments, some of them find little connection between the real instruments and what they have learnt. Many neither see that they have built up from fundamental laws a magnificent explanation of the working of lenses and mirrors, nor feel that they know all the better for their studies how optical instruments work. Few emerge from school able to focus a telescope or microscope easily and comfortably.

Many of us have accepted that pattern of teaching by habit and do not notice the defects in the development from the pupil's point of view. His tests of the Laws of Reflection and Refraction are overburdened by the difficulties of precise tracing of rays. He finds the Law of Refraction peculiar rather than welcome, because he has built up no strong need for such a rule. (When Snell discovered the law, adult scientists were indeed ready to welcome it because their mathematical development of optics was waiting for it.)

The pupil is carried from a Law of Reflection to a 'mirror formula' by geometry that seems to him obscure because he has not understood the essential property of images (... *all* rays ...). When he meets the need for approximations, the sense of obscurity is joined by doubt.

For lenses he has to jump to the formula, because the geometry is now too difficult. Or else he is carried through a story of little prisms, which strikes him as artificial – and anyway some geometry is missing there too.

Such teaching given to pupils at a later stage of skill in mathematics might show them well-organized optical science. But if pupils do return to optics later we usually offer them, quite wisely, a wave-treatment.

As a further commentary on the system described above, we should note that the 'longitudinal formulae', $1/v \pm 1/u = 1/f$, etc., are seldom used by professionals in optics, who are much more concerned with 'lateral expressions' for the changes of distance of a ray from the axis. They regard our longitudinal formulae as things which have just remained in school physics (like those messy methods of measuring specific heats which we still practise, although they have not been used in research for half a century). Furthermore, the 'cat's-cradle' construction usually makes such a small angle between the two essential rays of its 'scissors' that it is very inaccurate in pupils' hands. To make it more accurate, we ask pupils to enlarge the lateral scale; and then the diagram looks optically absurd because the apertures look far too wide.

Physicists have always regarded the Laws of Reflection and Refraction as fundamental laws, obtained by experiment, from which all geometrical optics can be developed. The actual experiments are not so easy if we pin the rays down to very narrow pencils: diffraction threatens trouble. Precise tests have to be made with large sheafs of parallel rays – i.e. with plane waves in a spectrometer.

Rays-and-Images Approach

If, instead, we were to start with empirical knowledge of rays and images we should feel our approach was less 'fundamental' but more realistic. We should really be offering young pupils a start that is equally well based on experiment and we should be able to deal with optical instruments earlier and in a way which would seem more direct. The only great loss would be that we should not have the Laws of Reflection and Refraction so early or make them so prominent in our collection of great general laws; and that is a loss, because we want pupils to see the part played by general laws in the structure of science. Nevertheless, we shall follow in this programme a different approach – a treatment in terms of *images*, which has been tried before and gives pupils more confidence and skill with optical instruments.

We start with the following properties of 'rays' (regarded either as ideal lines or practical pencils):

1. Rays of light travel in straight lines, in air, or water, or in any other uniform medium.
2. We 'see' an object by having our eyes receive, and make some use of, rays of light that come straight from each object point into the pupil of the eye.
3. Lenses, etc., bend rays of light that come from an object point and make them pass through (or seem to come from) an image point. Then, if the rays are allowed to continue to our eyes (suitably placed to receive them) we take that light as coming straight from the image point. We think we 'see' an object at the image.

Thus, a lens or mirror has to be treated as something that 'optically speaking' moves the object to the image position. The object is not really moved, but the lens or mirror forms an image which behaves optically like a new object, in a new place, usually of different size.

People look at images just as confidently as they look at objects. In fact, when a teacher looks round a class, he can often say 'Seven of you here are not looking at me at all – you are only looking at a virtual image of me.' Those are the pupils who are wearing spectacles.

Practical Procedure: Programme

The practical procedure we suggest is this. Pupils start by looking at images: first when a lens gathers many bundles of rays and converts a pinhole camera to a lens camera; then with a strong converging lens forming real images, and virtual images.

They hold up a weak lens to form an image of a distant view and look at that image with a magnifying glass – and now they have a telescope.

We cannot give much explanation of camera and telescope when pupils are taking this first look. We are just setting the stage. Before pupils can appreciate the description of a lens as an image-former, they need a feeling for images as places that rays of light converge to, and then pass through – or virtual images as places from which rays appear to diverge. For that, they must have plenty of personal experience with rays of light and lenses, and some examples of images, from the start.

So we provide for each pair of pupils a white table with a small lamp that shoots streaks of light out through the slits of a comb. We ask pupils to examine what those 'rays' do and what lenses and mirrors do with them. They see those 'ray streaks' meeting a lens and being bent to pass through an image; and they see in some detail how lenses and mirrors treat them. These are *not* the usual ray-box demonstrations, but a series of simplified class experiments with large glass cylindrical lenses made for the purpose. Then pupils can draw some simple diagrams – of real rays, not of construction lines – and go back to the instruments again.

These experiments should show pupils the following essential properties:

a. Rays travel straight out from an object point.

b. *All* rays from an object point pass through the image point.

c. Rays from a remote object point that pass through a lens proceed *straight to* a real image point after the lens, and continue *straight* on through that point.

d. Rays from an object point that pass through a lens which forms a virtual image emerge along lines that appear to come *straight from* the image point.

e. Every ray aimed at a central point in a lens (called the optical centre) passes straight through.

Statement (*b*) above is not quite true for real lenses. There are slight misbehaviours, which grow disproportionately worse for bigger apertures; and we have to learn to live with them and try to lessen them by skilful combinations.

Statement (*e*) needs modification for a thick lens; but we can reword it safely by saying 'emerges with the same direction', or 'passes through *undeviated*'.

These experiments provide enough knowledge of rays to enable pupils to understand what instruments do and even to sketch good optical diagrams.

Then pupils make more instruments: a telescope, this time with the final image to be placed at the observer's command; a magnifying glass; a microscope. After the real instruments, some more ray-streak models can illustrate them.

The Laws of Reflection and Refraction can appear later, as fundamental rules that both sum up and underline the behaviour of rays. We compare those laws with the behaviour of bullets and that of waves; and we embark on some discussion of theories. But, for pupils who will go no farther in physics, the main outcome should be a feeling that they understand some optical instruments – our eyes and the things that extend our vision. They should be able to use instruments intelligently, placing the final virtual image in a comfortable position.

Further Comments on Images

An image is not just a picture formed by chance arrival of patches of light. In terms of waves, all parts of the wave-front starting from a small source arrive in phase at the image. That requires all paths from object to image to take the same time. Put in mathematical form, that requires the optical path to be a *minimum* or *maximum* or at least stationary. In that last form we are back at an even more general rule than the Laws of Reflection and Refraction: a rule that contains those laws and the properties of images.

In another aspect, we might say the image is a region of maximum density of energy flow.

Images are respectable, fundamental components of optical knowledge. Image-forming is not just a practical application: it is in a way the essence of optics – it is what our eyes do and what we expect of the instruments we invent to aid our eyes.

Note on Aberrations seen with Ray Streaks

To pupils observing real streaks of light passing through real lenses these aberrations are obvious parts of natural behaviour. They see spherical aberration and find one way of lessening it; they twist their lens and see astigmatism; curvature of field is there, though they seldom notice it; and the few who discover distortion there see the reason for it.

These misbehaviours are not 'something going wrong with Nature'. They are failures to form a sharp image where we want it, which arise from two properties of Nature:

1. The Laws of Refraction, which rays of light 'obey' (subject to

diffraction), combine with the geometry of spherical surfaces to provide a sharp image of an object point *only if* the object point is near the axis of the lens and the aperture and the inclinations of surfaces are small. In *other* circumstances, the behaviour of the rays (obeying the Laws of Refraction) is as true to Nature as ever but does not provide the point image that we would like to have.

2. Light does have a wave behaviour, which guides the forming of patterns by the arrival of light energy, even though that energy arrives in compact photons. The wave behaviour makes bright patches, where light arrives, which extend outside any image predicted by ray theory. Thus, for example, a wide lens receiving rays from a point object on its axis fails to make a point image but crowds the rays through a 'circle of least confusion(!)' whose size is predicted roughly by ray theory, fully by wave theory.

NOTE TO TEACHERS: STROBOSCOPES AND MULTIFLASH PICTURES

We wish to provide some new devices to make it easy for pupils to measure and understand motion. One of these is a long, thin tape of paper, to be marked at regular time intervals by a hammer on a small vibrator. This 'tickertape' can be drawn through the vibrating marker by a moving pupil or a moving trolley, or even by a falling body. It provides an easy way of recording distances covered in short, equal, intervals of time, and we want pupils to use it for a variety of class experiments. Details of its use, and some practice drill in using it, are given in the *Guide* for Year III.

However, we need some other measurements of times and speeds. Pupils should be able to see that the vibrator marking their tickertape is vibrating regularly, marking constant intervals of time. And they may need to measure that interval – or the equivalent, the frequency of the vibrator. They need to measure speeds of moving objects which collide and recoil, where the tickertape would certainly get entangled. They should measure the wavelength of rapidly travelling water ripples. To meet these additional needs, we suggest two devices: a simple hand stroboscope that each pupil can operate for himself; and a form of photography that quickly yields pictures with several exposures, at equal time intervals, on the same print.

In the latter case a moving object appears in several places, and measurements of the distance between them gives us its velocity. Various schemes for taking those photographs, which we shall call 'multiflash' pictures, are discussed below.

We also suggest that the laboratory should make a device that shoots out a pulsed stream of water drops, 50 per second. That is described in the apparatus guide for Year III.

Stroboscope

This is intended for pupils to use in class experiments. There should be one for every pupil.

A crude form can be made from a piece of cardboard. A better one consists of a hardboard disc, 8–12 inches in diameter, with a dozen equally spaced slits cut in from its circumference. A piece of thick wood dowel serves as handle and as axle, and the disc is attached to it by a wood screw with safeguarding washers. A hole in the disc an inch or two out from the centre enables the operator to spin the disc. A massive disc is better than a light one because it spins more regularly. (But a disc to be run on a small electric motor should be a light cardboard one.)

The operator holds the disc in front of his face and spins it by hand. To observe events with a very low frequency, the operator covers up all but one of the slits. Then he sees the thing he is looking at only once in a revolution. With higher frequencies, more slits are brought into use.

At first, a pupil finds considerable difficulty in understanding how to interpret what he sees when there is more than one slit. So we should give pupils some simple drill, first with a single slit and then with two slits 180° apart, until they see that if they 'freeze' a motion with a two-slit disc, the frequency of the motion is twice the rotational frequency of the disc. Of course the frequency of the motion he is observing might be a multiple of that; and the observer has to decide that question by speeding up his stroboscope to higher and higher speeds to find if he can again freeze the motion – if he cannot he was looking at the direct frequency.

Pupils will use the stroboscope for looking at ripples, both to watch their progress more slowly and to freeze them for a measurement of wavelength. Also for examining the vibrator of their tickertape system. Before that, they should practise looking at a spinning bicycle wheel, to freeze the spokes, as in a cinema film. They may use it on a record-player; and some will want to work out the speed of the player from their own measurements. An interesting calibration can be made by looking at a fluorescent light, which does not glow steadily but gives pulses of light, 100 per second.

This simple stroboscope should become a friend that makes interesting measurements, a friend to take home and show to people. So we should not let the difficulties of multiple slits spoil the fun: a pupil who sees the use of the instrument and wants to extend the use will work out the slit story for himself. All the better if we do not try to hurry him or teach him too early.

Hints: 1. The word 'glimpse' is a useful one. 2. If pupils need to count several revolutions of the strobe disc and find they occur too quickly, or find it difficult to pay attention to them, a small flag of card stuck to the edge of the disc and arranged to hit another card once every revolution makes clicks that are easy to count.

Multiflash Pictures

In Year IV we shall need to take 'multiflash pictures', as described below. Where a school has the equipment for Year IV, we hope teachers will use it occasionally in Year III.

We need, for demonstrations, some way of recording precisely the position of a moving object at several instants of time on the same picture. Then if the instants are spaced at equal intervals in time, measurements of the picture will yield velocities. Even if we do not know the absolute scale of the measurements, the relative speeds will be almost as useful for our teaching. We expect to derive great benefits in teaching from any device that will take such multiple pictures, provided the pictures for use by pupils can be produced fairly quickly.

We would not suggest the use of any such device were it not for the enormous gain in teaching clarity and speed. The conservation of momentum, for example, is one of the most important fundamental principles of physics. In the past, few pupils have ever been able to see a convincing demonstration of it, or even a reliable test; but multiflash pictures and 'frictionless pucks' of one form or another afford an easy convincing test. We suggest that as an essential experiment in Year IV.

To take such multiflash photographs we shall *either* place a rotary shutter in front of a camera *or* illuminate the scene with a regularly flashing lamp. The latter can be a powerful steady source whose beam is interrupted by a rotating shutter or, as a luxury, a xenon lamp. Schools will find it easier to use the rotating shutter in front of the camera. That consists of a light disc with five or six slits cut in it, spun by a small electric motor. Small synchronous motors that are used for clocks do well.

An ordinary camera using 35 mm or 120 film is quite suitable – provided that it focuses down to 1 or 2 metres, has a lens with an aperture of *f* 8 or better and has a shutter with a 'B' setting. The detailed techniques of exposing and developing are explained in the *Guide to Experiments* for the Year.

The Polaroid camera is equally suitable, but is expensive and uses expensive materials.

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

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

Various CO_2 'pucks' have been tried: some use a supply of compressed air, others use evaporating to provide a 'gas bearing' of flowing gas under a massive moving disc. The Nuffield Physics Group have found a very good form that is easily provided with its gas supply: a ring magnet with an aluminium lid, under which one places a little solid carbon dioxide manufactured by letting some CO_2 out of a cylinder. The ring will coast along on a smooth table – better still on a plate of glass – with very little friction. It will make an elastic collision on approaching a similar ring; so, by taking multiflash pictures, we can measure the velocities and look for conservation of momentum – as a vector.

These ring pucks seem the simplest and most versatile. We do not advise schools to buy other, heavier forms.

Practically frictionless 'linear air tracks' are now becoming available. These are long straight beams pierced with many small holes from which streams of air emerge to provide a frictionless air-bearing for saddles that ride on the beam and demonstrate collisions, etc. They are fascinating marvels to watch and all who see them are tempted to buy one. However, they are expensive, they require careful adjustment and they are easily damaged, they give demonstrations in only one dimension. Also they usually require special devices for timing – so that the demonstrations look complicated to beginners. All those are minor objections compared with the major one, for our programme: that such a device provides for more *demonstrations*, when we want to emphasize *class* experiments. (A number of us who have bought them find that our initial delight wanes when we use them for elementary teaching – and we are tempted to return to simpler machinery. Linear air tracks should come to their own in demonstrations in colleges, where the adult audience of people interested in teaching dynamics will indeed gain much). (The newest design, an air table, is tempting, but it makes an even louder hissing noise as air escapes from its many tiny holes.)

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

Chapter 1

WAVES

Wave Behaviour with Models, Ripple Tanks and Stroboscopes

PROGRAMME

This Year begins with a study of waves, using individual ripple tanks for class experiments; and a study of optics – chiefly optical instruments – with another long series of class experiments.

After that we deal with motion. There is general experimenting and informal discussion concerning distance, time, speed, acceleration, motion of projectiles and satellites – preparing for a more formal study of Newton's Laws in Year IV.

Then the study of motion extends into a discussion of kinetic theory of gases, renewed from Year I. Since momentum and kinetic energy have not yet been established in quantitative forms, our general treatment of kinetic theory must wait till Year IV, but we can suggest a dynamical concept of temperature. We look at gas behaviour, with demonstrations of Boyle's law and the effects of temperature-change on pressure and volume of a gas, leading to the use of a gas thermometer and an absolute scale of temperature.

We use the electromagnetic kit for class experiments with magnetic fields, motor and electromagnetic induction. We also suggest a few experiments in electrostatics.

The First Class

The actual start of this Year may raise a difficulty, because both the ripple tank and the pinhole camera (with which one might begin the Year as an alternative) are experiments which extend over a considerable time and are done rather informally in a half-dark room. A teacher may feel that either of these offers a difficult beginning for the first week of the year! In that case it may be wise to start with a single period of demonstrations of *things that lie ahead* – somewhat like giving tourists a pamphlet of travel pictures before they visit a foreign country. We might show two or three of the following:

A big demonstration wave model. D 0a

A large lens producing an inverted image of a pupil's head 'in full colour' (C 10d). D 0b

A shadow picture of water drops from a pulsed water-jet, shown stroboscopically, as a demonstration of projectile motion. See D 67a. (For this first glimpse, the stream is probably best shown with a black background. It can be illuminated by intermittent light from the motor-driven stroboscope or, without any instructions, pupils can be given hand stroboscopes with which to look at D 0c the stream. For our later demonstration, it will be necessary to cast a shadow of the stream on a white screen, using stroboscopic illumination.)

Demonstration of a commercial electric motor in series with an D 0d
ammeter; the teacher, with a gloved hand, holds the armature.

Demonstration of a model of gas molecules in motion (if not shown D 0e
before).

Demonstration of a demountable transformer (if available), sup- D 0f
plied by mains a.c. on its primary, with a home-made secondary of
insulated flexible wire wound on by the teacher turn after turn
until it develops sufficient voltage to light a toy lamp.

Class Experiment with Waves

Let pupils send a transverse wave along a rope. (Show them how to C 1a
start a single pulse by holding the end of the rope in one hand,
jerking that end up and quickly down to a stop on the wrist of the
other hand. Do not ask them to look for reflection – just hope that
they will see it. A massive, loose rope is needed. Clothes-line is too
stiff. String is far too thin.)

Some pupils will manufacture 'stationary waves'. This will be useful later, though it is a nuisance here, so we should not discourage it. If they do make a stationary wave pattern, we should point out that the pattern is not travelling.

(There is a trick to produce stationary waves easily: stretch the *
rope and hold both ends fixed; put marks on it at, say, $\frac{1}{5}$ length *
from the end, $\frac{2}{5}$, $\frac{3}{5}$, $\frac{4}{5}$. Hold the rope loosely at one of these nodal *
marks and shake it at the right frequency. This is good physics *
because it drives the system at a node. Driving it at one end in the *
usual way makes it difficult for a node to form there.) *

If there is a 'slinky', the teacher can demonstrate various kinds of D 1b
waves with it. However, the longitudinal waves travel very fast; so
it would be good to show a slower wave model as well.

If the laboratory already possesses a wave model (such as a D 1c
machine for demonstrating the motion of particles in various forms OPT
of wave, or an apparatus of rods and springs which demonstrates
torsional waves) it may well be shown at this point; but we should
not take long to construct or discuss special models. We do not
advise schools to buy such a model.

With pupils in a line, each with one hand on the shoulder of the next, make transverse and longitudinal waves travel down the line. Here is an opportunity for suggesting that 'energy' passes along the line. Pupils are familiar with the word as applied to their own efforts. D2 OPT

This introduction to waves should be given just enough time to suggest the idea of a pattern-of-disturbance that travels. We should proceed to the ripple tank practically at once. At this stage, we should not give definitions or a formula; and we need not explain that waves carry momentum and energy. (For that matter, some waves do not transport any energy.) * * * * * *

The ripple tank will show the patterns of waves as we look down on a water surface. Before pupils embark on that as an 'open' class experiment, we should show them water waves *in section*. For that we fill a long tank of glass or Perspex with water and send waves along the surface with a small paddle or a block of wood moved up and down. Pupils view these waves in section through the side of the tank. The longer the tank the better for this; but it need not be wide. D3

When waves travel along the surface of water the actual motion of an individual particle near the surface is circular, and particles deeper down move in an ellipse. One may be able to observe this by watching the motion of sawdust in the water of a wave tank; but for most observers the motion is too fast. We can make much slower waves in the interface between two liquids if we fill the tank one-third full of water and one-third full of paraffin on top of that. If the paraffin is coloured, all the better. When the liquids have settled, with a clear smooth interface between them, we generate waves by moving a block of wood up and down, fairly close to one end. The block should be submerged, in the region of the interface, and held by a stick from above so that moving it does not make waves in the top air-oil surface. Cleaning the tank after this oil-and-water experiment is troublesome; but the demonstration does show waves in much slower motion, and teachers who have tried it consider it worth the trouble.

RIPPLE TANK

General Comments. This is a series of experiments whose running may well be easier for teachers who have never used a ripple tank for demonstrations in teaching. Those of us who have used carefully constructed ripple tanks for advanced teaching regard them as an important demonstration that requires careful C4 adjustment and can then be shown in quite a short time. The ripple tanks that we suggest for use in this programme are larger and simpler, and intended for a different use. A simple ripple tank offers pupils a chance to find out a lot about a natural phenomenon – wave behaviour – by their own experimenting.

Young pupils experimenting take a long time to 'get going'; and when they are experimenting in a new strange field – as this is, for them – they take still longer. To a teacher experienced in using ripple tanks with older pupils the delay and the lack of definite results will seem worrying and disappointing the first time he tries this with a class of young pupils. This is the time for patience, verging on an attitude of mute agnosticism coupled with encouraging hope. One can prepare oneself for that by playing with the simple ripple tank oneself, trying out everything one can think of, some time before using it in class. As with other class experiments in our programme, this is a case where one cannot judge the full value of the experiment, or the time it needs and deserves, until the second round – teaching again to a new class a year later. When one has tried it one year and found out how long it takes and seen the experimenters' delight and growth of knowledge, it becomes easier to run the next year. One will be ready to be patient with questions and to praise the results – and emphasize some results that will be useful later.

In any case those who have used this apparatus assure us that if young pupils are given plenty of time and encouraged to experiment informally – the teacher giving neither detailed instructions nor suggestions of what to look for – the yield is rich. Judging from preliminary trials, we suggest that the series of experiments with ripple tanks should take at least three weeks but not more than five.

A Strong Plea to Teachers. At some stage when pupils are working with ripple tanks, many a teacher feels disappointed with the resulting knowledge of wave behaviour that the pupils extract. He longs to give the pupils clear conclusions; and we hope he will not do so, because this is principally an experiment in which pupils learn about experimenting and gain a picture of good scientific work by doing the experiments on their own. But there is a still more serious temptation: to show films of ripple tank experiments which reveal perfect behaviour and suggest the results that the pupils should have obtained. That would indeed be disastrous treatment for young people who thought they were doing their own experiments as 'scientists for the day'. Extremely good films of ripple tank phenomena can be obtained from several sources;

but we must urge teachers not to show them, during the series of ripple tank experiments or at the end. With some groups it may be necessary to use one or two films for 'revision' in Year IV or Year V, when we find that ripple tank experiments have left too little memory of, say, interference. Even then, it is far better to get out the real tank.

Comment from P.S.S.C. It may be of interest to see the following commentary from a group of teachers working with older pupils of 16+:

> 'The work in this chapter has proved to be among the most exciting in the course. Very few students will begin it with any real familiarity with the ideas presented, despite years of casual observations with water waves. Here is a real opportunity to drive home some of the aspects of "the scientific method". Experience of quantitative and careful observation of wave motion – isolating events, correlating phenomena, generalizing results – can teach these students more science than hundreds of pages in books. You will need to be generous with ... time.
>
> *Extract from P.S.S.C. Teacher's Resource Book and Guide. That advice refers to older pupils. We should not expect such sophisticated outcomes with our pupils in Year III. The writers put quotation marks round their reference to the scientific method as a tongue-in-the-cheek hint that most scientists do not believe there is one single scientific method.*

Arrangements for Class Experiment. Any number of students could watch one ripple tank as a demonstration; but here we want pupils to work with their own ripple tank, make their own waves, and watch what happens. So, the teacher should not even have a demonstration copy of the tank to start the experiment except for a very weak group. He should keep his own ripple tank behind the scenes. Just observing ripples made by someone else is not as good as making them oneself and observing one's own ripples. Therefore, there should be one ripple tank for every three pupils or *at most* four.

If there is a choice between viewing the ripples on a ceiling or on a table or floor, one should remember that looking upward to a ceiling is much more tiring; bending one's head back has to be supplemented by rolling one's eyes upward, and that puts one's optical skill at a disadvantage.

Show pupils how to set up the ripple tank, with the legs firmly C4
attached so that the vibrations do not disturb the water. Show how to attach the lamp so that it throws a 'picture' of the tank and ripples on a sheet of white paper on the floor.

If it is possible to store the ripple tanks from one class period to the next without taking them to pieces, that would be an enormous advantage. If that is not possible, it may be necessary to arrange some simple drill for getting the tanks quickly set up and put away – experimenting with that is not intended to take time as part of an 'open' experiment.

Use of Ripple Tank in Class

A Series of Class Experiments. This experiment, C 4, extends through a long series of experiments with the ripple tank. We hope pupils will proceed through these at their own pace – without making notes at this stage but just watching and learning. Pupils will run through these experiments at different speeds and a fast pupil in a class may get far ahead of others. Therefore we suggest some experiments should be treated as 'buffer-experiments', options for faster pupils. Some of those options will appeal to other pupils with special interests; and unless they involve major changes of apparatus, any who wish to try them should be free to do so – as long as that does not make them fall far behind the rest. In any case, a slower pupil who has not reached the end of the series when the rest of the class are ready to proceed to other experiments will not suffer greatly. We should remember that the object of these experiments is not so much to provide a store of knowledge of wave behaviour, as to give pupils experience of working on their own at their own experiments, making their own mistakes, choosing and enjoying their own observations. C4

All the experiments in this series use the ripple tank. Pupils should soon be able to get out their tank and get it going quickly; and of course they must be ready to put it away (and mop up water that has spilled) at the end of the period. With cooperation from pupils in this 'housekeeping' aspect of these experiments, the ripple tank series will form a very valuable part of their experience in physics.

Some of these experiments need pieces of equipment that are not needed for other ripple tank experiments: for example, a rubber tube to be bent to a rough parabola, or barriers to limit a wave to a gateway. Teachers may wish to withhold these extra pieces until they are needed. Better still, they should be placed on a 'cafeteria' table from which pupils can take them when they need them. That will help the 'housekeeping organization' and save time.

Open Beginning. Begin by telling pupils to fill the tank with water to a depth of 1 centimetre (about 1 litre), and try anything C4a they like. In order to get the experiment going quickly, the teacher should provide a large tin can or some other 'dipper' which holds the right amount of water. Then the ripple tanks can be filled quickly.

Circular Pulses. After a few minutes, suggest making an isolated ripple or pulse with the tip of a clean finger: then with a drop of water from an eye-dropper. Ask: C4b

> 'What is the shape of the pulse as it travels out? Does it have the same speed in all directions? Does it keep the same speed as it goes farther and farther? Is the water moving along with the pattern? How could you find out whether the water itself is moving?'

Note that in asking questions – an activity that may help discipline in the half-dark room – we are not breaking our resolve to avoid detailed instructions. We are merely encouraging pupils to think and extend their observations. (If pupils answer the last question by suggesting lycopodium spores, praise them for remembering that 'waterproof powder' from another use in Year I.) * * * * * *

Straight Pulses. Provide a cylindrical rod (wood dowel or glass tube) to make straight-wave-front pulses. Give a hint of the technique: 'roll the rod through a fraction of a revolution in the water, using a hand placed flat on the top of it'. Pupils should find out how to make clearer pulses by choosing a suitable motion. C4c

Reflection of a Pulse. The teacher should then offer reflecting barriers: straight pieces of wood and then a piece of rubber tubing that can be bent into something like a parabola. C4d, e

We should not suggest either the form of a law of reflection or the idea of looking for one. * *

Idea of Rays as Guide-Lines. On the other hand, we should presently suggest the idea of 'rays' as guide-lines that show the directions in which waves travel. This introduction to rays will be very valuable when we try to link up the behaviour of light with the behaviour of water ripples. T

Both teachers and pupils may feel that rays are an unnecessary concept in dealing with ripples and ripple tanks; but we urge teachers to start sketching rays at an early stage, when pupils are looking at the way in which ripples (wave fronts) travel.§ In our optical teaching, we shall make much use of rays, *not* as construction lines but as the lines of travel along which light comes to our eye from an object point or an image point, and therefore as *lines that pass through images*. That will be the basis of our description of images; and images will be our essential concept in dealing with the behaviour of optical instruments. So an early mention of rays will be helpful.

Ripple Tank with Vibrator: Continuous Waves. The teacher should show pupils how to connect up the vibrator that acts as a continuous-wave generator, both for circular waves and for straight line waves. After that comes a time to leave pupils to play with the tank and find out things for themselves. C4f

Stroboscope. Then the teacher should provide hand stroboscopes, *one for every pupil.* If this instrument has not been used before it will need a careful introduction and some teaching; yet this is a good natural place to introduce it, because its success in 'freezing' periodic waves is so startling and satisfying. (For suggestions of practice with the stroboscope, see the separate Note on stroboscopes at the end of the preface.) C5

We describe the use of stroboscopes in considerable detail – and give many suggestions for teaching them in the *Guide to Experiments* – because these are unfamiliar instruments to many teachers as well as pupils. Our emphasis in giving such details should not be taken to mean that we suggest the teaching should emphasize stroboscopes. They are only useful gadgets which will make the teaching easy and quick. Teachers are urged to make use of them but not to let them bulk large or present difficulties to slower groups.§§

Continuous Waves and Stroboscope. Pupils will find that continuous ripples are much easier to see when they use a stroboscope. C4g

Estimate of Wavelength. When pupils have learnt to 'freeze' their wave pattern, we can ask: 'Is there an interesting measurement that you could now make?' In other words, we try to elicit the idea of measuring wavelengths. We do not supply an immediate

§ 'We used two pencils on the white paper for "incident" and reflected waves. This eventually persuaded the weaker form to volunteer "rays".'

§§ A teacher in trials commented: 'Many boys have made their own stroboscopes at home.' 'As a preliminary to the suggested approach, I showed them the "trolley vibrator" under stroboscopic illumination. This got them very interested.'

answer, 'measure the wavelength', but wait for suggestions. If we leave the question to brew some children will have the answer by the next day, and it is worth waiting for. In many a class this measurement can well wait till later (C 40).

Different Frequencies: Different Wavelengths. Pupils can C4h
measure the wavelengths both for circular ripples and for straight-line ripples. They can change the frequency by changing the adjustment of the vibrator. That leads to a complicated story, because in the case of water ripples the speed is not the same for all waves but is a function of the wavelength (and of the depth of water). However, pupils should see ripples of different wavelengths; and we hope they will connect the difference with frequency.

Image formed by Reflecting Wall

Straight Reflector. Returning to reflection, we can now ask T
questions:

1. 'When a circular ripple (pulse) is bounced back by that straight wall, where does the returning wave *seem to come from*?'

That is a leading question that will help us in discussing images in C4i
optics. Some pupils will at once say the reflected ripple comes from the wall itself. If so, we must explain that though the ripple is sent back by the wall itself we are asking where the centre of the new ripple is. And if pupils say that the centre is at the wall we must ask what a ripple starting from there would look like. In any case, appeal to experiment again at once; let pupils try it with the ripple tank. When they guess the position of the 'place the reflected ripple seems to come from', ask them to try making a ripple that starts from there, simultaneously with starting the original ripple. This gives a strange effect of the two ripples seeming to pass right through the barrier.

The pupils should use a finger of one hand to start the original ripple and a finger of the other hand to start a ripple at 'the place the reflected ripple seems to come from'. Using two hands like that does not make the experiment easier, but it should make the idea of the experiment clearer. The experiment is easier if the pupil marks the position of the *image* – a name that we should not give at this point – with a small coin placed there in the ripple tank.

2. 'Can you see any simple story about the direction of straight waves before and after meeting a flat wall?' C4j

We should guide pupils into setting the wall obliquely at various angles. It is important to warn pupils that they should avoid placing the wall at 45°. At that angle, the pattern is ambiguous. (This is rather like the suggestion we make in geometry that pupils who are trying to prove something for *any triangle* should not draw their specimen triangle an *equilateral* one.)

We do not mind if this fails to elicit a law of reflection – that can so easily and quickly come later. In fact we are not going to make great use of that law, but pupils should know of it.

Curved Reflectors. Next ask the question:

3. 'What happens to straight line waves when they hit that parabolic‡ reflecting wall? Can you turn that story backwards and make straight-line waves come out from the wall?' C4k

4. Pupils should try reflections by a circular barrier, particularly the amusing case of the ripple that starts at the centre of the circular arc. C4*l*

5. *Optional.* It is well worth while to provide one elliptical reflector for pupils to borrow and try or for the teacher to use for a demonstration. This needs to be made very carefully from an accurate drawing of an ellipse. The wavelength of the ripples is small, and accidental irregularities in the ellipse will spoil the great beauty of the simple story. The ellipse can be made of thin brass strip bent to fit the drawn curve and joined with a butt joint and a strap outside it. The strip must be free from irregularities due to earlier bending. Or we can use a sheet of plywood with an elliptical hole cut in it; but it is very important to have this hole cut to an accurate ellipse.‡‡ C4m OPT

‡ Some pupils know what a parabola looks like. Those who do not should throw a ball in the air and watch its path.

‡‡ Rough bending of metal strip or quick sawing of a wooden template will produce an 'ellipse' that looks good enough; but this wave demonstration will be a poor failure.

If the ripple is started from a point which is not one focus of the ellipse the reflected ripple will have an odd shape and it will not converge to an image point at the other focus or anywhere else. Therefore it is important to locate the focus accurately and start circular ripples from there with a finger or a pencil or a medicine dropper. Perhaps the easiest way of locating the focus is 'trial by ripples'. Once it is located the ellipse should be marked with notches or wires so that the focus can always be located easily. And, in the tank, the focus should be marked by a small coin placed there. This is just an experiment to see for delight; but it will repay the trouble of making a good ellipse. A suitable size would be: long axis about three-quarters of the length of the ripple tank, short axis about half.§

Problems for Pupils. We might ask very able pupils a difficult question that uses an ellipse as a *source* instead of as reflector: P

1. Suppose you took a metal ring, a circle two feet in diameter, and dipped it suddenly in and out of the water of a lake. That would start a pulse. When the wave has travelled out for a hundred feet what would its shape be? (*Answer:* a circle of radius 101 feet.)

2. Now suppose you made a pulse by dipping an ellipse quickly in and out of the lake, with long axis four feet and short axis two feet. When that wave has travelled out about 100 feet what would it look like? (*Answer:* almost a circle; its radius would range from 102 feet to 101 feet.)

Ripple Tank Experiments. All these class experiments with ripples will take a far longer time than one would expect; and the longer the time the more the pupils will gain in useful understanding. The first period with the ripple tank may well seem completely wasted, with messing about, dabbling in water, looking at patterns and getting nowhere. Neither teacher nor children should be discouraged by that. In subsequent class periods, children will develop both skill and knowledge. Later, when we have studied properties of light, we shall refer back to a ripple tank and may set it up and look for some properties again. * * * * * * * * * *

§ 'With the ellipse I was asked to start ripples at both "foci" at once. There was then an argument. Did the ripples pass through each other, or were they reflected in the middle? I had the good suggestion from one boy to start one ripple before the other. This then convinced everybody that waves passed through each other and I felt that everybody felt a sense of achievement and common purpose. I felt they needed to be brought together after working on their own for six weeks, and I think they appreciated this.'

Interference and Diffraction. This is not yet the time to show or teach interference thoroughly. We suggest a first look now, without much prompting and certainly without a careful teaching of 'results'. (With a slow group this may be postponed, at some risk of the delay piling up to a disappointing block in Year V.) * * * * *

Suggest to pupils the idea of making two pulses – each made with a finger. Ask: C4n

'What happens when one ripple crosses another? Do they upset each other? Do they each come out from the encounter the worse for wear?'

Young's Fringes with Ripples. Then we should see whether we can suggest looking for interference. It would be better to have the first glimpse of interference arise by accident when pupils make ripples with two fingers than to have it as a directed experiment. We can ask hopefully: C4o

'Can you see any strange patterns?

'Now try making two streams of waves, using two fingers of one hand as a "double source".

'Try that, if you like with two vibrators or‡ by driving two sources with one vibrator. Try using the stroboscope. Also try blinking your eyes. C4p

[As a different question:] 'Suppose you wanted to get two lots of waves, and only have the straight-line-wave-generator?' C4q

Diffraction. Failing with that last question we can try another tack:

'Have you tried letting waves go through a narrow gate? You can use pieces of wood waterproofed with wax as barriers or harbour quays.' C4r

‡ Driving a double source with one vibrator is, of course, the easiest way of producing the two sets of ripples. With two separate vibrators, a considerable amount of adjustment is needed. The only advantage of the latter is that it emphasizes the idea of two streams.

We welcome interest in diffraction; but we say nothing much about it at this stage, and certainly do not refer it forward to diffraction of light. At most we say: C4s

> 'Waves seem to do that. Have you tried still narrower harbour entrances?'

If such suggestions fail, we should postpone diffraction; but we should encourage some form of trial with two sources. We should *not* give a demonstration of interference fringes with our own tank. That would indeed spoil the great value of this ripple tank as a medium for pupils to do their own experimenting and arrive at knowledge which they feel they possess personally. Yet we should encourage them, by direct suggestion if necessary, to look for an interference pattern when two sources a few wavelengths apart run in phase and generate ripples.§ C4o,p

Teaching Interference. Interference, of great importance in modern physics, will be taken up – with the ripple tank again – at a later time. We shall suggest a device (two slabs of Perspex engraved with a wave pattern) to help this teaching. D35a

We should do well to avoid the misleading name 'interference' at this stage. It is a most unfortunate choice for a descriptive word in science. The principle of interference states that waves do not interfere with each other‡ but can cross each other unharmed and as they are crossing simply give the sum of their two separate effects. If those effects are both in the same direction the sum is large, but if they are in opposite directions the sum may be small or even zero – which is what we sometimes call 'destructive interference'. We should certainly avoid that term at present. We should simply point out that the two sets of ripples seem to add up in some parts of the pattern and cancel out in other parts. A useful description is: T

> 'Here one ripple arrives as a signal that makes the water go up and down flip-flap, flip-flap ...; and the other ripple arrives also making the water go up and down flip-flap. ... The two wave-signals add up to FLIP-FLAP, FLIP-FLAP. ... But here, where the wave from that source has travelled a little farther than the wave

§ 'The weak form got very good interference fringes; they talked of "cancelling out".'

‡ This statement relates to *linear* systems within the Hooke's-Law range. Outside that, with non-linear behaviour – so important nowadays – waves *do* interact (see Note on Interaction in General Introduction).

from this source, the two do not arrive in step. One of them makes the water go up and down flip-flap, flip-flap ... and the other makes the water go ...?'

We get from pupils the obvious answer 'flap-flip, flap-flip' and ask what one would expect when those two motions act together. We leave things at that stage, simply saying:

'This is a thing that waves can do; they can add up to a big effect or they can add up to nothing at all. Waves can do that. In fact waves always produce patterns of that kind, with bands of big effect and bands of small effect. But the other things that often travel along, cricket balls, raindrops, bullets – any pieces of matter flying along – would find it very difficult to make a pattern like this.‡

'You could hardly expect, if two machine-guns are firing bullets out towards a distant target, to find some places where bullets + bullets make more bullets and other places where bullets + bullets make no bullets!'

Diffraction. Most pupils will have acquired some knowledge of diffraction, by playing with barriers to make various gateways. If some seem to have missed such observations completely, we should suggest some experiments to try. C4r, s

Scattering. Pupils should also try putting a very small obstacle in the tank, to see what it does to the waves. With straight-line waves, some pupils will see the circular scattered waves, and others will miss them altogether. This is just a thing to have seen, for those who do see it. C4r, s

Pupils will have seen reflection and probably understand the equal- *
angle law, even if they do not formulate it. And they will have *
gained a familiarity, though possibly an unconscious one, with *
diffraction. We should persuade them to see interference as in *
Young's fringes and discuss it. *

‡ Private note to teachers: This last remark is a horrible piece of sophistry to evade the criticism that in modern physics we now know that a cricket ball or raindrop is associated with a wave that 'directs its progress', just as an electron is. Of course the wavelength for a big object is so short that we do not expect ever to have the slightest chance of observing any effect of diffraction or interference.

Refraction is much more difficult to see – that is why we have left it till now – and the teacher should give pupils considerable help in that.

'Try making some ripples travel from deep water into a much shallower region. You can make a shallower region by putting a sheet of glass in your tank, try that: freeze the ripples with your stroboscope, and look for anything interesting. You may see something more easily if you do not quite freeze the motion but let it appear to run slowly.'

Refraction is so important for the arguments of theory which we shall discuss with faster pupils that we should try to make it clearly visible. This will need very careful cleaning and levelling of the ripple tank. The water must be *very* shallow, and the vibrator should be set to a low frequency.

Some pupils will notice a shorter wavelength in shallower water; some will notice a change of speed at the boundary: but these are difficult things to see, and the teacher may have to go round from one ripple tank to the next asking questions and giving hints. Again, this is not a matter for a clear demonstration experiment given by the teacher: magnificent though that can be, it would spoil the progress of the present class experiment.

We need not press hard for refraction to emerge from these observations. Pupils can return to it when they want to know about waves meeting a boundary between regions where they travel with different speeds. Getting the ripple tank out all over again, a month or more later, may seem a lot of trouble; but, if we try it, we find it is, as Baedeker says, 'very rewarding'. * * * * * *

It is far too difficult to make any measurements that hint at Snell's law with ripples. Even if we could do that, we should not spend time proceeding to a difficult law at this stage.‡ * * *

‡ In comparing the Optics in this programme with the Optics of Part Two of the P.S.S.C. programme we should remember that Snell's law was specially chosen by the original Physical Science Study Committee in America to be used as a very good example of a physical law. That was an interesting choice and probably a wise one for pupils of age 16+. Although our younger pupils can use sines – or at least can handle the graphical equivalent – we think this law would seem too difficult to impress them as a surprising and magnificent clarification of natural behaviour. In Snell's own day, it was a welcome discovery: the time was more than ripe: physics was waiting for it to replace some unsatisfactory approximations. But the time is not ripe in the state of knowledge of our pupils; they are not yet desperate for a rule to catalogue the progress of rays of light through optical systems.

Films of Ripple Tank Phenomena: a Warning. There are good four-minute films that show clearly just what we want pupils to find for themselves. Even if shown after the real experiments, for 'revision', these films will undo the result we hope for and spoil the spirit of learning (some of physics) by investigation. So we advise very strongly against using them. *

Wavelength, Frequency, Speed: and $v=nL$. Our pupils are older than the explorers of Years I and II and we should expect them to develop ideas of physical quantities to be measured. Then they will meet the interesting business of relationships between physical quantities, as matters for experiment and speculation. In this Year, 'force' should no longer evoke the qualitative feeling of a push or a pull: that should be accompanied by a request for a number, the reading of a spring balance, or the number of standard pulling threads in parallel, or anything else that gives satisfying sense of a definite measure. Here, faster pupils should try making measurements of ripples. And we should lead them to the relation $v = nL$. *

If pupils are to measure wavelengths, frequency, and speed for a train of waves, they will find speed the hardest to measure; because they must follow a chosen crest as it moves – they cannot use the stroboscope there. So we must make the speed as small as possible; and that means making the frequency as low as possible. The motor must be adjusted to run at its slowest. Of course that will also make the frequency easier to measure.

Wavelength. In this first study of waves, wavelength – which the stroboscope makes obvious – should be measured. Pupils will not ask 'what for?' They are now at the stage of exploring the world when it seems quite sensible to 'measure everything you can think of'. C4h T

Frequency. We may have to suggest the idea of frequency directly: T

> 'How often does the vibrator hit the water? How many complete ripples does it *send out* every second, every hour? We have a name for that; we call it the "frequency" of the vibrator. That is the number of complete vibrations (cycles) the vibrator makes per second. It is therefore the number of complete ripples that come out per second from the vibrator. Suppose the frequency is twenty – that means twenty ripples per second. Does the vibrator itself have a frequency?'

Pupils should measure the vibrator frequency (or the frequency at which ripples emerge from it). C4u

$v = nL$. The clever experimenter might arrive at this relationship by measuring speed, frequency and wavelength. It would be a remarkable piece of experimenting and it is doubly difficult since that bright young investigator would not know what he was looking for. We shall have to suggest and discuss the relationship. We may be able to check it roughly by experiment; but this is really a case where geometry and argument are not out of place. We say:

'Suppose a man marching along takes 70 strides a minute, each stride 2 ft long. How far does he go in a minute? ... Yes, 140 feet. T
His speed = 70 [strides per min] × [2 ft stride] = 140 ft/min.
Suppose the man takes n strides per minute, each of length L feet. Then he travels nL feet in a minute.
His speed = [no. of strides per min] × [stride] or $v = nL$.

'Now think of waves. When a train of waves has travelled one wavelength along, it shows the same pattern exactly. One wavelength is one "stride". If the vibrator turns out n whole wavelengths per second (frequency n oscillations/second) the wave speed is given by

speed = [no. of wavelengths turned out per sec] × [wavelength]

$v = nL$.'

We should not drive home the result by asking for it to be written down in formal fashion and learnt by heart, or by giving a long series of examples on it. At this stage we merely mention it as a case of a relationship between some measurable things. And we say that there are many things in physics like that which are interesting and useful parts of our knowledge. * * * * * *

Some pupils may raise questions about wireless waves: do the BBC statements of wavelength refer to the same thing as our wavelength here? Does the BBC tell us frequencies? What are kilocycles, megacycles? Having answered these questions, we can use data from the BBC to calculate the speed of wireless waves. Of course we must not use this as a scientific way of discovering the speed of electromagnetic waves. We must make it quite clear that we are only working out a number to tell us what the BBC thinks is the speed of its waves. T

The Progress of a Ripple: Group Velocity (*optional advanced extension*). Some pupils may point out that when they start an isolated 'ripple' it seems to have a structure of a few wavelengths in it, and it travels out in a curious way, with the markings of those individual waves *travelling through* the whole pulse – so that the waves *inside* travel at a different speed from that of the overall pulse. We should say: T

> 'Yes, that is so for water waves, your ripple is a small group of waves, and it travels out as a whole with what we call "group velocity". That is a speed you measure if you use a ruler and stop-watch or take a couple of flash camera photographs. The wave-markings inside the group travel with a speed that we call the "wave velocity" or, more correctly, the "phase velocity". For many kinds of waves (waves on a rope, waves of light, wireless waves, waves of sound) the group speed and the phase speed are the same. But for water waves they are different (and for light waves in other media than a vacuum they are different).'

To a very able pupil, we might even say:

> 'Nowadays we believe that moving electrons have a wave belonging with them. The group of waves represents the electron itself in some ways, and travels with a group velocity which is the electron's speed that we can measure. The component waves in the group travel faster, so in a strange way one might imagine them going ahead to arrange where the electron is to arrive. That is a strange story about electrons but that is what we find from experiments. We now find it holds for other moving bullets such as atoms. We suppose there is even a wavy nature attached to a moving cricket ball – but, for that, the wavelength would be so small that we should never notice any wavy effects.'

Programme

We now leave the ripple tank for a series of class experiments to study rays of light and optical instruments. We shall bring ripple tanks back into use if we need them for comparison with the behaviour of light. We shall certainly bring them back when pupils measure light waves by Young's fringes. * * * * *

Teachers who have tried this programme often say they plan to change the order in a 'second round' of teaching this year's material and bring in some optics of rays and instruments before the whole series of ripple tank experiments is finished. Teachers trying this programme for the first time will probably find it easier to go right through ripple tanks first; but they should keep in mind the possibility of changing the order in a later round. * * * * * * *

Chapter 2

OPTICS

Images and Rays, Instruments

INTRODUCTORY DEMONSTRATIONS BEFORE BEGINNING OPTICS

As an introduction, give a few demonstrations of light rays:

a. Show light from a bright, compact small source splashing out along a white wall: an obstacle casting a shadow with sharp edges. D 6a

b. Screen with a slit lets through a single 'ray' that proceeds along a straight line. D 6b

These are meant to be simple, quick demonstrations to whet pupils' appetites. They should *not* be done with a special 'ray box' or other elaborate apparatus. Above all there should be no lenses.

c. Show a rectangular glass (or Perspex) tank of water containing fluorescein – or a little milk to scatter light – with a narrow beam of light, a 'ray', visibly following a straight line in water. At this preliminary stage, avoid showing reflection or refraction at boundaries. D 6c

d. If that is shown it is well worth the trouble to repeat the demonstration a week later with a carefully arranged tank of water and brine. Strong brine is gently introduced‡ under the water in a half-filled tank, and the boundary allowed to smooth out a little by diffusion or judicious stirring. Then a 'ray' from a bright compact source is directed, almost horizontally, through the region of variable refractive index. With care we can show a visibly curved 'ray' to observers in front of the tank. To an observer at the end looking along the 'ray', it is still straight. D 6d

e. Show a 'ray' on the white wall being reflected. We look at a few angles and ask pupils if they can see a connecting rule. (We do *not* announce a rule – and even if pupils tell us one, we do not reword it in formal style – we are in a hurry to get on with class experiments.) D 6e

‡ There is no need to make a special device for inserting the brine. Attach one foot of rubber tubing to an ordinary funnel and fit a screw clamp to control the flow. Hold the funnel so that the tube reaches the bottom of the tank and pour in the brine. Gravity will serve to maintain discipline and, anyway, we want some mixing.

f. We throw a rubber ball against a hard, massive wall and ask if it follows the same 'angle rule'. We ask whether light may perhaps be a stream of elastic bullets, from the lamp or from the scattering material, to our eye. We point out, however, that waves are also reflected like that. D 6f

At this point we do not make any decision between these two speculative ideas about light; we do not even discuss the evidence. We just point out that they are both of them speculation, and we say we wonder whether we could ever decide between them. Also, we wonder what use such ideas will be to us. T

We now proceed to several series of class experiments. Since these follow a rather different approach from the usual one, we include some comments on that treatment in the section below; a fuller discussion of our reasons for it is given in a Note at the end of the preface for this Year. * * * * *

Note to Teachers on Optics and Optical Instruments

The treatment we suggest differs considerably from the usual one, in which the reflection and refraction of rays of light are first studied and codified in clear laws, those laws are used to predict or explain the behaviour of mirrors and lenses, and then, after measurements of focal lengths and object-image relationships, optical instruments are discussed. That procedure works well as a logical training, but here we are thinking of people who will carry only a general memory of optics into later life; and we want them to consider that optics makes sense, as a science that deals with telescopes and spectacles and eyes and other instruments.‡ * * * * * * * * * *

‡ To encourage home trials by pupils as an important educational experiment a small private fund is available to underwrite the possible loss or damage of apparatus while on loan. We hope teachers will sometimes allow equipment to go home for an evening or a weekend. 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 the best ambassador.

During this year we hope that the simple telescopes will be taken home by pupils who wish to show them, and even the full equipment for ray streaks. That would have to include the transformer and lamp, but though heavy, they are not likely to suffer much damage. The lenses need care so obviously that they are likely to be treated very well on loan. Westminster Electromagnetic kit provides excellent material for some experiments at home. Some of the simpler components can probably be replaced by things made at home or bought by pupils; but the magnets will be essential for success with the little motor. We hope that teachers will let the magnets go home on loan despite their reputation for disappearing. (*Contd*. at foot of p. 144)

We make a strong plea that pupils should understand how a camera works, e.g., know why a cheap camera is likely to give great depth of field; understand what spectacles do for people; and know how to focus simple optical instruments such as a telescope. Then we add a taste of theory by discussing rival theories. If that is their picture of optics, it is likely to last and it will not damage the reputation of physics.

Where there are opportunities and time and interest later on, some pupils can embark on a more purely scientific study of optics and find it a very interesting field of great laws and rival theories. We intend no disrespect to the conventional treatment but we offer our present choice both as more practical and for an economy of time. We propose to make some parts of the usual physics course give place to more teaching of atomic physics; and we have chosen to leave out considerable parts of optics. In defence of that move, we must point out that to many pupils the traditional optical measurements and even the subsequent study of optical instruments form a rather puzzling business – it is not easy to teach geometrical optics for a lasting understanding. See the Note on Optics Teaching in the General Introduction.

Synopsis of Programme of Optics

The treatment we suggest is this:

Home-made Pinhole Camera as a class experiment to show rays of light 'making a picture'. Let this graduate into a lens camera, in which the lens clearly picks up many rays from an object point and makes them all converge to an image point.

(*Contd.* from foot of p. 143) The fund is intended to make it easy to enable schools to allow such loans. Where a school lends 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 the cost to be met. 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.

Converging Lens catching the Image of a Window – a class experiment, almost an informal drill. Discuss that as image forming. It also gives a rough measurement of focal length. Then use the same lens as a magnifying glass. This introduces the idea that such a lens forms a real image of distant objects, a virtual image of an object close to it. It also gives pupils some knowledge of their own eyes' range of accommodation.

A Simple Astronomical Telescope. A first quick look just to enjoy making it work, and to hear the story: 'A weak lens forms a real image of the distant cow: then you look at that image with a magnifying glass. That makes a virtual image far enough away for you to see comfortably, so that you think you see the cow much larger than life, or else much nearer than it is, or both. Since the cow you think you see is upside down, it probably is only an image.' Pupils have a weak spectacle lens and a magnifying glass and the teacher gives considerable help in arranging these so that the final virtual image is back at the object. This is a first look at a telescope for fun, to remove the mystery, and to promise future knowledge and skill. The essence of these *class* experiments is personal experience.

Ray Streaks. Experiments with streaks of light from a small lamp. These splash across a sheet of paper and hit cylindrical lenses, etc. We give each pupil his own simple apparatus. (This is not a demonstration with the usual ray box outfit.) Pupils find, by playing with these, the essential properties of lenses (and mirrors) in forming images.

Astronomical Telescope, repeated, this time with pupils doing the focusing, and skilful pupils making a rough estimate of the magnification when the final image is back at the remote object.

Magnifying Glass, as an optical instrument. Pupils practise placing the virtual image 10 inches away. Some pupils may estimate the magnification. (With very able pupils, there may be time to discuss magnifying power, briefly.)

Compound Microscope (*for skilful pupils*). A crude model with two lenses, to see it working in open air.

The experiments with instruments should give pupils considerable practice in placing the final virtual image comfortably. After this, pupils should be confident and skilful in focusing optical instruments, so that they can make good use of them.

Eyes. Simple discussion of eyes and spectacles, with special model eye. Spectacles are regarded here as image-formers which bring an image of the object being viewed to a comfortable position for the eye.

Ray Streaks. Pupils return to the class experiment with ray streaks and set up their own simple demonstrations of rays through a telescope and a microscope, using a pair of lamps as object (one of them with a colour-filter).

Diagrams. In class and in homework, faster pupils should learn to draw 'full-cone diagrams' to show the progress of the full cone of rays from one or more object-points that enter the full aperture of the lens. They should also draw 'narrow-cone-to-eye' diagrams that show the eye looking at the image. (A separate note describes techniques.)

The 'Formula' relating u, v, and f. If there is time, pupils may make measurements with a lamp and screen to see whether the 'formula' $1/v \pm 1/u = \text{constant}$ holds for their converging lens. This will *not* play an essential part in problems. The only use that we shall make of it is to develop skill in locating virtual images.

If the use of the formula starts to develop a series of careful measurements and the use of ray diagrams to solve formula problems, our teaching has taken a mistaken turn that will occupy considerable time and deflect attention from our main work – and it would be better to do without the formula.

If, however, we can just announce the formula and ask pupils to find whether the behaviour of their lens fits with it, we can then use it to encourage the locating of virtual images. Pupils will find quite easily that the 'formula' gives a constant value for real object and image distances; and we ask if it might extend to virtual images – the kind of risky extension by which science often progresses. Testing that extension will give pupils practice in placing or locating virtual images – which are so important in optical instruments. *Only if the 'formula' is used for this mild competitive encouragement should we give it any attention at all.*

The Formula $1/v \pm 1/u = 1/f$ does not play an important part in our present treatment. The focal length, f, is only a special case of an image distance. Yet $1/f$ is an important number: it is the constant value yielded by the 'formula' for all pairs of object and image distances; and it is called the *power* of the lens. We should

make sure that pupils make a very rough estimate of the value of f *
when they meet a lens; and they should have a general idea of the *
position of the image if the object is at a distance $2f$, and at much *
greater and at much smaller distances. *

Laws of Reflection and Refraction. Simple demonstrations *
and measurements of rays being reflected and refracted. The laws *
are mentioned but no extensive use is made of them. *

A Short Look at Theories. We describe the bullet theory and *
point out (without algebra, since momentum has not yet been *
treated formally) that speed in water **should** exceed speed in air. *
Then we describe an alternative wave theory. *

Wave Behaviour. Short description of refraction of waves. *
Ripple-tank demonstration. Action of lenses and mirrors in im- *
printing change of curvature on a wave-front. *

Interference of Light as Evidence of Waves: comparison with *
ripple tank. Estimate of wavelength. *

CAMERAS

Pinhole Camera: A Class Experiment

The pinhole camera experiment, to be done in a half-dark room, C7
forms the beginning of a series of class experiments in optics. It should be easy and fun to do, rather than a serious discipline in assuring oneself that light travels in straight lines. (For that matter, a real test of rectilinear propagation by use of a pinhole camera requires a considerable amount of measurement and logic.)

We want this to lead straight on to the idea of a lens-camera having *
something that gathers up many rays of light from each point on *
the object – instead of the very narrow pencil that gets through the *
pinhole – to form a much brighter picture on the photographic film. *

After that we shall show the detailed action of lenses when a sheaf *
of rays from an object point are bent to pass through an image *
point. *

Arrangement of Camera. Every pupil, or at most every pair of *
pupils, should have a pinhole camera. *This should not be a carefully* *
constructed box with a sliding arrangement to change its length and a *
special pinhole provided in the front. That may be a useful demonstra- *
tion or class experiment in other programmes of optical teaching *
but here we need something that is simpler, something that pupils *

can deal with themselves and easily copy at home. So we provide pupils with a small cardboard box, such as sweets come in, with a hole about $1\frac{1}{2}$ inches in diameter cut in the front and a large square hole cut in the back. * * * *

The front hole is covered with a sheet of black paper, pasted on, in which pupils can make pinholes. (Then after it has been used, the camera can be restored by pasting a new sheet of black paper on it. It is not necessary to have black paper; opaque paper, preferably dark, will do. Black paper serves well; so does common brown paper.)

The hole in the back is covered with some kind of translucent screen.‡ The screen should be fixed over the hole at the back with Sellotape and kept there permanently; but the front screen has to be changed after each class.

The length of the camera is only important in the sense that we need to match that length with a lens in one of the experiments. If the lenses available have a focal length of 14·3 cm (power +7D), we should have a camera just 6 inches long. How much more than the focal length the box length should be depends on how far from the object lamp the camera will be used. Since we can choose that distance we can certainly make some adjustment by placing pupils suitably. A 20-cm focal length lens with pupils standing a yard or two from the lamp will need a camera 8 or 10 inches long and that is unnecessarily big. Pupils can of course hold the lens out in front of

‡ For this purpose, where the pupil will stand behind the camera looking straight towards the object, the screen should be made of a material that scatters light through a *small angle* around the straight-through direction. Then the pupil will receive plenty of light.

A screen that scatters through a wide angle will distribute light to many observers standing behind, but none of them would receive enough light to see a bright picture. A wide angle scattering screen is what is needed when an illuminated translucent screen is used as background to make a silhouette as a demonstration experiment for a large class. It is also what is needed for rear projection to a large class subtending a large angle at the screen. For that latter use, architect's tracing linen seems to be best of all available materials. It is inexpensive, it is easy to install, it is difficult to break, and it scatters the light it transmits over a very *wide* angle.

For use in pinhole cameras we need the opposite extreme, a screen that scatters transmitted light over a *very small angle*. Kitchen greaseproof paper is very good. Kitchen waxed paper may be better still, though it is more easily broken. Almost any kind of tissue paper rendered translucent by treatment with paraffin wax or oil will serve. Ground glass is too easily broken. Frosted plastic is unnecessarily expensive.

the camera but that does not seem quite so convincing. Therefore, it is better to have lenses of 10 to 15 cm focal length and a smaller camera to fit with that. It is neither wise nor necessary to have very special lenses just to put in front of a pinhole camera. It is rather better to choose the camera to fit the common lenses we use. Meniscus lenses of power +7D are cheap (less than four shillings each when bought in quantity) and easily obtained from spectacle manufacturers, and are recommended.

The lid of the cardboard box should be removable so that when distant objects are viewed the lens may be held *inside* the box. (The pupil removes the lid, and holds the box upside down.)

For pupils experimenting with pinhole cameras on their own in a *
half-dark room, it is an enormous help if the teacher has tried out *
the apparatus himself beforehand. That is not because the effects *
are in any way mysterious or unexpected, but because the teacher *
needs to be able to recognize troubles which arise from the actual *
apparatus and to give help when necessary without giving long *
directions beforehand which would forestall troubles but spoil the *
experiment. *

The best lamp for use in a half-dark room is a large carbon-filament *
mains lamp with clear bulb. That should be very bright and run at *
full voltage, or even higher. (When it is used as an object for *
model telescopes later on it should be run on a variac or rheostat *
to make the filament duller.) *

Pupils should stand about two yards from the lamp and hold their C7a
camera at arm's length in front of them and point it towards the lamp. Each pupil should have a pin and make: (1) a small pinhole, (2) a big pinhole, then (3) several small pinholes, then (4) a whole 'pepper' of pinholes.

From Pinhole Camera to Lens Camera

After trying those, and moving nearer to and farther from the lamp C7b
pupils should be asked to slide a lens in, just in front of the pepper of pinholes. When they do that, the teacher should guide them to put the lens at a distance which will make a clear image on the screen. After trying that pupils will naturally try the lens at various distances, and try moving to different distances from the lamp; but the first sight of it should be a brilliant gathering up of all the pinhole pictures into one bright sharp optical image on the screen. Of course one does not tell the pupils that that is going to happen. One merely places them at the best distance or suggests where they should hold the lens as they slide it in front.

After that, pupils should try one more size of pinhole, a big hole made with a pencil or a finger pushed through the region of peppered pinholes. Then adding the lens once again they can get a very bright image on the screen.§ C7c

Camera: Focusing. With the lens held at some definite distance in front of the camera, pupils will find there is only one object distance for a clear image on the screen; and we should tell them that this is a disadvantage of using a lens. C7d

They should try a different object distance and refocus by moving the lens nearer or farther in front of the box.

Of course, faster pupils will look for various characteristics such as sizes of the picture, fuzziness and sharpness, for different distances and sizes of pinhole.§§

Depth of Field (*advanced buffer option*). If time permits, pupils should repair the front window of their cameras (or use spare cameras that have not yet had their front window broken), and try having a large pinhole (say 2 mm) with the lens held in front of it at the correct distance for the object. They will see that they get a sharp, though not very bright, image on the screen and that when they try other object distances they still get a fairly sharp image. Then they can enlarge the hole (10 mm) and again find that the picture is fairly sharp for several object distances. With a still larger hole (25 mm) the picture is not sharp unless one uses the correct distance. This illustrates the story of the cheap camera with 'fixed focus', which should be investigated further by discussion and drawings. C7e

Note to Teachers: Pinhole Camera Experiment. This is an experiment for delight. There will be plenty of more disciplined experimenting later this year and we should not spoil the beginning of optics by expecting elaborate reasoning or careful carrying out of some prescription. * * * * *

A common difficulty which needs a warning is that many pupils forget that they are looking at the screen behind the camera and * *

§ 'Good. It wasn't long before one enterprising youth dispensed with his camera and was producing a huge image of the filament on a lab wall – soon copied by the rest of the class.'

§§ 'We were diverted to the extent of spending a whole lesson talking about cameras. They brought their own along and were interested and forthcoming about the function of the various parts. This could well be a profitable inclusion.'

hold the camera just in front of their nose. The cure for that is to say: *

> 'Remember, you're looking at a picture on the screen and you should hold it away from you just as you would hold a book away from you to read it.' *

View with Lens Camera. At the end, a blind should be raised so that there is a view through an open window that pupils can look at with their new 'lens camera'. C7f

RAYS AND IMAGES

Experiments and Arguments with Lenses

The lens placed in front of the pepper-of-pinholes obviously collects up a fan of 'rays' (each of which was proceeding to a separate picture on the screen) and bends them all to travel to a single image on the screen.§ T

Assuming that these 'rays' – really thick pinhole-passing bundles of rays – travel straight in air before and after the lens, we are forced to think that this is what a lens does: it takes a fan of rays from an object point (a 'source' of light) and bends *all* of them so that after passing through the lens they *all* go straight to an image point. Pupils will see that happening soon, in the class experiments with ray streaks and cylindrical lenses; but we should first give them a demonstration and a discussion.

Three-Dimensional Demonstration: Smoke Box. We show a lens producing with a fan of rays of light, *in three dimensions*. The comfortable arrangement is to have a large box with Perspex or glass front, that can be filled with smoke, and place a big converging lens inside the box. Failing that, the smoke must be in the open air of the laboratory – and the disturbance is worth it. For smoke, the corrugated cardboard that is used for packing does well. A bee-smoker – bellows and holder for cardboard – is an easy smoke-producer. Or dust of blackboard chalk, shaken out of two dusters clapped together, will suffice. (The trick of doing the demonstration under water containing fluorescein is too confusing.) D8

For source one wants the brightest compact source available. A carbon arc is best of all. The new compact bulb with tungsten filament protected by iodine is very good. It is the one to use unless

§ 'This has been accepted readily, *particularly after seeing smoke box.*'

an arc is available. A projection bulb with a compact filament will suffice; but one will never know what one has missed. The lamp must be well housed to avoid stray light spoiling the demonstration.

Light from the lamp hits a screen (between lamp and Perspex box) in which there are holes $\frac{1}{8}$ inch to $\frac{1}{4}$ inch in diameter – a pepper of big pinholes – and proceeds as a fan of fat 'rays' through the smoke to the big converging lens. After the lens the 'rays' converge and pass through an image and continue on, through the smoke. This is a magnificent sight, worth many a cough from pupils and many a complaint from cleaning and ventilation authorities. (Children who catch the idea with delight may try to cut a pepper of holes in a blind at home and demonstrate this with rays of sunshine and smoke produced by home methods.)

The pepper of big pinholes and its placing should be arranged so that the fan of rays just covers the aperture of the lens. However, if a few rays miss the lens, the moral is useful: 'rays continue straight on'. If the lens is a very strong one with big aperture both spherical aberration and colour effects may be noticeable. We should certainly point out the latter and comment on the need for achromatic combinations in cameras.

The rays are most easily seen by observers looking 'upstream' towards the source; so the class should, if possible, form a line and walk round and round the box.

(Teachers who have once used a three-dimensional smoke box *
will want to show other things such as a plane mirror, concave *
mirror, diverging lens. The box is troublesome and expensive to *
make, but well worth the trouble. The base and back and top can *
be of wood, but ends and front must be of Perspex or glass. A *
big rubber bulb should be arranged to provide puffs of air to *
make the smoke circulate.) *

Rays caught on Paper (Pupil Demonstration). *After* showing D/C9
the smoke box we should show a smokeless version of the same thing in which the smoke is replaced by a sheet of thin paper or translucent material waved in the path of the rays and moved along to catch the 'image point'. That will show colour effects clearly: 'You can see: the lens is stronger for blue light than for red.' (Teachers all find that 'stronger' is a more convincing term than 'smaller *f*'.)

As an alternative to the sheet of paper, a small transparent lunch box may be filled with smoke, closed up, and moved along to give a momentary picture of rays.

Class Discussion of Rays: the beginning of Ray Diagrams
We are just starting an exciting time of investigating rays, images and instruments; but we should not interrupt that with careful drawing of diagrams – and certainly not with the formal diagrams that use a 'ray through the focus' to solve problems. *

However, we shall presently introduce a scheme of drawing diagrams that show clearly the rays and images that our eyes use in looking at things with optical instruments. We shall provide for both teachers and pupils a separate booklet of pictures to show the drawing of such ray diagrams. Some early sketches in that collection show a pinhole camera at work; and then a lens camera at work. One diagram shows the need for focusing with a lens camera, and illustrates the problem of depth of field. So some teachers will wish to distribute these booklets at this stage and ask pupils to look at some of the first sketches. The fact that the later pages deal with optical instruments which are yet to come in our programme does not matter. Their sketches show genuine optical behaviour and will neither mislead pupils nor give the show away and spoil the fun. Nevertheless, those later sketches should not be studied or used until pupils have worked with the instruments themselves and with models of those instruments that use real rays of light. *

So all we suggest for a class discussion at this point is a very short talk, with blackboard sketches, of the way in which the lens in the front of the pinhole camera seems to 'collect up the rays' and 'bend them so that they all run together at a sharp image point'. T

IMAGES

Formal Description. We must now introduce the name 'image', for the place through which rays pass. If we were teaching older pupils we should do well to give a formal definition of an image as follows: *

> 'The image of an object point, formed by lenses, mirrors, etc., is that point through which all rays from the original object point are made to pass after emerging from the lens, mirror, etc. *
>
> 'In the case of a real image, the rays converge to the image point, pass straight through it and continue. In the case of a virtual *

> image, the rays of actual light do not pass through the image point but only appear to diverge from it.
>
> 'A large object is treated as made up of points; and the image of the object is made up of point-images of those points.'

And we illustrate that with sketches in which the rays do not bend when they pass through the image but go straight through and continue, diverging from the image point. The only places at which bending occurs are the surfaces of lenses or mirrors.

We should illustrate the general concept of an image by a diagram showing a sheaf of rays from an object point going into a 'black box' in which there are, presumably, lenses and/or mirrors, and emerging from the black box with a new set of directions which all pass through one image point, real or virtual.

(The mysterious 'etc.' in our definition refers to diffraction: a zone plate produces images of a sort, behaving like a lens with a whole series of different focal lengths.)

Simple Description. For our pupils here, we should say something much simpler: T

> 'You see a thing by receiving rays which come straight to your eye from each point on the thing. A lens bends the rays that come from a bright point and makes them all pass through another bright point that we call the image. You see that image by receiving rays that come straight from it to your eye.
>
> 'That is what a camera lens does for us. It makes an image of the thing we want to photograph, and we put the photographic film just at that image. But perhaps the image is there anyway, whether the photographic film is there or not, whether the camera box is there or not. Perhaps you could see the image by letting your eyes receive rays of light that have come to the image and passed on through it. Look at that for yourselves.'

Class Experiment: Discussion with a Common Lens

Pupils may sit in class seats for this or work at laboratory benches. The teacher should give *each* pupil a 'magnifying glass' – any large converging lens: best of all, about 14 cm focal length (+7D), about 2 inches wide, but smaller and stronger ones will do, though they will make images that are too small for comfort. And he should suggest that pupils feel its spherical surfaces with their fingers. C10

'Remember how the lens you put in front of your pinhole camera collected up all the light rays to make one bright picture. We call that an "image". The lens does that to the rays of light anyway, whether your pinhole camera is there or not – whether you are there or not! T

'Try that with your lens now. Face away from the window (or from a lamp). Hold a sheet of paper at arm's length in front of you. Hold the lens nearer to you, so that light from the window (or from the lamp) goes through the lens and makes a sharp image on the paper. There is the image that you saw on the screen of your camera. C10a

'Now take away the paper. Does the lens still bring the rays of light to an image there? Move your head round to a place behind the paper and look. It is easier if you keep your head where it is and move the lens. You need to face the window now. C10b

'Hold the lens out at arm's length *towards* the window (or the lamp) and look towards it. Can you see the image? ... Yes, it *is* upside down. Didn't you see that with the camera?

'If you can't see the image, try looking for it with a scrap of thin paper. Hold the paper a little way behind the lens, then a little farther back, then farther. Remember that you see a thing with your eyes when it is some distance in front.‡ You can't read a book crammed against your face.'

‡ Even with careful instructions and considerable help, many pupils find it difficult to see the image in mid-air. It is a great help if they form half the image on a piece of paper, the other half overlapping the edge of the paper so that they see it in space. Then they concentrate attention and the focusing of their eyes on the part of the image that they see on the paper, quickly take the paper away and see – we hope – the whole image in mid-air, without changing attention or focusing of their eye.

Range of Vision: Accommodation

'Now stop using the lens. We shall come back to it. Look at a book and find out what your "range of comfortable vision" is for your particular eyes.‡ Yes, the people with spectacles should keep them on.' C11

(Note that the lens experiment C 10 continues with parts (c) and (d) after comments on spectacles; and (e) after the note on focus.) * *

Spectacles raise interesting questions and we should meet them with pleasure. Unfortunately many modern spectacles include a correction for astigmatism – a cylinder surface to correct for unequal curvatures of the front of the cornea. In those cases, the wearer should keep them on. Otherwise, if spectacles have only spherical surfaces, the wearer should try experiments with and without them and learn what they do to his own 'range of comfortable vision'. We must be ready to say presently: * * * * * * * *

'Spectacles, like any other lens, are image-formers. They take the object that you want to look at and move it (optically) to an image for you to look at instead. The image is at some place where it is comfortable for *your* eyes to see it. T

'Astigmatism, for eyes, just means your eyes have a front surface a little more like a rugger ball than a soccer ball. That is common and harmless; it is corrected for by spectacles with one surface "elongated" the other way. But in that case you should keep your spectacles on.

'This applies to *all* spectacle wearers: your spectacles are designed to add just the right amount of lens power to your eyes to make the combination, spectacle + eye, equal to an "average eye". An "average eye" is nothing very special; but books are printed with the type chosen so that your arms can hold them comfortably, and average eyes read them, at a distance of about T

‡ Teachers will find that young pupils have a tremendous range of accommodation. Any attempt to settle on 10 inches or 25 cm as the closest distance of comfortable vision will lead to confusion and disbelief. We must accept the actual range that each pupil finds. But then we suggest that older people do not have such a large range. They cannot see things clearly when they are held so close; it may be uncomfortable for their arms, it is likely to be poorly lighted. And ordinary type will look very large when held so close. Books are printed with type that will look a comfortable size when held about 10 inches away, and at that distance one's arms are comfortable and the lighting can be arranged fairly easily. So we pretend that 'average eye' likes to have things 10 inches away, or farther, for comfortable vision.

10 inches. And distant mountains and stars are the farthest things any eye wants to look at. So the average eye has a range of comfortable vision from about 10 inches to the farthest mountain – from 10 inches to infinity.

'At your age, your eyes have a much larger range: they can see things comfortably when held closer – though you may have to squint. That range decreases as you grow older. It is said that an oculist can tell your age from your eyes' range of comfortable vision about as accurately as a vet can tell a horse's age from his teeth.'

Discussion with a Common Lens (continued): Real Image

'Now face the window. Hold a sheet of thin (or waxed) paper between you and the window about 10 inches from your eyes; hold the lens out beyond the paper and move it till you see the image of the window caught on the paper, seen faintly through the paper. Let me look at it.' C10c

That is a point at which the teacher should make sure that each pupil has caught the image and is looking at it from behind.

'Now move the paper sideways till the image is at the edge, half off the edge; and go on looking at the image. It is there, just where it was on the paper, there in mid-air. We call that a real image.'

At this point the teacher should again go round from pupil to pupil helping the many who have lost the image, by catching it on the edge of the paper again, pointing to it, removing the paper, pointing to the place in space where the image is, clutching at the image ('Is this a dagger that I see before me?'), and saying:

'Look, the image is *here*, just here. No, *not* back at the lens, not on the lens, but out here. Move your head to-and-fro sideways a little. Look at my finger.'

The teacher should place his finger at the image, or point at it and try to catch it with his finger and thumb; or he may hold a scrap of paper at the image again, momentarily.

'Look at my finger and *go on looking* just here. The image is just here where my finger was. Imagine you are looking at my finger just here; and you will see the image here instead.

‘Yes, of course it is upside down and it is smaller than life; but you can get close to it and see it. Which can you see in greater detail, a real cow 100 yards away or a little image of a cow upside down, dozens of times smaller, but nearby at a close comfortable distance for seeing? … Oh yes, you are quite right; the real cow would be better if you could go up close to it because the image would be so small. But you could look at the image with a magnifying glass and then you would gain. Then you would have a telescope: we shall come to that soon. (It is no good holding up a magnifying glass by itself to look at the original cow 100 yards away; all you would see would be a very small real image upside down.)’

Pupils should thus learn, just by handling a large weak magnifying T
glass, that there is a real image of a distant object behind the lens. The image does not always have to be caught on paper; it is there anyway, and can be looked at by an eye that is suitably placed.

The eye must be a comfortable distance‡ away from the image, just as it must be for looking at a book. And the eye must be within the region covered by rays of light that go *through* the lens and on through the image and spread thereafter – seeming to come from the image.

Presently we shall ask faster pupils to draw ray diagrams that show *
‘full cones’ of rays of light from various object points (through the *
complete aperture of the lens to corresponding image points, and *
straight on through those image points). The eye must be placed *
within the full cones spreading from the image points that it *
wishes to look at. This is *not* something that we explain to pupils at *
this stage. This is given here only as an indication to teachers of *
what is to come. *

When pupils have a clearer idea of the lens forming a real image of C10d
a window or a lamp, let them do the same thing for the face of a boy or girl brilliantly floodlit. If possible let pupils move their lens nearer and nearer to the model’s face and notice how the picture, in ‘perfectochrome’, moves back farther from the lens and grows in size. They should try this both with a piece of thin paper to catch the image and without the paper.

‡ As explained earlier, young pupils who may have a vision extending as close as 3 inches will need considerable persuasion before they will work with the official 10 inches. We have to explain that we are asking them to arrange their telescope for an average adult eye.

Note to Teachers: 'Focus' and 'Focal Length'. Note that we have not suggested any mention of the image being at the 'focus' or 'principal focus'. That is an intentional omission. In elementary optics 'the focus' is apt to assume a peculiarly important position in pupils' thoughts; rather like 1066 in History. It becomes a mysterious, important place through which 'parallel rays' (parallel to anything, in the mind of a confused pupil) must go.

Since we shall not use the principal focus in ray constructions, we need not give it such a strong position. Of course, pupils should know that there is a focus, a burning place or hearth where the lens forms the image of the Sun. They should see that and hear the name, but they should not think of the focus as the only really proper place for an image.

Nor should we make the 'focal length' too strong an object of worship. In practical use, a lens has a great deal more than just a focus and a focal length. The Physical Society's Report on the Teaching of Optics long ago wisely directed attention away from the focal length of a lens towards its 'power', measured by $1/f$.

If f is in metres the power is in 'dioptres'. The power is not solely the reciprocal of the focal length; *it is the essential constant in the longitudinal formula.* It tells us, for all pairs of object- and image-distances, u and v, the constant difference (or sum) of $1/v$ and $1/u$.

And, in terms of waves, $1/f$ gives us the change of wave-curvature imprinted on any spherical wave by the lens.

Discussion with a Common Lens (continued)

Meeting a Lens: A Rough Estimate of Focal Length. Nevertheless, we should now show pupils how to make a rough estimate of focal length; but we do not embark on a long study of measurement.‡

> 'When you are introduced to a stranger you start by shaking his hand. When you meet a strange lens you should "shake hands with it", by holding it up and catching the image of a distant window on a piece of paper. C10e
>
> 'Then you can measure the distance from lens to image, which is a very useful distance to know. We call that "focal length". The stronger the lens, the shorter the focal length, the quicker it T

‡ The large lens suggested for the smoke box demonstration has roughly the same power as the lens we suggest for the class experiment. Pupils might be interested in seeing it.

brings rays to a "focus" at the image. The word "focus" comes from the Greek word for a hearth, because it is the place where the lens forms an image of the Sun, acting as a burning glass.

'If the window is quite close to the lens, the image is a little farther away, not at the principal focus where the lens forms an image of a very distant object. But, for first acquaintance with a lens, any window that is a few yards away will do.

'You should always do this on meeting a lens: catch the image that it makes of a fairly distant object and make a note of the distance from lens to image.

'If the lens fails completely to make an image that can be caught on paper anywhere, it is probably the opposite kind of lens, a "negative" lens (a concave lens) which forms an inaccessible image of a distant object.

'If the lens seems to form streaky images spread out in one direction more than another, it is probably an "astigmatic" lens used for spectacles. Do not use it for your optical experiments because it will complicate things.'

Discussion with a Common Lens (continued)

Looking at a Virtual Image. 'Now try something else with the same lens. Hold it close to your eye and use it as a magnifying glass to look at your own thumb. C10f

'Hold the lens close to your eye, the thumb at the right place for looking at it, and then whip the lens away and see whether you can see your thumb. Without the lens your thumb is too close for you to look at it and see it comfortably at that distance.

'Now put the lens back. You can see your thumb comfortably, and it looks big. Where must the image be? What is the range of places for objects that you can see comfortably? Yes, from about 10 inches in front of you right out away to the most distant mountains, "at infinity". Where must that image of your thumb be when you can see it comfortably with this magnifying glass? No, not behind your head. You know the lens forms an image of the distant window far back behind the lens. But then you have to put your head farther back still to look at that image; and here you have your eye close to the lens and yet can see your thumb comfortably. The image that you are looking at *must* be out in front of you, like anything else your eyes can see comfortably. It must be on the *same side of the lens* as your thumb, but farther away.

'We call that a "virtual" image, one the rays of light seem to come from, but don't actually pass through. You cannot catch that image on a piece of paper.

'Virtual images are a little harder to think about; and we shall come back to them when you have watched lenses doing things with rays.'

This introduction to the idea of a virtual image is very important, but it should not be stressed strongly at this point, or virtual images will acquire a reputation of being difficult and mysterious – and perhaps not even proper images. The experiments with ray-streaks will make virtual images easier to understand. *

Spectacle-wearers. This may be the time to point out to spectacle-wearers that they are looking at a virtual image whenever they wear their spectacles, whether they like it or not! T

Virtual Images are Really There. When pupils look at a virtual image we can help them to understand what they are doing by pointing, and clutching with fingers, at the region where the image is – some 10 inches or more away from their face – and telling them that the image *is* back there: T

'Keep both your eyes open and try to look at something back there. You will find that easier presently.'

Both Eyes. Pupils who find it too difficult to keep both eyes open should hold a hand, or an eye-shade, over the eye that is not looking through the lens. We must tell them now, and in later experiments, that tightening the muscles round the unused eye to keep it shut makes it harder for the neighbouring eye to see comfortably: T

'How would you like to write with one hand while I torture the other hand?'

If teachers like to make a stock of simple eye-shades, of a piece of card with an elastic band, they will find that letting pupils use these removes many a complaint of 'eye-strain' – usually just an excuse to avoid a difficult experiment – and promotes faster progress *

with images and instruments. If pupils will take them seriously, *
they are a great help. *

Results. This discussion should leave pupils with two clear general ideas: T

1. That one's eyes can see things comfortably if they are anywhere in front from his 'near point' to infinity.

Each pupil should know his own range of comfortable vision; but we should ask pupils to accept an artificial average for adults: a range of 10 inches (25 cm) to infinity.

2. That a simple converging lens, the big weak magnifying glass that they have been using, forms an image of any object which sends light to it. And the position of that image is connected with the position of the object. If the object is far away the image is near the principal focus. As the object moves nearer, the image moves farther away. And when the object is very close the image is no longer on the other side of the lens but is a virtual image on the same side as the object but farther back.

Demonstration of Object Image Distance Relations. The teacher should give a quick demonstration showing how the image formed by a converging lens moves as the object approaches it. Starting with a lamp at a great distance, he should catch the image on a piece of paper. Then as the lamp is moved nearer and nearer to the lens he moves the paper to catch the image at each stage. The changes of magnification should also be noted. When the image has run away to infinity, as the object approaches the principal focus, a demonstration becomes of little use, because the teacher can only assert that the image is a virtual one. This is a stage at which pupils should take matters into their own hands and look at the virtual image and its changes of position as the object moves on up to the lens. It may be helpful to sum this up in a description like this: T

> 'When the object starts very far away, at infinity, the image is here at the point which we call the focus. It is very small. As the object walks towards the lens, the image starts from the focus, crawls out from it – a little faster – and faster still – until, when the object is at two focal lengths away, the image is at an equal distance and of equal size, upside down, and walking away with the same speed as the object. As the object walks still closer the image now runs away faster and faster till, when the object has

got to the other principal focus, here, the image has run to infinity. After that, as the object walks in closer still, the image has, so to speak, "run round the world" and appeared on the other side – far off, at infinity. It comes tearing in, trying to catch the object up and as the object walks to the lens the image just catches it up at the lens itself. In all those later stages, of course, the image is a virtual one, running in from infinity on the same side as the object, growing smaller and smaller as it runs till it just matches the size of the object when they both reach the lens together.'

Some such description is useful, provided pupils do not think it is a collection of details that they must learn by heart for examinations.

Pupils do not need any more detailed idea at this stage of the way *
in which the image shifts when the object shifts. We certainly *
should not give them the 'formula' $1/v \pm$, etc., or details that in- *
terpret it. Pupils will do best if they just know that the lens has *
this behaviour. When they see lenses bending rays in the class *
experiment with ray-streaks they will be able to link up the two *
parts of the story.§ *

This 'making acquaintance with a lens' should be done quickly, *
with a lens for every pupil, but more as a simple class drill than as a *
loose class experiment that would take more time. As soon as *
possible, we move on to experiments with 'ray-streaks', visible rays *
of light which enable pupils to see what a lens really does. *

TELESCOPE: CLASS EXPERIMENTS

Setting up Telescopes. For pupils to make a telescope and C12
enjoy feeling that they have a real instrument in their hands, we must provide simple apparatus, a few essential instructions – and then encouragement rather than more detailed instructions – and time for pupils to try things out. For a first try, the important thing is to make the instrument work so that pupils are pleased with success.

(At a later try pupils should consider where the images are and *
think about the way in which the lenses produce the images. *
Only with a fast group should we also ask for measurements of *
magnification as an essential outcome of that later experiment. *
Yet if we can offer a coarse scale on the wall as object and en- *
courage pupils to make a rough guess at the magnification, many, *

§ Some pupils did comment that if rays are too diverging the lens can't cope – it cannot converge the rays enough to form a real image.

both slow and fast, will be helped to do the focusing correctly. The scale should be a vertical one with heavy horizontal lines every 10 cm and should be well lit by a lamp directed at it. A scale arranged like that avoids the disadvantage of foreshortening if some pupils view it obliquely.)

Notes for Teachers, on Telescope Equipment. By tradition, one always sets up a telescope on an optical bench; but that would merely provide a sturdy support: the provision for longitudinal adjustments and measurements is wasted on us, and the provision for lateral adjustments, which would be so useful, is usually missing. For pupils at this stage, each lens could quite well be held in a separate retort stand. However, if some *simple* optical bench is available, it has one strong advantage: we can raise it to shoulder height and have a telescope that can easily be manœuvred and used without stooping.

Teachers who are used to having to stoop to look through an optical system on the table – or to kneel or squat in order to look through the system with neck and head upright – will find it is a great relief to have an instrument such as a telescope, or a model microscope, up at eye level, placed horizontally so that one can look through the system comfortably.

For that, the optical bench, a simple rod with lenses attached to it by clamps that can slide along, should be supported near its centre of gravity by a bosshead on a strong tall stand, at such a height that the lenses are at eye level when the pupil stands upright. The Nuffield Physics Group have designed a very simple slide of this kind, for model telescopes, etc., that can be held on a retort stand. It is intentionally made much simpler than an optical bench, so that one will not be tempted to extend these experiments with optical instruments into a series of measurements.

Class Experiment: Telescope

On the 'telescope rod' pupils should set up one weak lens (f=30 to 60 cm) to serve as objective and a small strong magnifying glass as eyepiece. C12 The objective may be a weak spectacle lens, preferably plano-convex or meniscus, with the convex face towards the object and away from the observer. The eyepiece should have a focal length of 5 to 10 cm. We suggest a lens of power +14D (f=7 cm) and diameter 25 cm, preferably plano-convex although a bi-convex lens will do.

Note on Plano-convex Eyepiece. If the eyepiece is plano-convex or meniscus, it should be placed with its plane (or concave) side towards the eye. That arrangement, which looks like the opposite of the best arrangement for minimizing spherical aberration, is the correct one for an eyepiece because that lens is dealing with small pencils of rays that come from the real image, which the observer is looking at with the eyepiece. Those narrow pencils are like thick rays, and they are all almost parallel to the axis. We ask the eyepiece to deal with these thick rays as well as possible, and for that the eyepiece should have its convex face turned to receive those thick rays. On the other side of the eyepiece the narrow pencils, or thick rays emerging from the plane side of the eyepiece, will pass through the eye-ring, so they form a strongly converging group. The eyepiece, arranged this way round, treats those thick rays with less spherical aberration than it would the other way round. Those which hit the outer region of the eyepiece lens are bent a little more than the ideal amount, because there is a little spherical aberration, but if the eyepiece were the other way round that extra bending would be much greater, and would have two effects: it would give extra magnification to the outer parts of the final virtual image, making distortion; and it would give curvature of field to the image so that outer portions are farther away than the central part. To see how that curvature of field arises one must look at the differential 'extra bending' between the outer and inner rays of each small pencil. This story of the eyepiece is not something to discuss with pupils at this stage or for many a year. It is inserted here only as a discussion with teachers who are experimenting with the instruments.

For first experiments with a telescope *the object* should be an electric lamp with a clear bulb, at the other side of a half-dark room. The best lamp for this is a large carbon-filament mains lamp, such as the one suggested for the pinhole camera. With a large class there should be several such lamps, to avoid clashes between telescopes. For a first look, the lamp may be run at full voltage; but there should be a variac (or a rheostat) so that the filament can be made duller if pupils wish. C12

Obviously, pupils should presently turn the telescope round and look out of a window; but the artificial object is easier to start with.§

First Simple 'Explanation' of Telescope. Pupils will have seen a single lens forming a real image at the end of the pinhole camera T

§ 'Delight when they catch one another upside down!'

experiment – and, if they have any sense of delight in science, they will have been upsetting people at home by trying the same thing with every magnifying glass they can lay hands on. (Unfortunately most modern spectacles include a correction for astigmatism so they give a disappointing puzzle when pupils extend their operations to them as well.)

Here, we simply say:

> 'The objective is a weak lens that forms an image of the distant lamp just as a strong lens does, but not as close. Move a piece of tissue paper forward and back behind the lens and catch the image of the lamp.'

(That is why we want a bare filament lamp, for a bright image.)

Then we say:

> 'Look at that image with a magnifying glass.'

For this first look, early success is essential, or optics will make a *
poor start of peering and doubt.§ The teacher should help each *
pupil to move his eyepiece back from a piece of paper on which *
another pupil is catching the image, and should say 'Now you *
take the paper away while we look through the eyepiece.' *

Better still, the partner takes the paper 'half away' – so that the *
image is at its edge.§§ *

The three main difficulties for beginners here are: *

a. There is a considerable range of positions of eyepiece which will *
give a final virtual image within the large range of accommodation *
of a young pupil. *

§ 'They were not convinced that their telescopes were any advantage over the naked eye until we looked at some books in a bookcase behind the lamps. When they found they could read the titles on the spines through their telescopes, but not without, they seemed very much happier.'

§§ One teacher reports the following ingenious scheme: 'With pupils A and B, pupil A catches the image on a piece of translucent paper. Pupil B, with his eye fairly close to the eyepiece, holds his own finger in such a position that he can see it comfortably through the eyepiece. Then pupil B moves the eyepiece and his finger, always in focus, until pupil A tells him that the finger is level with the piece of paper. At that point, finger and paper are removed.'

b. The pupil is not familiar with the idea of looking at a virtual image some distance out in front. He has a strong natural prejudice that things looked at through a magnifying glass must be very close to his eye – this is true of the object, of course, and he transfers the idea to the final image he is looking at, and then he arranges to have that image much too near.

c. The observer's eye needs to be in the right region or else the field of view will be very small. The right region is the 'exit-pupil' or 'eye-ring'.‡ We can see that eye-ring, and even catch it on a piece of paper, if we hold any telescope at arm's length and direct it at a bright white sky: the eye-ring is the bright disc of light just outside the eyepiece. A good telescope is designed to have the eye-ring only a short distance outside the eyepiece, so that the observer can bring his face close to the instrument. But in our simple telescope, the eye-ring is likely to be several inches back. (In fact, its distance from the eyepiece just exceeds that focal length of that lens.) If the teacher has practised placing his own eye at the eye-ring so that he gets a large field of view, he will find it easy to guide pupils to a suitable position.

If he faces a pupil who is adjusting a telescope, he can see the eye-ring on the pupil's eye, when the latter is at the best position.

‡ *Note on 'eye-ring'. All* the rays of light that go through the telescope come in through a round hole, the aperture of the objective lens. Then any ray that hits the eyepiece comes straight to it from some point on the aperture of the objective lens. And when such a ray emerges from the eyepiece it must go straight through the image of that point on the objective lens-aperture. (Any ray from an object point goes through the image point – that is the definition of an image!)

Thus, all rays which come in through that round hole and hit the eyepiece must then go through the image of that round hole that is formed by the eyepiece. That image, itself a round patch, is called the exit-pupil or eye-ring.

Since the observer wants his eye to receive all the rays which go through the telescope (so that he observes a wide field, fully illuminated), he should place his eye at the eye-ring – because, like any image, that is a place that 'all rays go through'.

If the pupil of the observer's eye is smaller than the eye-ring he will use only part of the light that goes through the telescope, the part that goes through a smaller 'hole' in the objective than the full aperture. In that case, we might economize and reduce the aperture of the objective. If the observer's pupil is larger than the eye-ring he will receive all the light that enters the objective, and could profit from a still wider objective. However, a wider objective would cost more and its outer regions would produce aberrations, unless the lens were a well-designed compound one, increasing the cost still more.

Note: If the lenses of the telescope are held in separate stands, there is more danger of their being twisted so that they produce some astigmatism. We must move round among the pupils and make sure they have their lenses 'perpendicular' to the telescope axis. T

To deal with difficulties of focusing or image-placing we say to the pupil, while placing the final image: T

> 'You want to see things comfortably. Remember that you cannot see things comfortably if they are too close to your eye. We shall move this eyepiece nearer and farther from that image until we can see an *image of that image* at a comfortable distance. Look at that lamp itself, with your naked eyes. How far away is it? One yard, ten yards, a hundred yards? Suppose we could make the telescope give us a magnified image right back there where the lamp is. That would be at a comfortable distance. We had better try that. ... Now look ...'

And, for placing the observer's head,

> 'Try pulling your head a little farther back, there is a good place to put your eye which will give you the "fullest picture". No, that's too far; try nearer; that's better.'

Placing the Final Virtual Image. If we have done the adjusting of the eyepiece for the pupil, and he has looked, we should then move it and say: 'Now it's your turn; you have a try.' Staying beside the pupil and knowing roughly where the eyepiece was for the right adjustment, the teacher can help the pupil by encouraging remarks or even just by anxious breathing. At this stage, success is the important thing. Then we ask that pupil to shift the eyepiece and try to teach his partner, while we move on to other pupils. C12

(It is much more difficult for most pupils if we ask for the final image only 10 inches away. That should be an extra, optional, exercise for skilful young optical experts.) C13 OPT

The first time, the telescope should just be used for looking at things. When we return to it later pupils should try estimating magnification, and some may practise moving the final image to different distances, ranging from infinity to ten inches.

EXPERIMENTS WITH RAY-STREAKS AND CYLINDRICAL LENSES C14

These experiments are intended for two purposes:

1. To enable pupils to find out, or see for themselves, some simple important properties of lenses, rays and images.

2. To enable pupils to illustrate, with real rays, the behaviour of some optical instruments.

A Series of Experiments

As with the earlier group of ripple tank experiments, C 4, all the experiments of this series are grouped together under one number, C 14, because they are intended to form a sequence that pupils will work through at their own speed.

Some pupils will take much longer than others to try out the suggested arrangements, and they should be given time for that. Faster pupils will find suggestions at the end of the series for quick, difficult, extra experiments, to serve as 'buffers' while others catch up.

We hope teachers will not divide this group of experiments sharply into separate parts, (*a*), (*b*), (*c*), ... and give a definite time for each, but will encourage pupils to continue from one to another at their own speed. That does not mean that we suggest giving pupils the complete selection of lenses at the very beginning. We should provide more and more equipment in stages.

The apparatus suggested for these experiments (and used by the trial schools) differs considerably from the usual arrangement of a ray box with a lens and a set of slits. Our group of class experiments is intended to go much farther than a demonstration or even a class experiment to trace rays through a lens. Treated as an 'open' experiment, the group offers to show pupils the way in which real rays of light behave with real lenses as used in optical instruments. They see rays coming straight out (in all directions) from an object point, becoming fainter as they go farther; being bent by a lens so that they all converge to an image point and stream straight on through it; or being bent so that they splay out from a virtual image point. They see that the real behaviour of rays falls short of the ideal of passing through images exactly; and they learn a little about correcting for that 'aberration'. Then they make models, with real lenses, of optical instruments such as telescope, microscope, eye with spectacles, seeing in each case how the lenses treat a sheaf of real rays.

This equipment is meant to act as an interpreter taking young people for a real trip through a foreign land. Just as in a real trip, the contact is artificial in several ways: the views are chosen for the tourists and pointed out to them; and the interpreter modifies the reality. Here we suggest arrangements of lenses and we choose lenses that will show interesting things clearly; and the story is modified by our having to use *cylindrical* lenses. Yet we then leave pupils alone to try things, and they learn a lot without realizing it. After using the real instruments with spherical lenses, they will come back to these model experiments and gain valuable understanding.

Therefore we suggest it is worth while to use our special equipment. Here are some details:

Equipment

Lenses. The lenses are plano-cylinders of glass, ranging in power from +7D ($f = +14$ cm for a telescope objective) to +17D ($f = +6$ cm for a strong magnifying glass or telescope eyepiece). Glass is chosen rather than plastic because its higher refractive index does not require such steep curves for the same power, so that the aberrations made by the outer parts of the lens are not so severe. However, the lenses have a wide aperture – 2 inches – so that aberrations are noticeable; and then the aperture can be cut down by using small blocks of wood as barriers or stops.

Lamp. For 'object' we use the vertical line filament of a lamp. To make rays that will form long visible streaks across a sheet of paper, we need a bright lamp: 24 watts is the minimum and 48 watts would be better. Light from the filament, which is placed a few inches above the table, spreads across white paper on the table. A metal screen with a vertical slit in it placed near the lamp lets a single 'ray' of light stream through, across the paper. Actually, the 'ray' is a narrow pencil of rays: it is a thin vertical 'knife-blade' of rays. Since the lamp is above the paper that 'knife-blade' cuts the paper and makes a long visible streak where light is scattered by the paper. That visible *ray-streak*, with many others like it, is all that pupils see, but that will tell them how rays behave when they meet lenses, etc.

If the lamp is lowered, nearer to the table, the streaks extend farther but are fainter. Pupils must be able to raise and lower the lamp easily to adjust the length of streaks to the needs of each experiment.

Since stray light will be inconvenient, the lamp must carry its own shade with a wide slit at one side; and there must be an outer shield resting on the table to stop stray light and yet allow the lamp and its shade to be raised and lowered.

All these experiments will need a darkened room: half to three-quarters black out.

Comb. For most experiments pupils do not use a single slit but have a comb of many parallel, vertical, slits. An ordinary hair-comb does poorly for this, because its slits are not long enough; so we provide a painter's graining comb of steel, which has beautifully even slits. Since graining has died out as a decorative art, these combs are not easy to obtain now; but we hope schools will obtain them and not be content with fewer slits or shorter ones. Nor should home-made slits be used even if cut very skilfully with a saw; because there will be unevenness which will spoil the experiment.

Slits and Slit Holder. For a few experiments – less important than our main ones with a fan of rays passing through each image point – pupils use a single ray to see how it is treated by various parts of a lens or by a plane mirror. That is made by the single slit mentioned above.

Pupils also need a metal screen with three slits, to make some simplified ray pictures for instruments (as will be explained later in detail).

Each of these screens and the comb will in turn need a simple holder. Pupils will move the object lamp to various distances, so the slit holder must *not* be attached to the lamp. It should be freely movable on its own. Therefore we suggest a small block of wood carrying a small vertical 'bulldog clip' that can hold any screen.

Barriers or Stops. Although the lamp is housed in a shade and shielded, light from it will spread in a fairly large angle and some light will miss any lens pupils are using. Therefore they need some blocks of wood to act as barriers or stops, to shut off unwanted light. These barriers can also be moved in to narrow the aperture of lens that is used; therefore they are essential parts of the equipment.

Paper. The ray streaks are made visible by white paper, not *
too glossy, spread on the laboratory table. (There is a tradition of *
raising that paper on a drawing board. That is of no advantage.) *

Need for Cylindrical Lenses. With cylindrical lenses, placed *
with their axes vertical, the ray streaks that converge to an image *
go straight through the image point and show on the paper just as *
clearly beyond it. With spherical lenses, rays of light are bent in a *
vertical plane as well as in the horizontal plane; and the picture *
will disappear beyond a real image point. Rays of light that would *
show the ray streaks continuing beyond such an image point would *
have had to come up through the paper from some lower part of *
the lens! Therefore cylindrical lenses are essential and teachers will *
find that pupils do not seem to regard them as spoiling the story – *
particularly since we also suggest a very good three-dimensional *
demonstration with a spherical lens in a box of smoke. *

Equipment List. The following equipment‡ is therefore suggested for this group of experiments, for *each pair* of pupils:

Lamp with vertical line filament, 24 watts (or 48 watts) in shade with aperture at one side, on a small stand to make the height adjustable, with a shield on the table to cut off the rest of the stray light.

Transformer for lamp (one to serve several lamps).

Wood block with bulldog clip to hold slits. Also 2 or more plain wood blocks to act as stops or barriers.

One or two graining combs to act as multiple slits. One metal screen with a single slit. One metal screen with three slits.

White paper, foolscap or larger, not very glossy.

Plano-cylinder lenses as follows. (These should be of glass with good optical surfaces, two inches wide by two inches high. There should be a few spares, so we advise sets of twenty lenses of each kind for a class of sixteen pairs of pupils. These lenses are not easy

‡ Since this list will remind teachers of various forms of ray-box equipment, we wish to warn them once again that the use to which we put our 'ray-streaks' apparatus is much more general, as a series of class experiments, so that it requires much fuller equipment arranged for class experiments. Therefore we urge teachers not to rely on ray-box equipment already in the laboratory but to install the full sets described here.

to store safely unless they can be placed in proper boxes. Therefore we advise schools not to purchase them except in boxes that will hold a batch of twenty of a kind. In dealing with these lenses in a half-dark room, it is a great help to have lenses of different powers labelled with different colours according to some code. We suggest small sticky labels or a splash of paint in one corner.)

Converging, +7D (focal length 14 cm, for general use and for telescope objective).

Converging, +10D (focal length 10 cm, for general use and for objective of model microscope).

Converging, +17D (focal length 6 cm, for general use, magnifying glass, eyepiece of instruments, and possibly for stronger objective for microscope). Since in the last case we shall need both eyepiece and objective, two of these lenses should be provided.

Diverging −17D (to see what a diverging lens does, and in particular to help to teach the idea of a virtual image).

There should also be some mirrors:

A small piece of plane mirror to be held vertical.

A cylindrical mirror, of wide aperture (at least 120°).

Teachers will find it wise not to give pupils the complete assortment of lenses and mirrors to begin with. It is better to supply each as it is asked for. In some cases, pupils will need more lenses than they have; and then they should be encouraged to borrow for a short time from a neighbour.‡ *****

The Series of Ray-Streaks Experiments

Ray Streaks. The lamp with bright line filament and a comb in front gives a sheaf of rays that travel out in straight lines; and this itself is optical observation. Do not have pupils record this; but let them look at it and see that the rays are straight. C14a

‡ Alternatively, extra lenses can be placed on a side bench as a 'cafeteria'. Pupils can then help themselves to a different sort of lens, try it, and return it. This illustrates an important point in the management of this series of experiments: that pupils should be expected to proceed at their own rate, occasionally drawing upon extra apparatus when necessary.

(If the rays look crooked, the teacher should examine the filament, because a crooked filament will give fuzzy rays and in some circumstances they may even look crooked.)

Lenses. When a positive cylindrical lens is placed to receive a fan of rays, it will make them converge and pass through an image. Pupils should use a lens of power +7D (that is, 14 cm focal length), or +10 would do, and see that the rays are straight after the lens – that rays from a single object point do, after passing through a lens, pass through an image point, and go straight on through it. C14b

Again, no notes need be made because this is general information which will be reinforced by pupils seeing it again and again.

Pupils may need some help in raising or lowering the lamp house so that the streaks extend far enough out along the white paper on the table. Apart from that, they should be encouraged to move the lens, twist the lens, shut down the aperture of the lens, by moving in wooden barriers, and so on.

Good Image. Then they should treat the lens more carefully: first make sure that its face is perpendicular to the central ray, then shut down the aperture until they get a fairly well-behaved image. C14c

They will probably ask for another lens to add in series, and should borrow an equal one from neighbours. C14d

Stronger Lens. And then they are ready for a stronger lens. We give them one of power +17D, (focal length 6 cm). When pupils complain about spherical aberration, we should say: C14e

> 'Yes, that is a real "disease" of lens behaviour; we have to learn to live with that.‡ We either use a small aperture of lens (as in a T

‡ Of course spherical aberration ought not to be called a 'disease'. It is natural optical behaviour. It results from rays of light being bent, according to the natural laws of refraction, at the surfaces of a spherical lens. It is our wish that the lens should form a perfect image; but it happens that that is not the natural result of combining Snell's Law ($\sin i/\sin r$ = constant) with the geometry of spherical surfaces. Fortunately that combination produces an *almost* perfect image, for rays from a point object, when the object is near the axis of the lens and the aperture is small, so that none of the rays hit the lens surfaces very obliquely.
Thus spherical aberration is an unwelcome natural behaviour, not a misbehaviour and certainly not a disease.

cheap camera) or try to put several lenses together so that the misbehaviour of one lens compensates for the opposite misbehaviour of another. That is a very difficult business and if you tried fitting several lenses together yourself you would find it difficult and confusing. We shall not go into it here.'

Negative Lens. Then we offer a negative lens, power −17D (focal length −6 cm). We offer that at this early stage, partly for general experience, partly to introduce the idea of a virtual image without complicating matters by making it seem a special case of behaviour for a converging lens. Pupils see the ray streaks splaying out steeply from a virtual image and can point to its position when we ask them. This is a stage when the teacher should go round and ask questions about that image and ask whether, from the point of view of eyes looking at it, it would look any more unreal than a real image. C14f

It may be helpful for the teacher to say, 'Suppose you are looking head-on at on-coming traffic, and do not know whether the cars have come from side roads or directly along the main road. Your eyes cannot tell if the light has been bent, when you look head-on.'

Moving the Object (Lamp). It is now time to try moving the object, both sideways (watching how the image also shifts from side to side) and longitudinally (to see where the image goes when the object moves to a different distance). C14g

For that, pupils should return to a converging lens, +7D (14 cm) or +10D. After watching how the image waggles to-and-fro sideways when they move the lamp sideways, they should try moving the lamp to much greater and much smaller distances. Here, a case of a virtual image will again appear.

Such observations with ray-streaks are *the best way for students to learn quickly what virtual images are.*

Virtual Images. Thus, in looking at the behaviour of lenses when a fan of rays meets them, pupils will find cases of a virtual image and the teacher should at once give that name and encourage pupils to think of that as a perfectly good image although one cannot put one's finger on it. (Soon we shall be talking to pupils who wear spectacles about the virtual image that they are always looking at; but we should not mention that yet.) C14h

Looking along a Ray. From time to time, encourage pupils to squat down and look along individual rays from the other end; then looking along and through the lens they will think each ray is completely straight, not even bent by the lens. That will help in the discussion on virtual images. T

This is a point at which we should give some encouragement towards believing in virtual images and not thinking them too queer to be useful. But we should not stop the laboratory investigation to give a lesson on the blackboard with diagrams of rays. This is a time to go straight on with experiments enjoying them as much as possible.

Single Rays. Then ask pupils to narrow their investigation down to a single ray by using a screen with one slit instead of a comb, and watch what happens to that ray when it hits various places on the lens. They should start with a weak lens (+7D, focal length 14 cm); then they may try stronger lenses. C14i

Plane Mirror and Concave Mirror. This is the time to give pupils a plane mirror to watch what that does with a single ray. C14j

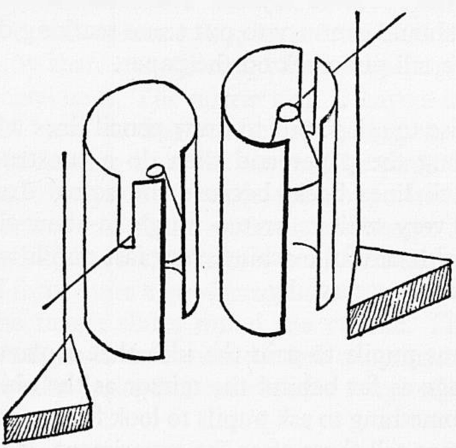
We shall not do justice to spherical mirrors in optical instruments *
in this course; but we shall use a plane mirror as an important easy *
case of an image-former, which we can treat experimentally with *
rays of light and with water ripples and possibly for a very fast *
group by ray drawing. *

Optical Centre: Undeviated Rays. Ask pupils to find the place in or on the lens through which rays proceed without being bent. Give the name 'undeviated ray'. C14k

Pupils should try directing the ray at the optical centre from several different directions to see that in every case the ray's direction is not changed. Tell them that we shall use the idea of an 'undeviated ray' again and again in drawing pictures to illustrate optical instruments. (Two undeviated rays, from 'top' and 'bottom' of the object, will enable one to deal with the magnification.)

Two Object Lamps. One pair of pupils borrows a lamp from neighbours (who join this experiment). The two lamps are placed close together side by side 2 or 3 feet from a comb and lens to represent two points on an object. C14l

A piece of coloured cellophane should be placed in front of one lamp, to distinguish its rays clearly. This will show the relationship between object size and image size. It is necessary to explain to pupils that the two lamps are meant to represent the 'top and bottom' of an object, or any two specimen points on some object. It is not obvious to beginners that we know a great deal more about the behaviour of an optical instrument when we see what it does with two such points, or with an extended object. To us it is clear that we then know something about the magnification the instrument provides; but we need to point that out to pupils. We also explain that this object is 'across the axis', not an object lying along the axis of the telescope. Arranging the lamps for this presents considerable difficulties and we should help pupils to arrange their lamps successfully.



Familiar Knowledge: Notes? All this is just a time of playing with rays and lenses to gain familiarity. Stopping to make detailed notes in notebooks would cause unwise delays; and far from making discipline easier will make it harder by interrupting what should be a stream of keen experimenting. * * * * *

Using Three Rays: Artificial Simplification. Later on, when we wish to illustrate the action of optical instruments without being confused by spherical aberration of the outer rays hitting a strong lens, we avoid the trouble by giving pupils a screen with three slits instead of the comb. Then they should use the ray through the central slit as the axis of the optical picture and the other two rays as a pair of symmetrical rays each hitting a place far out on the lens. This is, of course, cheating, merely concealing the spherical aberration that is there. Pupils should know that; and they should know C14m that spherical aberration is only a minor 'disease' for most lenses, but a very important major one that must be corrected in the more complicated lens systems of microscopes.

Cutting off Rays. When pupils are doing experiments with a fan of rays, it may help if the teacher moves round amongst them, to straighten a lens or offer an extra lens to move in. And he can slide a small piece of cardboard in across the fan to cut off ray after ray. That demonstration of successive rays being cut off (or admitted) seems to help pupils to understand what is going on. C14n

Then pupils should shoot a fan of rays at a plane mirror. The lamp house should be moved quite close to the mirror so that the virtual image is obviously somewhere on the actual paper. Pupils should look along the reflected rays to 'see where they seem to come from'. They should even try to put some marking device at the image, such as a tall pin stuck on the paper. C14o

It is probably unwise to ask pupils to draw pencil lines where the ray streaks run along the paper and then do a construction of running those pencil lines back, because the actual drawing is going to be either very tedious or too rough to show the story clearly. However, with careful teaching, very fast pupils who have the time could do that successfully.

In any case we want pupils to gain the idea that a plane mirror forms a virtual image as far behind the mirror as the object is in front. This is not something to ask pupils to look for or verify; it is not even something to tell them after the experiment. If this kind of practical work is to have any value in showing what science is, we must wait until pupils find this for themselves. We may urge them towards it and give hints if necessary; but even slow pupils can 'discover' this, and will have great delight. At once we break off from ray-streaks and ask pupils to look at it 'in the flesh': a real candle in front of a plane mirror (see below). Remember that our ray-streaks are only for investigation and illustration, to make the three-dimensional optics of everyday life clearer.

Experiments with Mirrors

As a class experiment, we ask pupils to place a candle, as object, in front of a large plane mirror and look at its image. Then they should try to place a second, similar, candle just where they think that image is. (Remind them that the second candle is not the image itself of the first, perhaps not even *at* the image of the first: it is only C15 an 'image-catcher'.) Then they should try removing the mirror quickly while they are looking at the first candle and its image – or they may raise their heads quickly and look over the top of the mirror.

To the rare pupil who says at this point, 'I saw that when I T
watched circular ripples being reflected at a straight wall', we give high praise. To the still rarer one who then says that this suggests that light may be waves we need give no praise: he already knows he is to be a scientist.

Spherical Mirrors. Although we shall not use spherical mirrors for instruments, we should give three experiments with them:

1. A class experiment with a wide fan of ray streaks directed at a C14p
concave cylindrical mirror.‡ A glass mirror will show the effect more brilliantly than a metal one, but it is so fragile that schools may prefer metal ones. The mirror should have a large 'aperture' (at least a 120° arc) so that instead of passing through an image point, the rays envelop a caustic curve. The pupil slides in a card to cut off ray after ray; or two cards, from opposite sides, to narrow down the aperture and obtain a reasonable image. Then the pupil slides in a card with a wide slit in it to let through a narrow fan of rays that will form quite a good image. As he slides the card across the comb, the image slides round the caustic. This experiment (F. A. Meier's famous 'mirror and comb experiment') is a delight to see and contains in its demonstration a range of quite advanced optics.

This can be done as a home experiment, using the inside of a shiny H14p
tin for the mirror, and an ordinary comb to make the rays. The Sun does well as a light source, or a transformer and lamp might be borrowed.

2. The optical illusion demonstration in which a spherical mirror D16
forms a real image. A small object, say a red marble, is placed near the centre of curvature of a large, good spherical mirror, a small distance below the axis. The marble is held, upside down, concealed in a small box. Another marble, a blue one say, is placed as a decoy, at the *same distance* from the mirror and above the axis; so it is just above the red marble; and, being placed above the box, it is

‡ Since this is the only time cylindrical mirrors are used with ray streaks, it seems extravagant to buy a full set of them. We suggest that schools should buy a few and place them on a side table as a 'cafeteria'. Pupils can take a mirror when they reach that experiment, try it, and return it.

clearly visible. An observer looking at the blue marble sees (if it is well placed) what he thinks is an equally real red marble beside it.§ See *Guide to Experiments*. Some pupils will enjoy looking at the real image with a magnifying glass.

With a mirror of large aperture we can add a further convincing touch: we switch on a small spotlight that illuminates the visible blue marble. The 'imaginary' red marble is at once illuminated too. A pupil who understands why that happens is doing very good optical thinking.

3. A spherical mirror in a smoke box. D8

Mirrors as Image-formers. With mirrors as with lenses, we
make the image the primary thing, leaving the laws of reflection *
and refraction to emerge presently as the primitive guides to the *
making of the images that we find so interesting to us personally. *

Understanding by Images. To pupils taught thus, the projec- *
tion lantern – in which the condenser forms an image of the source *
in the projection lens, while that lens forms an image of the slide *
on the screen – should seem an interesting intelligent arrangement, *
and they should succeed in drawing a good diagram for it. The *
optics of dark-field microscopy should be easy and even the *
Schlieren method, which many people misunderstand, can be *
made clear. *

Experimenting v. 'Messing about'

Just playing with a lot of lenses, with some of them twisted side- *
ways, and perhaps a mirror as well, will seem to any good teacher *
a very confusing business; and yet it seems to some pupils a very *
interesting business. This is obviously a case where experimenting *
can degenerate into 'messing about'. That may be a threat to disci- *
pline and perhaps damaging to progress; so we should discourage *
it gently but firmly beyond a fairly early stage.§§ *

Optics at Home. However, if a pupil wished to take the whole H17
outfit home with him for the weekend, lamp, transformer and all,

§ 'This was the first time the whole class had been *convinced* of the existence of an image in space.'

§§ 'But, in fact, some of the faster ones did this. One went round and said "Well, that's all very well, but what happens if you try this?" and got some interesting and advanced optics. Free teaching, for a later stage.'

that would probably be very valuable if it could be allowed.‡ We do not have in mind the fastest or brightest pupils particularly for that. A slow pupil may gain even more by developing a sense of being an expert, a feeling that he is 'the man who knows' what lenses do. This may even be valuable in its effect on parents and what they think we are doing. One might fear that parents would consider such experiments childish and messy and inconclusive; but in that we are forgetting the way in which a good parent can encourage a child to pose as expert.

FURTHER EXPERIMENTS WITH RAY-STREAKS. INSTRUMENTS

According to their speed and interest, pupils may want to continue *
the series of experiments straight away, with models of optical *
instruments. However, some pupils will want a change now, so it *
may be better to proceed to real instruments – a second round *
with the astronomical telescope, the magnifying glass examined for *
magnifying power, and a crude model of a compound microscope. *

In that case, we must certainly return to the ray streaks experi- *
ments and set up models of those instruments as soon as the real *
ones are done, or this whole series of experiments will lose its main *
point. We suggest the following class experiments with ray streaks, *
now or later. *

Model of Telescope with Ray-Streaks (probably best done after C 18)

Place the lamp several feet away and suggest to pupils they should C14q
raise it as far as they can without making the streaks too short, so that the streaks are bright enough to see easily. Use the weakest

‡ 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.

converging lens, +7D (14 cm), as the telescope objective and place a graining comb outside it a few inches towards the lamp.

We should *not* tell pupils 'which way round' to place that lens. We should ask slower pupils which way round they think would be better and suggest they should try. We might just blame faster pupils for foolishly forgetting what they have learnt if they start with it the wrong way round or if they come to ask which they should do.

We use the strongest converging lens, +17D (6 cm) as eyepiece; and in this case we tell pupils it will be better to place it with the light meeting the curved face. Pupils who have not yet done an experiment with a real astronomical telescope may not know quite where to place the eyepiece. Those who have should know; and they should enjoy placing it suitably and seeing what it does to the rays of light. If aberrations spoil the picture, pupils should of their own accord move in barriers to reduce the aperture.

Pupils should try removing the combs, so that they see the full cone of light. The teacher should move round among pupils and help them to arrange the model so that the rays emerge from the eyepiece in an almost parallel beam. Or, with faster pupils, one might suggest having a beam that diverges from an image which is about the same distance away as the object (lamp).

When visiting pupils, the teacher should tell them how to move the lamp sideways and watch the ray streaks emerging from the eyepiece to see how the virtual image moves. With care and a little acquired skill, pupils can see the magnification clearly.

However, the magnification is shown more clearly if pupils have two lamps, representing two points on the distant object. For that, one pair of pupils should borrow the lamp belonging to a neighbouring pair and all four of them make a model telescope as follows: the two lamps are placed very close together several feet away from the objective lens. (If, by good luck, one lamp is brighter than the other the rays from these two object points will be easily distinguishable. Better still, a filter such as a piece of coloured cellophane or gelatine should be placed in front of one lamp. The lamps should be very bright, over-run.) The lenses must be carefully placed so that the rays from both lamps make only small angles with the axis of the objective; and the eyepiece must be shifted until it treats the two sheaves of rays equally. Pupils will see the two real images formed by the objective lens clearly; but the rays emerging from the eyepiece now form a rather complicated picture – except that now the 'eye-ring' will be clearly visible as a place where the two sheaves of rays cross, making a narrow region where an observing eye receives everything. Here it may be wise to change from the graining comb to a screen with just three slits.

Ray Streaks with Three Slits. If the screen with three slits is placed just before the objective lens, the rays from both lamps that pass through the central slit can be made to meet the objective lens near its 'optical centre' and these will represent 'undeviated rays' from two object points. The rays through the outer slits will hit the objective lens near each edge. Although the bending of those rays will be somewhat greater than it should be for perfect image-formation (the symptom of spherical aberration) that trouble will not be noticeable – because there are only three rays – provided the slits and objective lens are arranged to make the pattern as symmetrical as possible. For that, the triple slits must be moved close to the objective lens. C14q

Teachers who have once done that for themselves will find it easy to show pupils how to do it. Then, both with a moving lamp and with a pair of lamps, the whole behaviour of the telescope will look very close to the formal optical diagrams that one draws for such an instrument. (Of course this pattern will not contain a 'ray parallel to the axis that passes through the focus' and we hope that that construction will have dropped out of use here.)

Open Cones of Light: No Slits. Some pupils find it much easier to see what is happening in a model of an instrument if they remove the comb and let a full cone of light proceed from the lens to the image point of each lamp. This is a modification that teachers should try with pupils; though they should avoid changing completely to this, because then some of the behaviour of rays will be forgotten. C14q

Use of 'Field Lens in Telescope' (*buffer option for fast pupils*). A fast group, or a specially keen pupil, may like to try adding an extra converging lens (fairly weak) *at* the real image formed by the objective of an astronomical telescope. If a converging lens is placed exactly at the image, it does not alter the convergence or divergence of the fan of rays that passes through the image. To pupils who question that, we say 'If you stick your thumb on the glass of a magnifying glass and look at your thumb through the glass does it C14r look anywhere else except just behind the lens?' (If the distance from object to lens is zero, the distance of image from lens is also zero and the magnification is 1.)

However, this extra lens does do something: it tilts the whole fan of rays so that the fan emerges pointing in a different direction, unless it happens to hit the extra lens just in the middle. When we make a ray-streak model of a telescope with two object points (two lamps) the fans of rays through their two real images cannot both pass through the centre of the extra lens. Then we see that, although the extra lens does not alter the rays within the fan itself, it does tilt the two fans to pass through a more central region of the eyepiece. What is the advantage of that? The answers are: 'A larger field of view, less aberration, an eye-ring which is not so far outside the eyepiece.' The enlarged field of view is the important thing. We should not tell a fast pupil any of these but should coax him into thinking of them.

Model of Compound Microscope with Ray-Streaks

This is an important ray-streak experiment for all pupils to do just before or after they make a model microscope with spherical lenses and use it to see it really magnifies. C14s

However, the ray-streak model is difficult to arrange in a way that shows the optical story sensibly, even when using the screen with three slits. So we suggest using the converging lens of power +10D (10 cm) as a low-power objective, in which case we must make our whole model rather long.

Tell pupils to place the objective with its *flat* face towards the lamp and move the lamp up closer and closer to the lens until the real image is about three times as far away as the object. Then place a strong lens, +17D (6 cm), to act as eyepiece. That will make an instrument about two feet long. By moving the lamp to and fro sideways, the pupils can see that this instrument does magnify considerably. It may be possible to crowd two lamps very close together to act as a double object.

(It is possible to make a much more powerful microscope model by using a lens of power +17D (6 cm) as objective and a similar one as eyepiece, but that is difficult to arrange, because the lamp has to be moved very close to the objective; and it is hardly possible to crowd two lamps together side by side close enough to act as a double object.)

Model of Spectrum with Ray-Streaks

Arrange a weak lens, +7D (14 cm), to form a real image of the lamp some distance away, say 2 feet. Insert a comb just before the lens, or just use an open cone of light. Then place a 60° prism just after the lens and turn it until the rays still form a fairly good image at approximately the same distance away though in a different direction. (In fact the prism should have the minimum deviation position for this, but of course we should not say so to pupils at this stage.) C14t

Pupils may notice signs of a spectrum at this new image position but it is not likely to be impressive, because prisms supplied for optics-teaching are mostly of low dispersion glass. The spectrum will be seen more clearly if a small piece of paper is held vertical above the table to catch the image. There pupils will see a series of images in different colours, which is the spectrum. Turning the prism to other orientations may give a wider spectrum, though it is likely to be less pure.

We do *not* recommend making a model of the spectrometer arrangement, in which two lenses are used so that the light hits the prism in a parallel beam. That makes too small a spectrum and pupils at this stage would see no purpose for the optical arrangement. *

Other Ray-Streak Experiments as buffer options, etc.

Teachers and pupils may enjoy devising many other ray-streak experiments: illustrating a Galilean telescope, curvature of field, distortion of field, a model eye with spectacles, etc. (For the model eye, a small cylindrical crystallizing dish filled with water will be a useful component.) *

A RETURN TO INSTRUMENTS

The Astronomical Telescope: Second Round

The first experiment that pupils do with a 'real telescope' should be quick and successful at all costs. Except with a fast group, the teacher should help pupils to place the final image, and to move their eyes back to a suitable place so that they enjoy having an optical instrument which does make distant things look much bigger or nearer. That is not the time for either drill or detailed explanation. 'Get the telescope set up and enjoy looking at things with it', should be the motto. C18 *

We hope the 'first round' with the telescope was like that. But now, after playing with ray-streaks, pupils should treat it more *

seriously. If they are to understand how a telescope works and to *
have confidence in making it work, we must now ask them to *
return to it and do the focusing themselves. And with very fast *
pupils we may ask for the image to be placed at a number of *
different distances. *

Some teachers in preliminary trials warn us that this return to *
the telescope may seem boring or unnecessary: pupils think they *
have already done the telescope and want to go on to something *
else.§ Therefore at this stage we should offer a carrot to encourage *
advanced work. We post a vertical scale on the wall and tempt *
pupils with the bet that they will not agree with each other about *
the magnification. Both the estimate of magnification and the *
placing of the image are challenges to the optical skill of these *
young people and if we present them in that light we may hope for *
hard work and success at this new level. *

This time we encourage pupils to move the eyepiece until they *
have placed the virtual image suitably for themselves. This needs *
careful teaching and much encouragement: there is a difficult hump *
here that we must get the pupils over. The teaching is difficult for *
pupils, and quite a strain for the teacher, but the reward is great: *
a competent skill in focusing optical instruments. *

It is essential for the teacher to go round and check each pupil's *
success in focusing. For otherwise many a pupil remains satisfied *
with optical nonsense – in good faith but a bad bargain. *

Teaching Focusing: Placing Images. There are a number of T
teaching tricks that can be used here to teach focusing:

a. Catch the real image (that the objective lens forms of the distant lamp) on a piece of paper. Look at that piece of paper with the eyepiece; and then take the paper out and put it back repeatedly, while dealing with the eyepiece – better still, take the paper half-way out.

§ 'This was very successful. The majority of pupils were able to place the image in a very short time. I think the ray-streak work was of great help. They showed considerable interest in what was really a "repeat" experiment. This was combined with an estimate of magnification.'

'No, I did not find this so, in fact the boys were thrilled to be able to set up the telescope so quickly.'

'Very diverse reactions. Some very keen to use it again, some not. More for than against. It is vital to have the first telescope session short. If they stop *while* they are finding it interesting they say "can we have them again?"'

b. Insist on the observer keeping both eyes open. Explain that this is something irritating and difficult at first, but easy to learn. This is not a case where the 'unused' eye learns to be temporarily blind (as with monocular microscopes). Here, we want that eye to look straight across the room at the distant object, and continue to watch it.

We say to the pupil (even tapping his eyebrow on that side with a finger):

> 'Keep this eye open. Look at the lamp over there with it. Go on looking at it. Think about looking at that lamp. Don't bother with the other eye, but just hold it in front of the telescope. *Go on looking at the lamp with the naked eye*, this eye. ... Now begin to think about the other eye as well, that is looking through the telescope. It is looking at a magnified image of the lamp. Move the eyepiece until the image looks just as clear as the actual lamp that you see with the naked eye. *Go on thinking about the naked eye*, but move the eyepiece and you will suddenly see the image just as clear as the lamp itself. *Go on thinking about the naked eye.*'

Many a pupil will succeed after that personal encouragement, with the teacher beside him. But there will be some who say that they simply cannot see the image with one eye while looking at the original object with the other. Most of these just need confidence, and we must give them full help, or they will get discouraged. The teacher should adjust the telescope for them and let them look through it with one eye, keeping the other eye open. He should talk to them about seeing both the image and the lamp 'over there on that wall'; and he should try showing them some trick methods that may be helpful (see below).

For this, the teacher himself needs to be skilful at moving the eyepiece until the final virtual image is situated back at the object. Practising for this will be fatiguing and even irritating at first; but an adult will find that by the third day of practising he has developed a comfortable skill.

(Of course a teacher who is sufficiently old in years has the great advantage that his range of accommodation is so small that he has only to wear his right spectacles for 'looking at infinity' and he can easily see whether an image is at infinity, because if it is anywhere else he is unable to see it clearly.)

c. As a trick to get the pupils to keep both eyes open and try to keep them focused for objects far away we say 'Raise your eyebrows and keep your eyes open, with "*wide-eyed surprise*".' That expression seems to be helpful.

d. Most amateurs use some form of 'no-parallax method'. We say to children:

> 'Look at the lamp over there with your naked eye. Look through the telescope at the big image. Now move your head sideways, this way, that way. If the image is back there on the wall with the lamp the two of them will stay together when you move your head; but if the image is much nearer to you it will slide across when you move your head.
>
> 'Hold your hands in front of your face at different distances and stick each thumb up. Wag your head from side to side and watch how the nearer thumb moves to the right as you move your head to the left. If your two thumbs are at the same distance, just side by side, they stay together when you wag your head.
>
> 'Now try that when you are doing a different job with each eye, one eye looking at the lamp, the other looking through the telescope at the image.'

We have to tell pupils to move their head a lot from side to side, moving our own head in an exaggerated motion to suggest it. For some reason their natural impulse is to wag it too little.

Some pupils will say that because their two eyes are doing separate jobs one eye's picture floats about on the picture seen by the other eye. This 'floating' is due to a harmless lack of coordination. The cure is to say 'It doesn't matter', and to suggest rubbing both eyes gently with knuckles.

e. Professionals often use their sense of where their eyes are focused. When they look through an instrument at an image 2 feet away and see it clearly, they know their eyes are focused for objects at 2 feet. This is not likely to be directly useful to a beginner; but occasionally it helps to tell him.

f. If the observer uses only one eye, and keeps the other eye covered, he can still compare the (virtual) image and an image-catcher placed above it, by bobbing his head up and down rapidly, thus looking alternately at the image and at the image-catcher in rapid succession. This is the only method for those pupils who have very unequal eyes or one eye that does not see well. (Those form a very small fraction of the population. The much bigger fraction who say they cannot place the image are most of them just in need of confidence and a first experience of success as for swimmers.)

g. With those who lack confidence, we can usually succeed if we give a great deal of help – practically locating the image for the pupil – then give lavish praise; then ask the pupil to locate the image again (giving an audible hint by heavy breathing as the pupil passes the right setting), again give lavish praise for success, this time more honestly; and finally encourage the pupil to succeed once more, this time with little or no help. Then we say, with honest delight: 'Look how skilful you can be.'

'The Image is Blurred.' Pupils will often say that the image is fuzzy or blurred. With any good lens (or a poor lens with a small aperture) any object near the axis leads to a good sharp image. Saying that the image is fuzzy or blurred merely means that one is trying to look at it with one's eye at the wrong distance from it, outside one's range of comfortable vision. We should not correct that mistaken remark fiercely or insistently at this early stage, but we may ask, 'Does a book become fuzzy because you move it too close to your eyes or because you hold it behind your head? Does your thumb really become blurred just because you whip the magnifying glass away?'

Young children have such a wide range of accommodation that they can see an object, or an image, when it is much nearer than would be comfortable for an adult; and their range usually extends beyond infinity.

The latter expression means that the child's eye can make a cone of rays converge to a sharp image point on the retina even when the cone arriving at the eye is already slightly convergent, going towards some previous image point behind the child's head. Then the child is looking at a 'virtual object'. (This ability of young eyes is traded on in the 'Baden-Powell Boy Scout Telescope' which consists of a very weak converging lens held at a short arm's length. The lens is so weak that it produces a real image several feet behind the boy's head. His eye intercepts the light on its way to that image – which acts as a 'virtual object'. His eye forms a retinal picture which is larger than the picture of the countryside formed without the lens. This device can also be used by a long-sighted adult without his spectacles or he can just hold his own spectacles out in front.)

Telescope: Measurements. When pupils set up an astronomical telescope for this second round, all should succeed in placing the final virtual image back at the object; and they should be able to readjust the instrument to that easily. The teacher should check each pupil's placing. C18

Specially skilful pupils should try placing the final virtual image at 10 inches, as one would for making notes in a notebook while observing.

A tall strip of paper on the wall marked with a horizontal line every 10 cm offers pupils a chance to estimate magnification. (The scale should be very brightly lit. It should be vertical, to avoid trouble due to foreshortening for pupils in oblique positions; it is easier to use if the lines are drawn with different colours in succession.) We should encourage as many as possible to make a rough estimate of magnification by looking with two eyes, one through the telescope at the image of the scale, the other, naked, eye directly at the scale.

(A discussion of magnifying powers, with a careful definition, is not as interesting to pupils as to us, and it does not strike any but the faster ones as a great advance in knowledge. So it is probably better to speak of magnification and estimate that, and leave it at that.) * * * * *

Optional Calculation. With very fast pupils we may say that if they make a *rough* estimate of 'focal length' for each lens, they can then predict the magnifying power of the telescope by calculating f_1/f_2. For that, the estimate of 'f' is good enough if pupils hold each lens in turn far away from a bright window and catch the real image on a sheet of paper. T

Model Telescope with Ray-Streaks. Now, if not before, pupils should do a class experiment with this. (See earlier description.) C14q

Magnifying Glass ***(with slower groups this may prove too hard)***

Pupils should use a magnifying glass as one of their optical instruments. We think that ought to be easy; but when we ask pupils to think about the virtual image and put it in a suitable place, they find it difficult. If we ask for an estimate of magnification, that is more difficult still. And if we discuss the magnifying power, we shall lose sight of the virtual image and pay too much attention to algebra. This is *not* the time for a discussion of magnifying-power formulae. C19

Pupils should use the same lens as for telescope eyepieces, a plano-convex lens of focal length 7 cm.

The object should be a *very* brightly lit piece of graph paper or millimetre scale. An easy way of providing good illumination is to install one of the lamps used for ripple tanks just above the object. The lamp can be held by a bosshead higher up on the same retort stand that carries the slide with the lens, etc. This arrangement is also very good for the compound microscope model. Pupils should try to place the virtual image on another piece of millimetre scale, as 'image-catcher', placed about 10 inches away. If they succeed, give praise and ask them to do it again. In making that adjustment, it is probably easier to move the lens or the object rather than the 'catcher'.

It is not necessary to point out that the image is magnified; but it is important to point out that the magnifying glass has pushed the image back to a comfortable distance where we can look at it easily. After all, that is what we use it for, to let us move the object close, and look at its image far enough away for comfort. (A short-sighted person can do that with his naked eye. Compared with us he has a 'built-in magnifying glass'!) T

Compound Microscope *(with slower groups this may prove too hard)*

Making a model compound microscope is much more difficult. That should come at the end of work with optical instruments, after pupils have learnt to place a virtual image where they wish, after a second round with telescopes in which they (most of them) do their own adjusting. C20

The arrangement for a compound microscope must depend on the equipment available in school. A plano-convex lens of focal length a few centimetres should be used as objective, with the plane face outward towards the object. (+20D, 5 cm, focal length, and diameter 10 to 15 mm does well.)

The eyepiece may be the same as the telescope eyepiece. A plano-convex lens of 7 cm focal length (+14D) and diameter 25 mm is suggested. It should be placed with its plane face outward towards the observer's eye.

A piece of graph paper or a short length of millimetre scale *very* well lit will make a good object.

Some people consider it best to fix these two lenses a suitable distance apart, 10 inches or more, on a wooden rod and use that as the 'microscope', focusing it by moving the rod (or else the object) until the image is back in the same plane as the object.

A class experiment with a model microscope like this is not likely *
to succeed unless it is done with apparatus that the teacher has *
tried out very carefully. If pupils can obtain an image that shows *
some magnification clearly and is at a reasonable distance, that is *
success. Measurement of magnification should be reserved for *
very fast and skilful pupils. Colour and distortion troubles will be *
visible, and some of the fuzziness of image will be due to spherical *
aberration. (An achromatic objective will improve matters greatly. *
Some suitable lenses are obtainable in secondhand optical shops.) *
We should praise pupils for obtaining an image that looks at all *
good and explain that good microscope lenses are expensive because *
they are complicated things that are designed to lessen some of *
these visible troubles. *

If some professional microscopes can be borrowed from the biology *
department, pupils will enjoy having a look through them, feeling *
that they now have expert understanding. *

Model of Microscope with Ray Streaks. Now, if not before, C14s
pupils should do a class experiment with this. (See earlier description under C 14(s).)

Eyes

Structure and Working of the Eye. We should tell pupils some T
things about their eyes as optical instruments. The technical names of various parts of the eye need not be given, but a big drawing of a section through the eye is useful, and a dissectable model of an eye is better still. Here are some brief teaching notes:

The eye is like a camera with quite a good compound lens system. (It is said that the eye is not completely corrected for spherical aberration and colour.)

The eye pupil is just the hole through which the light goes in. The iris is an adjustable diaphragm; but most of the adjustment of the eye, between sunlight and almost complete darkness, is done by changes of sensitivity in the retina – so that our eyes can vary over a range of 1,000,000 to 1 in sensitivity.

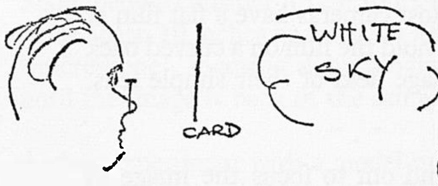
A camera is painted black inside; so is the eye, to lessen trouble due to stray light being reflected. Most cameras have a flat film at the back; but some small cheap ones hold the film on a curved back to allow for the curvature of the image field of their simple lens. The eye has a curved back.

A camera lens must be moved in and out to focus the image of objects at different distances. The eye changes the power of its lens system by means of muscles which change the crystalline lens.

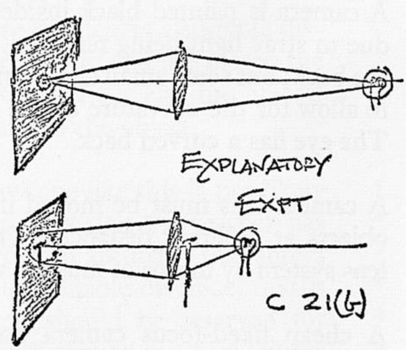
A cheap fixed-focus camera has such a small aperture that, even if an object is 'out of focus', the cone of rays from the lens to each image point is so narrow that it makes only a small 'blur patch' if the film catches it too soon or too late. The eye pupil closes down in bright sunlight, thus giving some 'depth of field'. And, in an emergency, a person who has lost his spectacles can read the telephone directory by putting a card with a pinhole in front of his eye and moving close to the page.

Inverted Image on the Retina. As in a camera, the image is inverted on the retina. There is no paradox there about 'learning to see upside down' because a baby learns to interpret optical sensations only by association with tactual ones. (Professor Cannon, who fitted his eyes with inverting spectacles, found it took him a little time to relearn. Then, after a time with the spectacles, he took them off and found the lesson well learnt – the world looked upside down for a while.) The usual experiment to illustrate this is surprising, but pupils find the reasoning obscure unless they see a demonstration with a model eye. (See sketch.) T

The experiment is done as follows: the observer holds a small piece of card an inch or two away from his eye against a background of bright white sky. He makes a pinhole in the card and looks at it. He sees a fuzzy white circle. He brings the head of a pin in, between the pinhole and his eye – close to his eye, in among his eyelashes. He sees a shadow of the pin upside down. For an object as close as the pin, shadowed by the point-source pinhole, his eye cannot possibly form an inverted image on the retina. The shadow on the retina is still 'the right way up'. The eye inverts the story by training and habit, because we know no better. After trying the pin the observer can bring in the edge of another card and cut off a semicircle. C21a



C.21(a)



C 21(b)

Explanatory Experiment. Pupils will be quite puzzled by the pinhole and pin experiment. However much we discuss it, many will *not* be convinced that this shows that the retinal image is inverted. But most will be convinced when they see an experiment with a large model eye in which this event of casting an upright shadow is demonstrated. We advise teachers to proceed at once to the model eye D 22(b). However, if that demonstration is not immediately available there is a simpler class experiment which may help pupils to understand the paradoxical inversion: T

Set up a lamp with a small filament as a bright object. Use a converging lens (e.g. the general lens of focal length 14 cm) to form an image of the lamp filament on a screen. Start with the lamp say 3 feet away from the lens and catch the image on a sheet of paper. Move the lamp up until it is much closer, say a few inches from the lens. Then the lens will no longer form an image of the filament on the sheet of paper held in the same place, but will make a round patch of light there. This is equivalent to the illuminated pinhole, held too close to the eye, making a blurred round patch on the retina. Then the pupil holds his finger between the lamp and lens, very close to the lens. The lamp will cast an *upright* shadow of his finger on the paper, in the middle of the illuminated patch. C21b

Spectacles

Commentary for Teachers. Discussion of spectacles will *
depend a great deal on the pupils who wear spectacles. Without *
them the discussion would be unconvincing and should be omitted. *
However, pupils with normal eyes can be shown what it is like to *

be short-sighted or long-sighted by being given a strong positive or negative lens to put in front of their eye.

The eye of fairly young adults has a considerable range of accommodation, 4 dioptres. The 'average' eye can see objects comfortably if they are anywhere between 25 centimetres (10 inches) in front and infinity. Over that range, the eye must change in 'power' (chiefly by changing the curvatures of its crystalline lens) by the difference between 1/0·25 metres and 1/infinity, that is a difference of $(4-0)$, or 4 dioptres.

Most eyes that differ from average have the same *range* of accommodation (in dioptres) but the near – and far – points are different. The latter difference is chiefly due to the front surface of the cornea having a different curvature from average. Therefore, a single spectacle lens, for a middle-aged eye, can change the placing of the 4-dioptre range of accommodation to the average placing. For example, suppose a short-sighted man can see things comfortably if they are anywhere between 10 cm and 16·7 cm in front of his eye. (Note that his accommodation therefore covers a range of 'power' of 1/0·10 metres to 1/0·167 metres, that is (10–6), a range of 4 dioptres as usual.) He should wear spectacles of such power that they form the image of a distant mountain at his far point, 16·7 cm in front of him. To prescribe spectacles for him we do not need any formula for thick lenses or for a combination of thin lenses in contact – which would be untrue of the actual combination. We simply *think* of the spectacle lens as an image-former that takes rays that come from an object point at infinity and makes them *seem to come from* a virtual image point 16·7 cm in front. He needs a lens of focal length $-16{\cdot}7$ cm or of power -6 dioptres. With that lens in front of his eye, he has the range of an average eye. When he holds a book 25 cm from his eye, his spectacle lens will provide a virtual image for him to look at. That will be 10 cm away in front of his eyes, at his near point.

Or suppose a long-sighted man has a near point 33·3 cm away. To read a book held at 25 cm (which suits his arms and is printed in type that gives a reasonable size of retinal image from that distance) he needs a spectacle lens that takes an object at 25 cm and gives him a virtual image at 33·3 cm to look at. He needs a lens of focal length 100 cm, or power $+1$ dioptre. Like the short-sighted man, this man too can keep his spectacles on for all distances. As a young adult, he probably has the standard *range* of accommodation, 4D. Then, with his near point at 33·3 cm his far point is 1 dioptre 'beyond infinity' – i.e. he can form a retinal image if he receives rays that are already converging to a virtual object 1 metre behind his head. He can profit from a 'Boy Scout Telescope'. His spectacles of power +1D pull his far point in from [1D beyond infinity] to [infinity]. So, when he wears them, his range is from infinity to 25 cm.

Although such spectacle-wearers could keep their spectacles on for all kinds of seeing, most remove them when looking at things within the range of their unaided eyes, for obvious reasons of comfort. Those who are astigmatic enough to have some cylindrical curvature added to their spectacles should keep them on.

The range of accommodation narrows down as one grows older. Old people have so little accommodation left that they need bifocals to provide a virtual image, at the right place for viewing, from either of two object distances.

Note to Teachers: Spectacle Lens Calculations. Calculating the power of spectacles is one of the cases where the formula $1/v$, etc., is of practical use. We should *not* make pupils learn to use the formula just for that, so we should not expect to find those calculations in examinations.

However, we should expect pupils to be able to do the following: describe clearly the limitations of various eyes; say what kind of spectacles are needed; and explain clearly in terms of images how the spectacles do their job.

A spectacle-wearer would prefer not to have his spectacles change the magnification. So the spectacles are placed approximately at the front principal focus of his eye. Then the combination produces a retinal picture the same size as without spectacles, but a sharp one. (This is not obvious. The algebra for two separated lenses is needed to verify it.)

We should bear in mind one peculiarity of real eyes: they do not have air in them. The materials inside do differ in refractive index, but the main change is at the front surface, hence the success of contact lenses. We cannot draw undeviated rays through the eye as we did for a thin lens with air on both sides. We need not mention this to pupils.

Model Eye

A demonstration model eye makes this teaching much clearer. There are some dissectable models available commercially, but the model described below is optically simpler and much more valuable in physics teaching. D22a

Fill a large spherical flask with water and a very little fluorescein – the less the better. Fit it with a more strongly curved 'cornea' by attaching a large weak glass lens to the front with plasticine.‡ D22b

A suitable flask is a round-bottomed 5-litre flask. That will have a diameter about 21·8 cm. For that, a suitable lens to be attached to the equator with plasticine is a meniscus lens of power +8D (focal length 12·5 cm).

Paste a ring of dark paper round the rim of this lens, as an 'iris'.

Then let this eye look at a very bright compact source of light – an arc or a compact filament lamp. Move that source to a distance at which the eye forms a 'point' image of it on the back of the flask. With the lens suggested (+8D) on a 5-litre flask of water, the object (lamp) will have to be about 20 cm in front, to be focused on the back of the flask.

At other object distances, there will be a blur patch instead on the back of the flask. A piece of wet paper placed there may help to show that clearly, but the chief thing to see is the progress of the cone of rays through the interior of the eye. (A shield should be installed near the lamp to cut off light that fails to enter the eye's 'pupil'.)

Then make a 'short-sighted' eye by changing to a stronger lens, stuck on the equator of the flask. (To save trouble, the lenses for normal, short-sighted and long-sighted eyes should be attached at different places round the flask's equator. The flask can be rotated to bring each lens into play in turn.) For a 5-litre flask we suggest a meniscus lens of power +11D (focal length 9 cm). With the source at the same place as before, this eye makes an image somewhere inside the eyeball, and the fluorescein shows that clearly. Then we add spectacles. We place the lamp at its *original* position, at which it was focused by the normal eye, turn the flask to the short-sighted eye position and add the right spectacle lens, by hanging a suitably chosen negative lens in front of this complete

‡ There are ingenious alternatives with watch glasses but these are harder to arrange and to repair.

short-sighted eye. That should be a lens of power −3D to make up the difference, (8D − 11D) or −3D.

We show that the short-sighted eye can see clearly without spectacles if the object is nearer. We move the lamp in to about $12\frac{1}{2}$ cm from the 'cornea' lens, so that the image moves to the back of the flask.

We change to a model of a long-sighted eye by changing to a weaker lens on the flask, $+5\frac{1}{2}$D (focal length 18 cm). Now, with the lamp at the *original* position at which it was focused by a normal eye, this long-sighted eye fails to bring the light to an image inside the flask. The light converges to a round patch on the back of the flask. A piece of paper held farther back behind the flask will catch the image – but refraction modifies its position.

We move the object lamp farther away till its image is on the back of the flask to show a long-sighted eye seeing a remote object unaided.

We then turn to the long-sighted eye and add a carefully chosen positive lens as a spectacle lens in front of it. That should be a lens of power (8D − 5·5) or + 2·5D (focal length 40 cm).

The full success of this model depends on careful choosing of the extra lenses.

With this model, it is easy to show pupils why the pin held close to our own eye and shadowed by light from a pinhole appears upside down. With the model in the form for a normal eye, we move the source much closer (to represent the pinhole) and hold a finger upright just in front of the 'cornea'. The shadow of the finger, in the huge illuminated patch at the back of the model, is upright.

A simpler form of this model is easily made from a goldfish bowl filled with water and a very little fluorescein. A small strong glass lens is hung in the water by tape from a stick placed across the top of the bowl. The lens should have a focal length of 5 cm or less and should be fixed in a hole in a disc of wood or metal, to which the tape is attached. Focusing is done by moving the lens forward and back inside the bowl. When short-sight or long-sight is simulated, a spectacle lens is held outside the bowl to correct it. This model, like the flask model, needs a strong compact source of light. D22c

Model to Show Accommodation. Stiff jelly is enclosed between two strips of thin Perspex, clamped together at each end, with the jelly bulging them apart in the middle to make a 'crystalline lens'. The ends of this arrangement are pulled by strings attached to a hacksaw frame. By changing the pull we can change the focal length of this jelly+plastic lens. D23

Dissecting Eyes

It is easy to learn to make a simple dissection of an eye. It is not a messy business; and, if one tells pupils they need not look at it, all will watch.§ One can get cattle eyes from the butcher. The eyes should be dissected within a day or two of slaughter, or there will be a confusing cloudiness. D24

A colleague in Biology will provide instructions; or the dissection can be done simply by making a cut with a razor blade and nail scissors in a circle where the clear cornea joins the white, tough, coat of the eyeball. The aqueous humour will run out, the iris can be separated from the rest, and washed in water. The crystalline lens can be picked out with a scalpel and tweezers. And then the jellylike vitreous humour can be taken out of the eyeball with a scalpel or knife. Although instruments can be borrowed from a Biology department, it is easier to keep at hand a scalpel, scissors, mounted pin, forceps, and single-edge razor blades.

We show the three sets of muscles (red meat) on the outside of the eyeball. (As a ball in a socket, it has 3 degrees of freedom (3 rotations), so must have 3 sets of muscles, otherwise successive rocking and swivelling motions could twist it and damage the nerve.) We can show the optic nerve as a fat white 'telephone cable' emerging at the back. And later we can cut along the nerve to the retina and show that it arrives at a special place, the blind spot.

Pick up the crystalline lens on a pin and show how it forms an image of the window. This gives an incorrect idea of its effective focal length, since normally it is surrounded by materials of a refractive index nearer to its own. So it is fairer to hold the lens in water and see what it will do.

Remove the jellylike 'vitreous humour' and show the retina, with its blood vessels outermost. Cattle, and many other animals, have an extra coating under the retina to reflect light back through it – that is the iridescent layer that one sees.

§ '"Please can we do it again?" was the comment.'

This dissection does not sound particularly easy, interesting or worth doing: it is all three.

Revision with Ray-streaks. At this stage, teachers may want to return to ray-streaks class experiments, to see lenses forming real and virtual images, as illustrations of eyes and spectacles. C14

'FORMAL' OPTICS Diagrams

Undeviated Rays. The ray-streaks will have shown pupils that rays through a certain 'optical centre' of a lens emerge parallel to their original direction, 'undeviated'. For a thin lens, such undeviated rays go practically straight through. We point out that if we know how far from a lens the object is and how far the image is, we can at once say how the image height compares with the object height (height being transverse to the axis). This is an important matter, since one of the chief benefits of a lens's image-forming behaviour is the change of size. T

The other benefit is change of distance: bringing a distant pine tree close to us so that we can look at its real image with a magnifying glass, or replacing an object that is outside someone's range of comfortable vision by a virtual image at a comfortable distance.

We insist that, whatever diagrams of rays and images pupils draw, they should always include undeviated rays – usually one from an object point on the axis, another from a specimen object point off the axis.

(One may mutter audibly,

> 'Anyone who doesn't put in undeviated rays as early as possible is either very lazy or very stupid: too lazy to do any physics or too stupid to see the enormous advantage of having undeviated rays there to make the image height true in the diagrams.')

Real Ray Diagrams. The following suggestions relate to drawing diagrams to illustrate the working of optical instruments. The tradition in optical teaching has placed great emphasis on diagrams, both to answer numerical problems and to show the way in which instruments treat rays of light or cones of rays. However, the drawing of diagrams takes considerable time and is apt to divert attention and interest from the real instruments. Able pupils will not understand optical instruments fully from their own experiments unless they do draw diagrams. So we make suggestions of diagram-drawing methods that will help our teaching, with fast T pupils. But we urge teachers with slower groups not to drive them to the long, harsh, rather puzzling discipline which the diagram-drawing we suggest might impose upon them. At most, teachers should try asking pupils to draw some of these diagrams and then leave them unless skill and interest develop quickly.

When they have gained, from the ray streaks, some familiarity with the way a lens treats rays, and with the meaning of 'real image' and 'virtual image', faster pupils should draw a few neat diagrams. We do *not* recommend putting in any 'ray parallel to the axis' in these, or the diagrams will soon be of the traditional type in which rays show a mysterious change-of-heart when they reach an image and thereafter sprout out to the next lens in a new direction. (We ourselves understand – and may use – those diagrams, which are purely quick constructions and do not represent the progress of real rays through an optical system. Pupils confuse constructions with real rays, and are then apt to think optical nonsense.)

We ask pupils instead to draw 'full-cone' diagrams that show the progress of all the rays from an object point hitting the full aperture of the lens. They should draw such cones from two object points, one on the axis, one off the axis.

Pupils should also draw diagrams of 'narrow-cones-to-eye' to show how an eye sees the final image. Details of the drawing of such diagrams and specimen diagrams for several cases of images, and for complete instruments, are provided in a separate booklet. We suggest that each pupil should be given one of these booklets. In some classes, pupils will use these booklets for guidance in drawing careful diagrams for homework. In other classes the booklets will serve merely as illustrations to be looked at after the experiments.

How much time pupils should spend on such diagrams, and how much care and neatness we demand, must depend on the judgement of individual teachers who know their pupils. It is easy to let this activity expand unprofitably. At most pupils should draw both types of diagram (full cone and narrow-cone-to-eye) for:

1. a converging lens forming a real image
2. a converging lens forming a virtual image
3. a plane mirror forming a virtual image

and

4. a 'narrow-cone-to-eye' diagram for an astronomical telescope.

Expanding beyond that minimum list is not advisable unless pupils have a lot of spare time for homework.

Object and Image Distances for Diagrams. To make diagrams showing instruments acting as image-formers, pupils need to know the distances of object and image from each lens. The usual practice is to give them object distance 'u' and focal length 'f' and ask them to calculate 'v' using the formula $1/v \pm 1/u = 1/f$. But, instead of that, pupils can quite well pretend that they are given 'u' and 'v' instead of 'u' and 'f'. Then they can draw the diagram, to illustrate the optical story, without using the formula. They can pretend that they have chosen (or bought) the right lens to make an image where they know – from the good optical sense they are developing – that they want it. Their only loss, if they do not know the formula, is that they cannot calculate 'f' and order the right lens from a lens maker.

As part of their good optical sense, all pupils should know whether the image is real or virtual, magnified or diminished for the following distances of object from a converging lens:

u very great; *u greater than f;* *u less than f;* $u = 2f$

They should know of 'f' as the distance from the lens to the image of a very remote object such as the Sun.

And it is very useful to know the general rule: 'In *any* optical system with only lenses (or with lenses and an even number of mirrors) when the object moves to the left, the image always moves to the left too.'‡

Measurements and the Lens Formula

Some skilful pupils may want to test the formula $1/v \pm 1/u =$ constant by measurements. Teachers who are practised in teaching these measurements are urged to treat requests for this work with much restraint. These measurements can take a lot of time, and may make a pupil feel temporarily powerful when in fact he is not adding much to his optical understanding.

The formula is hardly ever used in optical designing. It has remained an academic formula, useful chiefly for examination questions, and clouded by an unending wrangle about conventions of signs.

‡ We adopt the convention that 'moving to the left' includes moving out to infinity and continuing 'round the world', to come in from infinity on the right. Then this rule is universally true – as one may see by considering a lens as imprinting a constant change of wave-curvature.

However, if treated lightly the 'formula' can be put to one good use as a carrot to encourage pupils to practise placing virtual images. Nearly everyone uses an optical instrument sometimes and in most optical instruments – telescope, microscope, magnifying glass, spectrometer – the observer looks at a virtual image. Both for precision and for comfort, that final virtual image should be placed 10 inches or more away; but that is not a natural technique – people need to learn it.

In this programme of 'optics by images' we are offering to teach that technique: to give pupils a little skill and confidence in putting an instrument's virtual image in a comfortable position for good seeing. Practice in doing that – which *is* the necessary teaching – is likely to be unfamiliar, difficult, discouraging or boring. So it may be helpful if we can offer a competitive incentive: 'Can you place the image well enough to get reliable measurements to test a formula?'

In this case, we put the formula to what we should usually consider an immoral teaching use. We announce the formula and ask pupils to try to obtain measurements that fit it! That is putting an experiment in the worst light – far from our general attitude to experiments – but we can lessen the danger to pupils' picture of science by telling them what we are doing and why, though we do not put the project to them so baldly. We say:

> 'There is a formula connecting the distances of object and image from a lens ... u ... v, ... $1/v \pm 1/u$ is constant for a given lens. That formula can be predicted,‡ using geometry, from experimental measurements of the way a lens treats rays.
>
> 'If u is made very big – infinity – the image is at distance f. That is our definition of f. So, with $1/u = 0$,$1/v$ is $1/f$ and the constant in our formula must be $1/f$. We call that constant, $1/f$, the power of the lens.
>
> 'We shall not use that formula much; certainly *not* for any examination question. So we shall not show you how to predict

‡ Most physicists in deriving that formula, or the underlying form that is used for lens design, use a wave method. We might spoil the present teaching, which has not yet reached waves for light, if we told pupils that now. However, teachers might keep it in mind for a word later, because the wave method *is* so powerful. For example, it makes it easy to work out the power of a lens for 'flare spots' where the light goes zigzagzig through the lens with extra reflections.

it. But you might like to test it, to see if it holds for measurements with your lens.'

Optional Class Experiment. We give each pair of pupils a converging lens and a lamp to serve as object and a screen to catch real images on. We suggest using the lens of power +7D (focal length 14 cm) that was used with the pinhole camera, etc. It can be held in a lens holder on the slide used for the telescope. An ink mark on a lamp bulb, or the filament, will serve as object. C25 OPT

Pupils place the object at a suitable distance and move the screen until they have caught a sharp image of it. (Any pupil who points out that the image is likely to be sharper, because of less spherical aberration, with a smaller aperture and makes himself a stop for that, has an optical future.) Pupils make measurements of object and image distances, u and v, for three or four different object positions, preferably including the case when the object is very far away, at 'infinity'.

Quite rough measurements will suffice for this purpose. We are not aiming at making a precise investigation, or measuring a focal length for some special use. With greater precision we might be tempted to go into details of methods of measurement or corrections for thickness of lens; and the measurements themselves would take a lot of time; and that is not what we want here.

We give the formula and explain what it means and help pupils to take reciprocals. Here again we should run things quickly, providing a table of reciprocals – if possible one which gives them only to two or three figures. We ask pupils to add the reciprocals of u and v and see whether the total is more or less constant, as it must be if that formula gives a true story for their lens.

At this point we should talk to pupils about the importance of things that we find constant, in science. (See Note on 'Constant' in General Introduction.) That is, in nearly every case, how we express our laws of nature, in the form of something extracted from measurements which stays the same from one part of our experiment to the next. The constancy of that something is not only the essential part of our statement of the law: it is also an assurance about nature – that there *are* things that stay the same – such assurance is needed by all, children and adults alike – an essential basis for science itself. T

If all the lenses used by the class are of the same power – guaranteed by the teacher who has measured them or by pupils who have made quick estimates of the focal lengths of their lenses – looking for constancy is not restricted to each lens separately but can run over all the measurements made by the class.

The purpose of the experiment so far is to enable pupils to understand the formula and have a little confidence in it, as a secret preparation for the next stage. Then we lead them into testing the formula with virtual images. That will give them practice in treating virtual images, the whole object of the exercise.

We ask 'Does the same formula hold for *virtual* images?' We ask pupils to try one case of object and virtual image with the same lens. We give them considerable help so that they obtain a reasonable measurement quickly and can try that in the formula. After that they are likely to want to make more measurements on their own and that is where they will get valuable practice. T

For that first measurement with a virtual image pupils should place an object about half a focal length from the lens (say 7 cm for the lens of 14 cm focal length). The lamp is not suitable as object here; so we suggest using a piece of paper with a vertical ink arrow on it. (A pin will do, but we hesitate to bring in the traditional pin equipment which is likely to lead to a long diversion that would be quite out of place here.) The 'catcher' for the virtual image may be a tall retort stand seen above the lens and moved until the virtual image seen by one eye and the stand seen by the other eye seem to be in focus together, and remain together as the observer wags his head. C25

As soon as pupils have obtained one set of measurements of u and v for this, we hold a general discussion. We take one pupil's measurements and find the reciprocals and add them and look at the result with dismay. It is not the same as the earlier 'constant'. We ask for suggestions. It is quite likely that there will be none, and if possible we should then wait until the next class-time and again ask the question. That will do more good than answering the question straight away; but if it remains unanswered we must give the answer, in the form of a reminder that the image is virtual. We stop there again with a question, 'How can we show that in our calculation? What can we do?' If we cannot then elicit a suggestion, we must supply it: try giving the distance to the virtual image a minus sign, and its reciprocal a minus sign. The sum of the reciprocals will now be fairly near the previous total for most pupils. T

If pupils are intrigued by that, they will go on to make more measurements. If not, we should bring the experiment to a close.

Warning. This long discussion refers to an *optional* experiment that may be given to faster groups or other pupils with special interests. We hope that it will not be given to average groups because it will take more time than should be spared for this continuation of optics, and it may give optics a poorer reputation rather than a better one. In any case we regard it as far less important than the experiments with ray-streaks and the experiments with optical instruments.

Note to Teachers: Focal Length, *f*. In general optical knowledge, 'f' for a lens is an important constant such that $1/v \pm 1/u$ has the constant value of $1/f$. This applies to *all* object-and-image pairs, and not just to the special cases when one of them is at infinity. So optical experts regard that *general* property of 'f' as the important one. And many regard $1/f$, the 'power', as the more convenient quantity. With that in mind, we may be wise to place less emphasis on 'f' being the distance from a lens to the 'focus'.

We should make it clear that the image is only at the focus *if the object is at infinity* and *on the axis.*

For object points at infinity off the axis, the image is somewhere else in the principal focal plane (an optimistic word for the image-surface which is noticeably curved with real lenses). One ray of the parallel bundle passes through the optical centre, undeviated, and that ray gives us the place of the image in the focal plane.

If we start with an object fairly near the lens (say $u = f$) and move it farther and farther away to infinity, the real image moves in from its first position nearer and nearer the principal focus. In describing such changes, we usually say that the rays hitting the lens become more and more parallel as the object moves away. We should make it clear to pupils that any two rays (from an object) that make a certain angle with each other keep exactly the same angle and do not become more parallel as the object moves away! What does happen is that the selection of rays that the aperture of the lens receives becomes a smaller and smaller cone of rays as the object recedes.

BEHAVIOUR AND THEORIES OF LIGHT

Programme. *Pupils have gained a foundation of acquaintance with waves and light-rays. At this point, the proper way to build on that – with a good group of pupils – is to sum up ray-behaviour in Laws* *(treated briefly, stated informally), then raise the question of a 'theory' of light. In discussing theory, we should draw on our Laws for rays and on pupils' knowledge of waves from ripple tank experiments. We may show a model of refraction, and perhaps even describe a 'crucial' measurement of the speed of light. Then we show diffraction and interference, of both water ripples and light – and the balance swings in favour of light waves. We should end with a gentle warning against accepting a theory too firmly.*

That is the logical edifice that our programme deserves now; and teachers who feel the need should obey it. Yet, for many a class, that will demand more time than is fair for this section; and for many a pupil the discussion may prove too difficult to be interesting. If so, most or all of the material in the remainder of this chapter should be postponed to Year V.

In Year V, diffraction, interference and theories of light are offered afresh; and there they lead on to the dual view: light as particles (photons) and light as waves. The class experiment on interference of light is extended to a rough measurement of wavelength – which should certainly be postponed from Year III, for all but an extremely fast group. And the photon behaviour of light is taught by films, one of which shows filling-in an interference pattern. Therefore any teaching of interference that is given in Year III should refer forward to developments in Year V.

Pupils should meet the basic laws with which Optics is codified: T
laws of reflection and refraction. These should be seen with real rays. They need not be codified in careful statements of formal laws; but pupils should know what happens to rays when they meet a mirror or a boundary between two media. They should know about partial reflection at such a boundary and about total reflection – as interesting phenomena.

When they meet these behaviours of rays, we may suggest to them a simple 'theory' that bullets ploughing through matter without any friction might behave like that. That was one of the earliest optical theories. We should not tell pupils that this is the *correct* theory of light – nor should we tell them that it is quite wrong, in which case they would think it silly to mention it. (In fact, our view of light today embraces some of each view: waves to guide the progress of packets of energy, which we call photons.)

Then we let pupils see diffraction and interference. These are done in class experiments with some preparation by demonstration.

A discussion of those with ripple tank knowledge as background leads to a suggestion of a wave theory of light. Both the demonstrations and the discussion of theories appear fully in Year V.

At this stage, with young pupils still building acquaintance with physical phenomena rather than reasoning deeply about them, we should not spend long discussing rival theories; but we may introduce the idea of theories to 'explain' phenomena, then leave that discussion for further development in Year V.

Laws of Reflection and Refraction. Now that pupils have seen lenses and mirrors form images by changing the path of rays, we should give a short account of the events at those boundaries; and pupils should hear of the laws that are used to summarize our knowledge. The teaching can be done quickly and simply by demonstrations; or pupils can be given some apparatus to take home so that they can carry out investigations themselves.

For reflection, we want every pupil to be able to say – if possible as a result of his own observations – 'When a ray of light is reflected, the two angles are equal.' That contains the information of one law in informal wording.

If critics complain that the wording is too informal and not even sufficient, we might reflect that a great deal of scientific knowledge that looks formal and complete really needs a considerable amount of additional definition and commentary which we take for granted. (For example, Hooke's Law is an unrealistic ideal, incompletely stated unless we add commentary about its limits, state the categories of materials to which it applies and explain what we mean by 'extension', etc.) To a child 'the angles are equal' is a good clear statement of a delightful discovery about mirrors. If we insist on asking 'which angles?' a sketch gives a good reply.

If we were going to continue our optical studies into a detailed discussion of curved mirrors, we might wish to insist on the angles being measured from the normal – though even there one can use angles from the tangent. However, we suggest omitting curved mirrors entirely, except for general demonstrations.

The other law of reflection is clear common sense of symmetry in its idea but confusing in its formal wording. As scientists wrestling with the problem of conveying ideas to young people we ought to be clever enough to devise simpler wording and be content with that. It is probably wisest of all to leave that law unmentioned.

So we hope that, with slower groups, informal statements will suffice, such as 'the two angles are equal' and 'the reflected ray does not bounce off in a cockeyed direction'. T

With fast groups of future scientists the usual formal statements might be given. We trust that examinations will ask for well-understood knowledge of behaviour and *not* require the formal statements.

For refraction we have two possible levels of knowledge.

1. Pupils should see some examples of effects of refraction, in addition to the bending of rays by lenses that they have met so often. (See suggestions below.)

2. For very fast pupils the law $\sin i/\sin r = \text{constant}$ should be demonstrated. They should be able to state it in some form that they understand and might use.

Demonstrations and Class Experiments: Reflection and Refraction

Where the laboratory already has an optical disc (Hartl disc) for demonstration experiments it may be used here. It is a large disc with angle markings round the edge. It carries various devices at the centre: for example, a plane mirror. A lamp with compact filament sends a ray of light in through a slit at the edge, along a radius. That ray and the reflected ray make splashes of light on the white surface of the disc – in other words this is a demonstration ray-streaks apparatus, arranged for measuring angles. T

Reflection. Both teachers and pupils who are familiar with ray streaks experiments would probably prefer to replace such a demonstration by an experiment with a ray-streak hitting a mirror on a *paper* protractor. The ray should hit the mirror at the centre of the protractor's angle scale so that pupils can easily look for angle relationships. (Teachers who have tried asking pupils to make pencil lines to mark the paths of rays on a sheet of paper find that the experiment is rather tedious and the measurements not very accurate. So we suggest a simpler, quicker, look at reflection angles, by noting where the ray streaks cross the angle scale.) C/D26

We hope that the usual class experiment with a plane mirror in which pupils trace rays by pairs of pins can be omitted, as it seems * *

to take considerable time and it diverts attention from the great, *
precise law to the difficulties of manipulation. *

Refraction. For refraction an optical disc can be demonstrated with a semicircular block of glass, which must have its back surface frosted or painted so that the path of the ray inside the glass is clearly visible. Angle measurements with this are not very impressive and take considerable time. D27a

Measurements in a class experiment with a ray-streak and a semicircular block of glass (or tank of water) are likely to take even longer and be rougher and the geometry is puzzling to some. Careful measurements with pins and a rectangular block of glass are likely to be still more tedious; and though they are pleasing to some pupils with neat fingers, they are likely to obscure the essential investigation with their details of aligning and drawing and measuring. So we urge teachers *not* to use semicircular blocks or pins and rectangular ones. Instead, we suggest that most pupils will do much better with the qualitative experiment described below.

As a class experiment (or if time is short as a demonstration), pupils use ray-streaks to look at the bending of rays of light as they travel from air to water, or water to air, at a plane boundary. A large transparent plastic lunch box is used as a tank for water. It is filled with clean water to a depth of several inches and ray-streaks are directed at its side from a lamp and comb. The streaks will show on white paper on the table while they are still in air; but in water they will not show unless the *inside* surface of the base of the box is painted with flat white. (That is because total reflection at the air surface underneath the box will prevent light getting out to paper on the table.) D27b

With the lamp outside, sending rays towards the box, pupils can see how those rays are bent when they strike the water surface at various angles. This is not the stage at which they should make measurements of those angles. They might well sketch what they see and sum up the behaviour in some simple general wording of their own. We hope that they will also notice the partial reflection at the surface.

Then the lamp is carefully placed inside the tank, under water. With the comb nearby, it will send out ray-streaks through the water and pupils can see what happens when those streaks meet the water–air surface. They will certainly see rays being refracted as they emerge into air. We hope they will see total reflection without any prompting. If not, the teacher must give a hint.

It is possible to make the rays visible in water by another method; we add a little milk or mud or very little fluorescein; but the white painted bottom seems to be better.

Partial Reflection. We should make sure that pupils notice that when a beam of light is refracted at an interface, some of it is *reflected.* One sees that in looking at a picture mounted in glass. It bears on the conservation of energy. D27a

All pupils should see clearly that rays passing from air to water or glass are bent nearer to the normal; and that rays travelling in the opposite direction follow the same bent path.

With a fast group the teacher should measure angles for half a dozen rays and show them how to find a connecting law between those angles. However, with any other group, extracting the law of refraction will seem a difficult puzzling business: it is best avoided. The algebraic form of the law is *not* essential to the discussion of the 'crucial experiment' to distinguish between waves and bullets. T

Pupils with time and interest will gain much more if they do their own qualitative experiments such as:

1. Look at a penny in a beaker (or in the kitchen sink at home). (*Note.* Avoid using a narrow cylinder such as a test-tube, because the curved meniscus may spoil the simple effect.) C28a
2. See the 'bent stick' – a wooden rod in tank of water. C28b
3. Look at the 'apparent depth' of a pond, or look at one's toes in a bath. C28c

and

4. All should look at a ray streak passing through a prism, to see the bending of the ray. We do not suggest looking for dispersion yet, but we praise those who notice it. C/D28d

Spectrum

Pupils should see dispersion making a spectrum, now or in Year V. In the ray-streaks class experiment, they should see a single ray being bent at each face as it passes through a prism. Then they should see a spectrum formed with a fan of rays. For the latter (Experiment C 14d) they use a lamp, a comb with many slits and a weak positive cylindrical lens (+7D, focal length 14 cm) to form a real image of the lamp at a considerable distance. They interpose a small glass prism just beyond the lens, and turn the prism C29a (=C14t) until the rays emerging from it form a good image at about the same distance but in a new direction. At that image they will see a small spectrum, best observed by catching it on a small vertical piece of paper.

Then we should show them a demonstration. Newton was delighted, and his contemporaries were amazed, when he analysed a beam of sunlight with a glass prism. We should let our pupils share those feelings: without any complicated optical system, we should let a streak of light, preferably sunlight, fall on a small prism and then travel to a distant white wall. Ask pupils as a prize problem what they think Sir Isaac Newton, as a very good scientist, did as his *second* experiment. D 29b

The splitting up of light into colours by that prism was a delight, and it must have been noted by many, though they did not think about it as Newton did. But it was an act of scientific genius to pierce a hole in the card on which he caught the spectrum, and try a second prism with the light of one colour that came through the hole: no further production of a new range of colours. That is not only sensible experimenting: it gives a strong hint that the colours were there in a mixture, waiting to be sorted 'once-and-for-all'. D 29c

Simple Sunlight Spectrum Experiment: Needle and Prism. C 29d
Lend each pupil in turn a prism and a bright sewing needle. He H 29d
holds the sewing needle at arm's length in sunshine so that it makes a long, thin, virtual line-image of the Sun that acts as a slit. He holds the prism, with its refracting edge parallel to the needle, close to his eye and turns it until he can see the bright needle through the prism. He will see a spectrum and may even see absorption lines. This experiment is so simple and beautiful that we hope teachers will take the risk of lending prisms for it.‡

Theories

As children grow up they can develop more and more of a taste for theory, if we present it lightly to them by saying it is a hunch that the detectives gather from their clues and employ – with some clever guessing added – to help their hunt. Young pupils are ready to enjoy the romance of theoretical thinking. It is the adult non-scientist who is apt to condemn theory as difficult and no good. * * * * * *

‡ The J. Willmer Experiment Endowment Fund is available to underwrite loss or damage to prisms if teachers lend them for this.

We may be able to improve that aspect of the reputation of science in the adult world if we make some interesting uses of theory in our teaching. Year III is a good time to begin with a look at theories of light, and a short encounter with a theory of magnetism.

A Bullet Theory. We point out that reflection of light and the way in which light travels in straight lines both fit very well with the idea that light is a stream of speedy bullets.

Model: Reflection of a 'Bullet'. We give pupils a class experiment in which they roll a small steel ball or a marble very fast up to a massive vertical wall of glass. (Place a sheet of glass on the table for the ball to roll on; and place on that a block of glass with a vertical face to act as mirror.)

Discussion of Refraction

> 'But what about refraction? What do you think a fast bullet would do if you shot it into water? Yes, a real bullet in real water would go slower and slower, yet it would continue to travel in the same direction, except for gravity. But you can see that "light-bullets" bend their path as they enter the water. Newton thought about that and decided that the water would have to do something special to the bullet just as it approached. What do you *think* the water should do? Stop the bullet? Repel the bullet? Attract the bullet? Twist the bullet? Which of those would make it bend to a steeper path? ... Yes, *attraction* would do it. But if the water attracts the bullet, what happens to the speed of the bullet? (Remember these "light-bullets" travel on and on once they are in the water, so the water does not seem to slow them down with any friction.) ... Yes, the bullet must move faster in water than in air.'

So far – as Newton knew – a bullet theory accounts for the behaviour of light quite well, and makes the straight-line propagation of light seem much more reasonable than a wave theory would. There are two serious difficulties ahead: the fact that some of the light is reflected and some of it refracted at the boundary; and the phenomena of interference and diffraction. (It is probably wiser not to raise the former difficulty with pupils.) The two difficulties together forced Newton to suggest his strange scheme that endowed the surface with alternating 'fits' of easy reflecting and easy transmission. He knew very well that his theory implied some periodic motion attached to the moving bullets, so that one could assign a wavelength – yet he did not change to a wave theory, because he considered sharp shadows and straight rays too difficult to reconcile with waves.

Model Refraction of a 'Bullet'. (Optional now, may be postponed to Year V.) This is a model to show how the path of a particle bends at a transition between 'media' where it has different speeds. C31

In thinking of light as 'bullets' and endowing those bullets with properties that make their behaviour agree with observed refraction, we say that water or glass must attract them at a boundary with air, to make them move faster in the denser medium. The model uses a heavy steel ball as 'particle', rolling down a sloping board at a fairly constant speed. The board is made of hardboard or glass, covered with paper, with carbon paper on top of that to mark the path. With this surface, some slope is needed to maintain constant speed. The board is to be given in two sections, each with that necessary slope, joined by a narrow section that is much steeper. We provide a launching ramp for the steel ball that represents a light-particle. That is a block of wood with a sloping channel that enables us to launch the ball again and again with the same speed in any chosen direction.

The ball is launched on an oblique path on the upper board, and meets the steep downward incline where that section of board ends. Another board begins at the bottom of the incline. So the ball pursues a straight-line path, oblique to the edge of the incline, then rushes down the incline; then proceeds at a higher speed on the lower board, along a path in a new direction – showing 'refraction'.

(The P.S.S.C. Laboratory Guide which suggests this model – as a modification of a traditional one with a double roller – then asks 'Could you make a "lens" that will focus rolling balls?')

Refraction Model with Marching Pupils (*optional*). If there are facilities, and pupils like some drill, we can demonstrate refraction with a small army. We train the army to march on asphalt at a uniform frequency of footsteps: left-right, left-right, left-right, like a sergeant-major. We then train them to march at the same frequency but with paces of half length when they are on the grass lawn (or on ground marked with chalk, etc.). D32 OPT

Then we ask the army to march in fours along a line that we draw on hard asphalt to meet the edge of the lawn obliquely. They make this advance, after some careful practice in keeping step, and in keeping aligned in fours. The army's path shows refraction.

Marching the other way, from lawn to asphalt, the army also shows refraction. And if carefully drilled it discovers total reflection, to everyone's surprise.

The army can also march through a converging 'lens' drawn on the ground: the image is a pile-up of confusion.§

Interference and Diffraction

We now show pupils one more property of light. We have pointed out that sharp shadows fit well with a theory of speedy bullets; and pupils probably expect to see sharp shadows cast by a point source of light in all circumstances. And they probably expect to see a brighter patch on a screen where two lots of light arrive together: one lot of bullets+another lot of bullets should make still more bullets. So we show them: (*a*) strange bands of light and dark where two lots of light (from the same original source) arrive together in overlapping patches; and (*b*) strange bands of light and dark at the edge of shadows cast by a point source. T

a. **Interference.** Before giving pupils a class experiment with Young's fringes, we give them a demonstration, because this is strange enough and difficult enough to justify such preparation. And before we give a demonstration of Young's fringes we show the effect of light from a single slit. We illuminate a screen with a narrow vertical slit and look at the light which proceeds from that to a screen a considerable distance away. In order to get enough light on the screen, we illuminate that single slit as follows: We use a lamp with a very bright, vertical, line filament (tungsten iodine,‡ T D33a

§ 'This is *well* worth doing. When groups had tried and seen effect of refraction at plane surface so that they could do it "blind" they were strung out in line, arms linked sideways facing the high-jump take-off pit. This is of ashes and shaped like a plano-convex lens. They marched eyes closed. I can endorse the final statement. Wish I had filmed it!'

‡ In those demonstrations and class experiments with Young's fringes and diffraction, we need a very bright, compact source; a 'point' source or a line source – not just a source which gives out a lot of light, like a large filament; but one that gives a lot of [light]/[area of filament]. In other words we need a high brightness. The best lamp for that in our suggested apparatus is the little tungsten iodine lamp. That has a high-temperature filament which acts as a compact source. Although the filament is somewhat wider than it is high, the lamp should be run in the upright position. Therefore, when it is used to take the place of a slit (as in a coarse brightly lit version of Young's fringes) it may be regarded as a horizontal slit and the experiment done in a vertical plane, pupils looking for horizontal fringes one above the other on a distant screen. Failing that very bright compact source, a car headlamp bulb with a line (*Contd.* at foot of p. 216)

or better still an arc) and form an image of that small source on a very distant screen with a converging lens. Then we place the single vertical slit just beyond that lens. Pupils standing near the screen and looking towards the slit see that light is streaming out from it, over a wide range of directions.

> 'What do you expect to see if light from that slit goes on across the room and falls on the white paper over there? ... Yes, of course, a patch of light. Actually, the paper is semi-transparent, and you'll see the patch of light all the brighter if you go round to the back and look at it. Go and have a look. ... George, move your head away from the back of the paper to a comfortable distance: you don't read a book half an inch from your eyelashes.'

Having established the knowledge that light from a single slit will make a bright patch on the distant screen we replace the single slits by a pair of slits side by side, very close together. (The centres of the slits may be $\frac{1}{2}$ millimetre apart, each slit a few tenths of a millimetre wide.) We ask pupils to go and look at those slits from close by, on the far side, looking towards the light so that they see light streaming out through both of them.

(*Contd.* from foot of p. 215) filament may be used, overrun as much as possible. For some demonstrations of Young's fringes, that may be even better, because it serves as a comparatively fine slit itself.

In those cases where a real screen with a slit is inserted the lamp may be placed just behind that slit, or a lens may be used, and in that case the orientation of the slit decides whether the pattern is horizontal or vertical.

When one uses a lens behind a slit one's first move is to arrange the lens to form a real image of the filament on the slit itself, but that will spread light widely beyond the slit and will not give much illumination. Instead, the lens should be arranged to form a real image of the filament at a great distance, near the viewing screen itself. Then the lens is used like the condenser in a projection lantern and the pattern on the screen receives a lot more light. If that lens in any way confuses pupils' ideas of the phenomenon, it should be omitted – we do not want them to think that interference is produced by lenses, like a conjurer's mirrors.

Diffraction patterns are best shown with a point source. For a coarse demonstration which will make the patterns bright but not so sharp in their detail, the tungsten+iodine filament lamp should be used as the 'point source' itself, without a pinhole. Where greater sharpness is needed, or where a long line-filament is used, a screen with a pinhole must be inserted; and then the lens should be used before the pinhole as described above.

For the present work, we urge teachers to use the tungsten iodine lamp without any lens, slit or pinhole. It is more important for pupils to see the pattern well lit with simple equipment than to add sharpness at the expense of complexity.

'What do you expect to see now, when light comes out from both slits and goes across to the paper? What makes more noise than a pig under a gate? Go and have a look.'

It would be far better to have pupils arrange this example of *
Young's Fringes themselves and make the astonishing discovery *
on their own. We hope that some teachers will try that, but we *
must warn them that to be clear to children the experiment needs *
big distances, a very bright source, and a well-darkened room. *
In this case the result is so important that we would rather safe- *
guard it by giving a demonstration first. The use of a translucent *
screen of kitchen waxed paper, not of tracing linen, is really *
essential. Ground glass is expensive and gets broken. *

Young's Fringes are usually shown with an eyepiece to observe *
them. That is likely to spoil the cogency of the experiment for *
young pupils. There is a lens there, and they know that lenses can *
introduce peculiarities – particularly if one is not quite sure where *
the observing eye is being focused. So we plead strongly for a *
demonstration *without lenses*. True, there is a lens in one arrange- *
ment suggested above; but that is *before* the double slit, and it is not *
essential – it only adds greatly to the brightness of the fringes. *

b. **Diffraction.** Now that they have the lamp and a dark room, D33b
teachers may want to show another wave effect: diffraction. OPT
Although this is a delightful thing to see, clearly shown with modern light sources, even in a small room, it is probably too difficult and confusing for all except a very fast group. Postpone it to Year V.

We simply use a lamp with very compact filament as a source to cast shadows – an illuminated pinhole is much more troublesome. We hold various objects to cast shadows a few yards from the lamp; and pupils catch the shadow on a screen as far away as possible. The screen may be a sheet of white paper to be looked at from the front or, far better, a sheet of kitchen greaseproof paper or other translucent material, to be looked at from behind.‡ A sewing needle,

‡ *Translucent screens*. The material for screens to enable us to look at diffraction patterns and to see Young's Fringes must be one that scatters transmitted light through a small angle. The pupil stands behind the screen and receives light that comes practically straight through it to him. A screen that scatters light through a large angle might enable other students standing at one side to see the pattern, but the pattern would then be far too faint for them to see. So it is very important to make the screen of material which scatters through a small angle. Kitchen greaseproof paper or waxed paper is good for this. Architect's tracing linen is bad for this because it scatters through a wide angle – that is what makes it so useful for illuminated screens placed behind apparatus to show it in silhouette to a widespread audience in front, but that is not what we need here.

a pin, a screen with small holes drilled in it, and a small disc or steel ball stuck with wax on a piece of plate glass, all make good shadow-casting objects. Perhaps because it is natural, a human hair seems to do best of all. Pupils will see strange dark and light bands around the shadows, and may notice stranger things still. They should move the screen towards the shadow-casting objects and see these effects disappearing as they move closer.

Discussion of Young's Fringes

When pupils have seen the demonstration of Young's Fringes – one by one for this extraordinary glimpse – we give them first a discussion and then a chance to do the same thing as a class experiment. T

> 'That is extraordinary: bands of black and white, like a zebra. If light is bullets, can it do that? Here you have light plus light making LIGHT in some places, and light plus light making no light in other places. We can have bullets plus bullets making MORE BULLETS, but can we have ...? Have you ever seen anything at any time in physics where two lots of things arrived and made a big result in some places and made nothing (cancelled out) in others? (Bullets from a gun going through two slits might make *two* patches but not a whole row of patches.)'

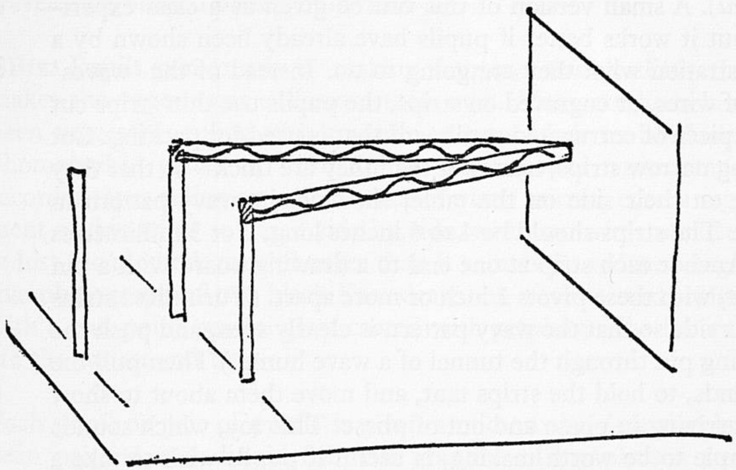
We ask that last question eagerly, hoping for a reference back to ripples. (Now the teacher's choice between adding Young's Fringes with ripples to the early ripple tank experiments and postponing them as a difficult problem, becomes clear. There should have been at least a brief look, for a rich reward in good science teaching now.) A wise teacher will not want to give the answer. This is a very important question: a young pupil will be proud, and the better scientist, if he can guess the answer. Leave the question for a few days.

Young's Fringes with Ripple Tank. Then return to the discussion, and get the ripple tank out again. Let pupils run their own ripple tanks with a double-pronged dipper run by a motor. Encourage them to blink their eyes, for a clearer glimpse of the pattern; and try freezing it with a hand stroboscope. C34 (C4o, p)

Geometrical Demonstration in Teaching Interference

The idea of waves adding when they are in phase to give a large wave and 'interfering destructively' when they are in opposite phase, is easy for adult physicists but strange to children. It is T easy for children too, once they have grasped the essential idea; but that seems to need some extra demonstration.

Some words are helpful too: 'this wave arrives and makes things go flip-flap, flip-flap ... the other wave arrives in step with the first wave and also makes things go flip-flap, flip-flap; then the two waves together make things go FLIP-FLAP, FLIP-FLAP. But when we move to another place over here where one wave has travelled farther than the other and arrives out of step, the first wave makes things go flip-flap, flip-flap ... and the other wave makes things go flap-flip, flap-flip ... and then the total of the two is ... ?'



The demonstration that is needed is something to show the difference of phase that arises from different paths. That is obvious to us but takes a little extra help for pupils to grasp. If teachers try the following demonstration they will discover that it is a help: D 35a

We take two strips of Perspex with wavy lines engraved on them to represent waves (or two long laths of wood carrying stiff iron wire bent to a wavy pattern). The strips should be as long as possible with at least 8 'wavelengths' on each strip.

To give the demonstration, in a vertical plane, support one end of one strip about a foot above the table, and the corresponding end of the other strip a few wavelengths higher up. Each of the laths must be held by a clamp which is pivoted so that the strip can rotate in a vertical plane. The other ends of the two strips are then held in the teacher's hand; and as he moves his hand up or down the waves meet in-phase or out-of-phase there – having started in phase with each other at the pivoted end.

Some teachers might prefer to work in a horizontal plane. In this case, two vertical rulers about a foot apart represent the slits. The Perspex laths are secured to the top of the rulers and held horizontally so that the free ends come together near a vertical screen. Now as the ends are moved across the screen, the waves meet in-phase and out-of-phase, having started in phase at the other end.

Class Experiment: Geometrical Wave Addition Model C35b
(*optional*). A small version of this can be given as a class experiment but it works better if pupils have already been shown by a demonstration what they are going to do. Instead of the 'waves' made of wires, or engraved on strips, the pupils use thin strips cut from a piece of corrugated cardboard that is used for packing. Cut two long narrow strips, narrower than they are thick – so that they will lie on their side on the table, showing the wavy pattern in section. The strips should be 4 to 6 inches long, 2 or 3 millimetres wide. Anchor each strip at one end to a drawing board with a pin as pivot, with these pivots 1 inch or more apart. (Turn these strips on their side so that the wavy pattern is clearly seen, and push the anchoring pin through the tunnel of a wave hump.) Then pull the other ends, to hold the strips taut, and move them about to show H35b
waves arriving in phase and out of phase. This toy, which sounds too simple to be worth making, is useful if pupils wish to take a demonstration Young's Fringes with light to show people at home. OPT

Class Experiment with Young's Fringes

This presents three difficulties: lighting, making the slits and the C36
calculation of wavelength. We hope that teachers experimenting with various arrangements for this class experiment will find ways of dealing with those difficulties. The experiment is worth doing as an essential milestone in optical theory, as an important measurement, and as something to take home with pride.

In Young's original form, an illuminated slit served as a source of *
light for a pair of slits at some distance, and those two slits in turn *
acted as coherent sources. Within our lifetime we shall see inter- *
ference experiments carried out with coherent sources of un- *
dreamed-of intensity – from 'lasers'. Lasers are potentially dan- *
gerous and still very expensive. For present teaching, however, *
we must be content with rather faint fringes and we must use *
either a first slit or a thin line-filament as primary source. *

Suggested Equipment. A lamp with a line filament, overrun if possible, seems best. Unless we have a really dark laboratory, not even translucent screens will show fringes easily if we use no lenses. But with a dark room and a good screen the fringes can be seen clearly without any lens except the eye itself.

Direct Method. Where the laboratory has bright sources well shielded, in a long dark room, pupils should use the simple direct method: catch fringes made without any lenses, on a translucent screen. They can if they like measure the fringes by making pencil marks on the screen and measuring them subsequently in daylight. But, except for an extremely fast group, any calculation of wavelength should be left until Year V.

Slits. Pupils gain greatly by making their own double slits – that makes the experiment still more their own. Many methods have been suggested: ruling with a needle or razor blade on blackened photographic plates or film; ruling on magnetic coated tape-recorder tape; ruling on an old piece of plane mirror; even a regiment of fine wires soldered side by side, with two wires removed (a historic method; much harder than it sounds); a reduced negative photograph of two black lines drawn on a white card; ruling with a ball-point pen on glass coated with graphite. The last two are the easiest and best.

Each pupil or pair of pupils is given a microscope slide that has been painted with liquid colloidal graphite. They place a steel ruler across the slide and run a ball-point pen along the edge; then move the ruler a very small distance and rule another slit; a suitable spacing of slits is half a millimetre apart, centre to centre, each slit being so wide that they almost merge into one wide slit.

Various special tools have been suggested and designed for ruling double slits; but most of them do a poor job compared with this simple method. One very good gadget is made by cutting off the blunt end of a sewing needle half-way down the eye, thus producing a tiny pitchfork which can be mounted in a wooden holder and used for ruling.

If we make the individual slits wider, the fringes are brighter but a smaller number of them receive illumination and appear in the visible patch. So the choice of slit-separation and slit-width is a matter for experiment to fit the conditions of the individual laboratory.

Calculation of Wavelength. (Optional, advanced extension.)

The geometry seems difficult; but in a very fast group pupils who have made the measurement with their own apparatus want to extract the tiny wavelength of light from it.

Pupils may estimate the slit-separation by comparison with a $\frac{1}{2}$ millimetre scale under a microscope; or if those scales are not available from Year I equipment, millimetre scales will do. Any estimate made in this experiment is only intended to be a rough one, just for the pleasure of finding how very small this wavelength is.

We might lead pupils through a simple form of geometry, using two similar triangles, to show that:

$$\frac{\text{wavelength}}{\text{slit-separation}} = \frac{\text{distance between successive fringes}}{\text{distance from slits to screen}}$$

(See discussion in Year V.)

The diagram we sketch for that should be realistic: slits very close together, screen far away. The model of plastic strips with wave patterns helps. Or we might show pupils how to get the relationship from the ripple tank for themselves. That will give them great pleasure if they can do it. They measure wavelength, slit-separation (the distance between the two prongs of the double source on the motor), the distance between successive 'bright' fringes at a measured distance from the double source. Then they either use these numbers to test the relationship above which the teacher gives them or, if they are very able and enquiring, may be left to play with those measurements and try to extract the relationship from them for themselves.

Waves or Bullets?

Interference effects such as Young's Fringes suggest strongly that light must be waves. In that case, would the speed in water (or glass) be greater or less than that in air? We ask pupils to go back to the ripple tank, insert a sheet of glass to make a region of shallower water, where they long ago found ripples travelling slower where refraction had bent their path in the way it bends rays of light entering glass. T

Before pupils look for refraction we need to give them some help with the connection between *wave-fronts* and *rays* for waves. We explain that rays are 'guide-lines' that we can draw to show the direction of travel of the wave-front. Then we sketch circular ripples travelling out, and add radial 'rays'.

We sketch rays travelling out from a source and add circular ripples. We sketch rays diverging from a source to a lens; then, after the lens, converging to an image, passing through the image point and diverging again – a typical 'full-cone diagram', in fact. Then we add circular wave-fronts that agree with that ray story.

We also sketch a sheaf of parallel rays being refracted, and add wave-fronts.

Refraction in Ripple Tank. Now pupils should be ready to understand refraction of ripples, if they see it. Refraction is the most difficult of the ripple phenomena to see, because if the water is shallow enough to show it well it damps out the refracted waves too easily. However, this is an important experiment that pupils should carry out with their own ripple tank. The teacher needs to be ready to diagnose trouble and give help. (Avoid a sloping tank: its changing depth may make refraction visible but a ray that shows direction of travel is curved.) C4t

It will become clear from the ripple tank demonstration that refraction like that of light rays going from air to glass or water belongs to *waves* that travel *slower* in the second medium. For '*bullets*' of light, momentum considerations predicted *faster*. So we have a critical test.

Crucial Test. It is safer to say critical than crucial. Even when we feel sure our test will settle the choice between two theories completely, we forget how ingenious the owner of any theory can be in modifying it to fit an unexpected experimental result! In this case, we have only to make Newton's particles keep the same K.E. when they enter water from air, instead of keeping the same mass, and we predict smaller speed in water. This cautionary tale is not one that we should tell pupils now, but it should be there in our minds to discipline our words. * * * * * * * * *

We then tell the story of the experimental test. The speed of light is measured by bouncing it off a spinning mirror before and after a long trip to a remote mirror and back. During the trip out and back, the spinning mirror has rotated through a tiny angle and T sends the light on to a slightly different position from its original source. With a long pipe of water interposed in the trip, the spinning mirror has time to turn farther: light moves slower in water.

(Note that in our suggested discussion we have not used the traditional Huygens's construction to show that $\sin i/\sin r$ is equal to the ratio of speeds. That construction is an artificial scheme that physicists have come to accept by repeated use; and it is far from obvious to pupils. Its use is wisely criticized in a Memorandum by Dr E. B. Mendoza.‡

Before we encourage pupils to celebrate the success of this decisive experiment and laugh at Newton's mistake, we and they should reflect that:

a. The wavelength of light, which we can now estimate roughly from Young's Fringes, is so small that we must expect sharp shadows on any ordinary scale of experiments, because, as the ripple tank shows, only when a gateway is very narrow, a wavelength wide or less, do we find waves spreading in all directions as they pass through. Any obstacle that is many wavelengths across does cast a 'shadow' when ripples meet it. It is only obstacles smaller than a wavelength that fail to stop waves; and just scatter a tiny circular wave among the original waves.

b. In this century, we have found that light *does* have bullet-like behaviour, sometimes. Whenever we do experiments to find out how the energy of light is arranged, we find it is packaged in very small bullets. Yet whenever we do experiments to find what path light takes when it passes by barriers or through slits, we find it has a wave behaviour. Our choice of experiment seems to control the kind of behaviour we find. That is a characteristic of modern physics – which extends to electrons, atoms, etc., as waves and bullets.

We can only mention this mysterious new knowledge. We should not confuse pupils or make them think we do not know what light is or atoms can do – we know their properties well – but we may give hints as far as our pupils' enjoyment carries their questions.

‡ *Contemporary Physics*, Vol. V, p. 217.

Film. At this stage of comparing waves on water with the behaviour of light, some films may be useful. At the time of the early ripple tank experiments we made a strong plea to teachers not to show the very good short films of ripple tank phenomena that are available. At that time, a film would spoil the feeling of personal discovery. It would put things right after the experiment had yielded less clear knowledge. Good though that clearer, correct knowledge is and delightful though the films themselves are, that would not be a wise place for them.

If the teacher feels that films are needed now, that is probably a sign that it would be better to postpone things to Year V.

Then, in Year V, we may want to show short films of ripples being reflected, refracted, and even making Young's Fringes. A short film of refraction of ripples, including a 'lens' changing the curvature of ripples to make them pass through an image, would be well worth showing.

Waves and Lenses

In sketching wave-fronts on a full-cone diagram or rays through a lens, we were already suggesting wave treatment for optics.

We now draw that again: circular ripples starting from a source (object point) on the axis of a bi-convex lens. We draw the ripples with source as centre, growing in radius as they approach the lens. We point out that if light waves travel much slower in glass (as they do, with two-thirds of their speed in air) the waves will be delayed in the lens. And, at the central part of the arc, the wave-front will be delayed more than the rest because it travels through more glass. So we suggest the wave will come out bent to a new arc, converging to an image point. Thus we can now think of a lens as imprinting a change of curvature on a light wave.

A simple measure of the curvature of a circle of radius R is $1/R$. So, a lens changes a wave of curvature $1/u$ to curvature $1/v$. Then $1/f$ is the *change of curvature imprinted*, enforced on the waves of light simply because they travel slower in glass than in air. The fact that $1/v \pm 1/u$ is constant contains a statement that a lens imprints a constant change of curvature.

We may tell pupils who are interested in design of camera lenses that that is how some of the best lenses are now designed and tested; no longer by laborious tracing of rays according to $\sin i/\sin r = n$, but by considering the proper changing-of-curvature. We test the design, by bouncing light waves back and

forth through the lens under test and judging mistakes in our *
design by looking for zebra bands, rather like Young's Fringes, to *
tell us where the lens has delayed the light too much or too little. *
Ideally, each part of a lens should delay the piece of the wave that *
hits it by just the right amount to make that piece of wave arrive at *
the image in phase with all the others. If part of the lens is too *
thick and makes as little as $\frac{1}{2}$ wavelength more delay than it *
should, the wave contribution that it transmits will do harm, not *
good. Then the maker has to polish off a fraction of a wavelength of *
glass just there. *

Interference Patterns

As a final look at light waves making patterns because they 'interfere' – meaning merely that their effects add up algebraically – pupils should see interference pattern made by light reflected from the two surfaces of a thin film. D37

A soap bubble shows irregular patterns because the thickness is irregular, but it also shows wonderful colours reminding us – as Young's Fringes should have shown – that wavelengths are different for different colours.

A soap film allowed to drain (in a closed box of damp air to prevent it from breaking down by evaporation) will develop a big black spot where it is very thin. We should expect the light waves from two surfaces very close together to reinforce, not annul. Here we must say to pupils frankly that there is a good reason for the black spot, but it is too difficult. (A Galileo, if asked about this, might say, 'Well, if the film is so thin that it isn't there, what would you expect to see: bright reflection or invisible darkness?')

Then show two plates of glass with an air film between, illuminated by sodium light (or by a mercury arc with a filter). D38

The following instruction is helpful: 'Hold the plates as if they were a book that you are trying to read by the light from the yellow flame.' That directs attention to the surface instead of the image of the flame.

> 'We press the sheets of plate glass tightly together like this, so that the two reflecting surfaces are very close. Yes, there's the black spot again. Now prop the other end apart with a very thin sheet of paper. You can count the zebra stripes. If you know the wavelength of light, what could you estimate by counting the stripes?'

(We might even mention that this is the beginning of the modern way of specifying the standard metre.)

We shall not proceed to gratings and grating spectra until Year V. *

PROGRAMME

We now make a complete change, and embark on an informal study of motion (preparing for more formal work with Newton's Laws in Year IV). That is followed by some simple Kinetic Theory; and then a return to class experiments with electric currents, using the Westminster electromagnetic kit. * * * * *

Chapter 3

MOTION AND FORCE

Informal Preparation for Newtonian Dynamics

TIME, VELOCITY AND ACCELERATION

Our aim here is to give some general ideas, partly by asking questions and partly by letting pupils do experiments, and to build up skill with measurements that can be used in Year IV in more formal experiments on Newton's Laws of motion. * * * *

Since pupils will make careful measurements and plot graphs of acceleration against force or mass, in Year IV the treatment here should be a quick light introduction, to pose some questions and to give a little experience with the apparatus. * * * *

Passengers have a better journey if they know where they are going. It is a peculiarity of Newton's Laws that, in teaching them, we ourselves are so well aware of the importance and use of these Laws that we are apt to forget to tell pupils where we are going. Start by asking some questions:‡ T

a. How does an earth satellite keep going without using up fuel?

b. What does a space ship do far out in space: travel slower and slower, travel at the same speed as time goes on, travel in a circle or a straight line or what?

c. When a policeman starting out on a motorcycle speeds up to 20, to 40, to 60 mph it takes him some time and some petrol to reach 60 mph. What is it that stops him reaching that speed at once? Is it air-resistance, is it road friction, or something else? (Try starting to run with and without your younger brother on your back.)

d. If a rocket has a downward blast just strong enough to keep it hovering a few yards above the ground without rising or falling, what would that rocket do with the same blast if it was aimed horizontally? What would the force-measuring machine on a test bench show if the same rocket was fired horizontally but kept tied up to the machine?

e. Can a rocket go faster and faster in a vacuum?

f. Does a railway diesel engine need friction on the rails?

‡ Note that these are only offered as specimens of the kind of questions that might be asked to arouse interest or start discussions. It is not necessary to ask all these. It is not necessary to give full answers: that is not the point of these questions – their point is to stimulate thinking. Teachers may wish to use a few of these, perhaps with some simpler ones.

g. If a diesel engine pulling *ten* carriages takes ½ minute to speed up to 40 mph how long would the same diesel engine pulling *twenty* carriages take?

h. Is there any force pulling or pushing the Moon, as a whole?

i. Some radioactive atoms shoot out a small particle from their nucleus, an alpha particle, which turns out itself to be a helium nucleus. Then the remainder of the original atom is quite a different atom with different chemical properties. When an atom at rest shoots out a high-speed alpha particle like that, does the rest of the atom recoil faster than the alpha particle or slower or not move at all?

Ask a few such questions and say that to find out about forces and moving rockets and speeding up trains we are going to do some experiments with moving things. Presently we shall look at all the clues we get from our experiments and see if like good master-detectives‡ we can draw some general conclusions about the way those things behave. Then we shall make some rules for force and motion, etc. Some of that will be done this Year, some next.

Before any formal treatment of the laws of motion, pupils need to understand velocity and acceleration clearly. Speed may be clear enough as a general idea, but speed as something measured – and then velocity as speed in a particular direction – will raise interesting new questions.

Acceleration as something measured is also difficult, the more so because to most children a unit which has the form of 'metres per second per second' is somewhat ludicrous. And the compact form, 'metres per second^2' recommended by mathematicians and many a mature physicist, is more puzzling still. With beginners, we should certainly measure acceleration at first in mixed units, such as 'miles per hour per minute'. The meaning is not obvious to a beginner when we say an electric train has an acceleration of 1·1 ft/second per second; but 45 miles/hour per minute has a much more satisfactory ring.

‡ This comparison of scientists with detectives appears from time to time in our programme. We hope that teachers will use it, because we think it offers useful insight to young pupils; but the wording needs to be changed to fit the taste and age of each group. It is significant that the suggestion of this comparison was brought to the Project at an early stage of its development by an extremely able lawyer who has unusual insight into the problem of conveying a good understanding of science to laymen.

It is important for us to appreciate the difference between an implicit and an explicit understanding possessed by children. Very often, a child has an implicit understanding of a concept long before he can make it explicit. Our purpose now is to foster the process of acquiring an implicit understanding; explicit understanding can come later. * * * * * *

Sometimes a carefully framed, gentle question for homework will help that development. 'Suppose your neighbour, who sits at the next desk, missed the lessons (or experiments) on ... what would you tell him to explain what happened? Give him some help in your own words.' T

The idea of acceleration can be given an informal start by keeping a long inclined track available at the side of the classroom and letting children roll marbles down it. This should be there a week or two before work on motion is started and should remain available for some weeks after. It might be a long plank placed with its edge upwards, with a groove cut in the edge all the way along to make a channel, like Galileo's plank. Or it can be a vee-shaped channel of metal; but a simple plank is better. The longer the better. Letting a marble go from the top to roll all the way down should be legitimate play. C/D 40

We should provide small pieces of metal like pennants, cut from tinplate, hung from simple axles; these can be moved to various places along the sloping plank so that the rolling marble hits the end of the pennant and makes a 'clink' as it passes. We should leave children to find out for themselves how the clinks sound when these pennants are uniformly spaced, one every foot, all the way down the slope. And then some will think of rearranging them to make clinks occur at regular intervals of time. Give praise for success: but do not give away the answer.

This is also something that a pupil may enjoy setting up at home. H.40

When we come to class and demonstration experiments on velocity and acceleration, we meet problems of measuring time. In the earlier work of the Year with the ripple tank, pupils will have played with a hand stroboscope, and will already be familiar with the measurement of short time intervals of the order of 1/30th or 1/50th of a second. There we were concentrating on repetitive time intervals; but now we need to measure time intervals of various lengths, and this suggests the use of clocks. * * * * * * * *

Clocks. Go back to the work of Year I, and ask pupils to measure the time taken by a pupil to run, say, 100 yards or 100 metres – or so many laps of the classroom's length. Suggest using the clock on the wall (which should have a large hand that goes round once a minute). Offer magnifying glasses to those pupils who have watches with a small 'seconds hand' that they can use. Then offer stop-watches (or electric stop-clocks). C41

Explain that we are not just going to measure something moving along at constant speed, but are going to make measurements of things more like a car that is speeding up or coming to rest with its brakes on. For that we need very careful measurements of time. T

As a preliminary example for practice we give pupils a trolley and a long sloping board as a roadway, and ask them to make measurements of the trolley's motion. (See below.)

Note to Teachers: Runway for Trolleys. In later experiments, our good trolleys will need a runway that is smoother and nearer to a plane than most laboratory tables. Also the trolley is to run on an inclined plane in some cases. So we must provide a long board, with a fence at each edge, as a road for trolleys to run on. *

For that, we suggest a plank of 1 inch plywood or chipboard, 1 ft wide by 8 ft long with a length of slotted angle along each side. If the size of the laboratory, or its storage arrangement, makes a shorter runway necessary, 6 ft will do; but the disadvantage is considerable – the accelerated motions we shall study cover large distances quickly in the later stages. *

A plank of ordinary wood is likely to prove false economy. *

Using narrower boards or replacing the metal edges by wooden ones will almost certainly prove false economy. We need enough runways and trolleys for pupils to work in pairs on a series of class experiments, intended to give personal contact with the measurements of force and motion, in contrast with a formal demonstration. The cutting of plywood and installing of metal edges will take considerable time but we believe it is worth while to provide good apparatus for these class experiments. *

(For our trials, schools obtained these runways ready-made – so that teachers busy with new teaching were not burdened with their construction.) *

The storage of these runways raises problems. We hope that they can be stored away safely; and we suggest they should not be used for other purposes (such as a large seesaw) which might damage them and reduce their value for use with trolleys.

There should be one runway and two trolleys, with associated timing equipment, for each pair of pupils. Problems of cost, storage, and space in the laboratory will tempt many a school to suggest the economy of working with three or even four pupils to a runway. That would be a very unwise economy; it would miss the point of our present experiment. Our aim is to give pupils personal experience in experimenting with force and motion, rather than to show them results. If three or four pupils stand around a runway we are in danger of having poor demonstrations instead of good class experiments. This equipment plays an important part in this Year and a very important part in Year IV, so we hope it will be installed in full quantity.

Rough Experiment: Attempt at Timing Accelerating Trolley. C42 Arrange the runway with a good slant (1 in 10) so that the trolley runs down with a noticeable acceleration. Ask pupils if they can measure the time the trolley takes for the first foot it travels and the next foot and the next foot and the next foot. Provide a stop-watch for each pair of pupils. This is just a rough experiment to see what the difficulties are like. It will certainly show that the trolley accelerates.

Trolleys and Timing

Discussion for Teachers: Apparatus. The distances involved in such experiments do not present a great deal of difficulty, but the times do; for now we are concerned with time intervals of the order of a fraction of a second; and these time intervals are no longer repetitive. So we need a technique for starting and stopping our clocks. An enthusiast might make a mechanism for starting and stopping a conventional clock, and produce a homemade stop-clock. But even then there would be serious difficulties when it came to timing the accelerating trolley and finding out exactly 'how far in how long'.

A number of devices have been suggested for marking the position of a moving trolley at much shorter time intervals. Most teachers will be familiar with Fletcher's Trolley. That device enables one to measure short time intervals; but unfortunately its technique of using a vibrator with a brush to draw a wavy line presents considerable difficulties in understanding. Few children see readily

what the relationship is between the obvious wavy trace and a *
distance or a speed. *

Some manufacturers have developed a demonstration trolley track *
which employs an electric stop-clock; but this appears too com- *
plicated to the pupils, as well as being expensive. We do not want *
to obscure natural behaviour by special ingenuity. *

In trying to provide informal acquaintance with force, mass, and *
motion, we urge teachers not to offer demonstrations but to provide *
pupils in small groups (preferably pairs) with simple apparatus for *
class experiments. Therefore we suggest the apparatus described *
below. *

Probably the best for use in class – and demonstration – experi- *
ments is the simple technique with paper tape devised and tried *
out very fully by teams working for the Physical Science Study *
Committee in the U.S.A. This is described below. The Nuffield *
Physics Group have encouraged the production of suitable equip- *
ment for this in England.‡ We shall describe that 'tickertape' *
method for present use. *

Vibrator and Tickertape to Measure Time and Distance

The moving object drags along after it a streamer of thin paper T
tape, 'tickertape', which serves as a measure to show the distance travelled. The tape travels under the hammer of a tuned vibrator (somewhat like an electric bell without the bell) running on a.c. The vibrator hits a small piece of carbon paper just above the tape driving the carbon paper down onto the tape as it passes over a firm anvil. This makes marks on the tape at regular intervals, one every period of the bell vibrator, one every 'tick'. (This a.c. vibrator has proved preferable to ones running on d.c. with unknown frequency.)

‡ At the same time the Nuffield Physics Group have developed a number of alternative ways of building and using trolleys.

They have devised a trolley which itself carries a speedometer, arranged to give an average speed reading over a short time interval every so often. That enables acceleration to be seen as visible increases of speed from one time interval to the next and the next.

Another trolley carries a small dynamo, whose output indicates the trolley's speed on a millivoltmeter.

Another scheme uses electrical pulses at a rate of 1000 per second and counts them with a scaler.

Still another scheme uses a beam of light which is interrupted by the moving trolley, with a photocell and capacitor arranged to measure the time during which the light is obscured.

A piece of carbon paper held in position would soon wear out under repeated impacts and fail to make good marks. To prevent that, the carbon paper is cut in the shape of the small disc and anchored to the table by a drawing pin through its centre. The tape runs under the carbon paper disc, out near one edge, and as it runs it makes the disc rotate, providing a fresh surface.

The device seems to be obvious to children. They can hear the vibrator running at a uniform rate and they only need one word of explanation; that the vibrator makes marks at equal *times* apart – and not necessarily at equal *distances* along the tape.

Investigation of Vibrators. Either now or after trying ticker-tape and vibrators, pupils should look at the behaviour of vibrators. C43

We provide a large model of the vibrator in the form of a hacksaw blade held in a clamp which is clamped to the table so that the blade projects out from the table and is free to vibrate to and fro.

Note that in clamping any such vibrator it is important to have the jaws of the clamp held tightly and symmetrically just where the blade emerges from the jaws.‡

To make sure of firm clamping, the blade should be placed between two small plates of metal which are themselves held tightly in the clamp. A small carpenter's G clamp is better for this than a laboratory clamp. And that clamp can in turn be clamped to a table by a second G clamp.

Ask pupils if they can count the vibrations of the blade – with a view to timing the counted number and finding the time of one vibration. The blade moves too fast; so it should be loaded by another small G clamp attached to its free end. (A rubber band wound to and fro on the handle of the small G clamp will stop the handle from rattling.) Pupils should time ten complete oscillations.

Pupils should look through the hand stroboscope at the vibrating blade and clamp. (See Note on Stroboscope, etc., in the General Introduction.) The observer holds the disc in front of his eye and turns it very slowly, changing the speed until he can freeze the motion. This is best done with a disc with one slit (all the other slits being closed with black tape). A partner measures the time taken for ten revolutions of the disc.

‡ Loose clamping, or one-sided clamping, leads to an annoying change of frequency with amplitude and a disastrous waste of energy at the clamp.

The vibrator is then speeded up by moving the loading clamp from the free end to half-way; and then by taking the clamp off altogether. It may be necessary to remove one tape from the stroboscope disc, so that there are two slits, 180° apart.

Then pupils may try to use the stroboscope to observe the vibrator that is used for tickertape. Unfortunately it is not possible to load that vibrator and slow its motion. So pupils must 'freeze' the full motion and ask a partner to time ten revolutions.

They will have to use a submultiple of the vibrator's real frequency, because the latter is too great.

This makes a set of experiments of increasing difficulty both in technique and in reasoning. This is a case where the teacher should give considerable help to those who need it. It is not essential for every pupil to get through the whole series – these are only intended to offer some practice. Because our use of stroboscopes and the tickertape technique are new to many teachers, we offer a number of suggestions for explaining them to pupils and giving practice in their use. But teachers should not infer from that that we regard these as very important innovations; they are merely useful devices for quick clear teaching, especially in class experiments. We hope teachers will not let these training experiments bulk too large or take too long.

Demonstration with Motor Driven Stroboscope. Among these class experiments, the teacher may want to clear up some points by giving a demonstration with a motor driven stroboscope which will be used again this Year and next. T

This is a cardboard disc (like the hand stroboscope but lighter) on the axle of a synchronous motor. Instead of viewing a vibrating system through the slits of the disc, we illuminate the whole system by light 'chopped' by the disc. We arrange a lamp with a very bright compact filament (a tungsten+iodine bulb) and a converging lens to form an image of the filament *on the stroboscope disc.* The filament should be imaged so that all the image falls on a slit when a slit comes round to that place. Then, as the disc rotates, the slits allow brief bright flashes of light to go through. As a simpler arrangement, that works adequately in most cases, the lamp may be placed close behind the disc, without any lens.

The light passing through the slit thus spreads out and illuminates a considerable field. Then a large number of pupils can watch the vibrating system placed in that field, or the light can be used to cast an enlarged shadow of a vibrating object on a distant screen.

If a variable speed motor is used, it can be adjusted to show the repetitive motion performing its cycles very slowly.

If the illumination is insufficient for a clear picture or good shadows, we suggest using a translucent screen of architect's tracing linen and asking pupils to view the picture from the other side, but that cuts them off from the real experiment.

Making Measurements with Vibrator and Tape. Explain that these experiments are to make the kind of measurement an engineer would make if he wanted to know about a car speeding up or its brakes working or even about a rocket accelerating up to its orbit. We shall start with some simple games to see how the tape and vibrator work. T

The tickertape is going to be put to many uses next Year; so this Year's work should introduce it briefly and give pupils a little practice in interesting uses. Then next Year the technique of handling it will not delay some important and difficult experiments. That means we should offer plenty of time for class experiments with this apparatus, but we should not labour experiments on $F = ma$.

Class Experiment to practise using Vibrator and Tape. C44
Find the time, in ticks, between two signals given by the teacher. Pupils draw the tape through the vibrator. They turn the vibrator on at the first signal (the teacher claps his hands) and turn the vibrator off at the second signal (second handclap). This experiment deserves a rehearsal. The main measurement should be followed by a collecting of results. Every result will be in 'ticks' and they will disagree. Ask 'why?'

Class Experiment: How many Ticks in 3 Seconds? This needs some cooperation among partners. It need not be done very accurately. It is just part of practice. C45

Demonstration Experiment: Measuring Motion of a Running Pupil. The best approach here seems to be to use a real and interesting example, with quite uneven motion.

A pupil pulls tape through the vibrator as he walks away and the teacher suddenly puts a hand out and stops the pupil. The tape record resulting from that is looked at very carefully and 'analysed' D46 for clues to the motion. The record can be clearly understood by the class. The dots have occurred at regular time intervals, the distance between them starting very small then becomes quite large, suddenly becoming small again. The simplest way of analysing this record is to produce a histogram. In discussion in class we should call that just a *chart.*

The teacher cuts the tape into lengths containing 10 ticks. It will save a lot of trouble if that period of time is named a 'tentick'. Then he asks what each length tells us. He places the lengths in a vertical position on a card, side by side, one after the other, to make a chart. All have seen the experiment done and should be quite ready to interpret the strange chart, ending with pleasure, 'It drops down there where George was stopped.' Without discussing that or even asking what it means, the teacher then suggests that pupils do the same thing as a class experiment.

Class Experiment: Running Pupil. Each pair can make their own record with any variation of motion they like. Each pupil should emerge with his own tape for analysis and cut it up and paste it to make a chart for his notebook. He should paste strips on a piece of paper, placing the bottom end on the bottom edge of the paper and letting the top edge of the strip come where it will. C47

Successive strips should be placed side by side, just in contact; then they form a chart that shows how motion changes. Each strip of tape indicates a speed, in the form of 'distance per tentick'. Each pupil should preserve his chart in his notebook and add some labels to it, such as 'starting up', 'running faster', 'sudden stop'.

Discussion of Chart of Tapes. The strip shows how far the moving trolley went in 10 ticks. It does not tell the speed in centimetres (or metres) per second unless one knows the time taken by one tick; but it does show the speed quantitatively. Since the tape is uniform in width, successive strips pasted side by side (in contact) show successive samples of speed, *taken for time intervals that are themselves spaced equal times apart.* It is more accurate, and clearer to some people, if the pieces of tape are not pasted in contact, but each along a vertical 'inch line' on inch squared paper. T

It is sometimes helpful to say:

> 'Now look at the *time of day* when you took the first sample (strip No. 1), and the *time of day* when you took the second sample (strip No. 2), and the time of day ... The time of day itself travels on by 10 ticks from one sample to the next.'

Alternative Story. If that confuses pupils, it is better to make a fresh start and say: T

> 'We want to know about the speed of the moving trolley. We made it run for 10 ticks (10 spaces between marks on the ticker-tape). We chop out that piece of tape and use it to show *how far the trolley went in that tentick.*
> 'We would like to know whether the trolley is moving faster or slower or at the same speed, later on. So we wait for a long time and then chop out another 10-tick length of tape. We can compare those samples of tape and see how the speeds compare.
> 'Try this: Chop out a 10-tick length of tape; wait for 100 ticks and then chop out another 10-tick length; again wait for 100 ticks and then chop out another 10-tick sample.
> 'When you "wait for 100 ticks" you should wait for just 100 ticks between the middle of the first sample and the middle of the next. Where is the middle in *timing*, the "half time" instant, in the first sample? ... Yes, it is at the end of 5 ticks. Where is ...'

Then encourage pupils to complain that these three samples are too few and waste a lot of tape. Offer to take the samples one after the other, without any 90-tick piece of unused tape between them. Then we are back at consecutive samples.

Other groups of pupils will be quite happy, without that special treatment, if we proceed rather quickly to the pasted-up exhibit, because then they see what we are driving at, and are keen to get on with some experiments.

Chart: 'Speed' v. 'Time'. When the pasted up chart is made, ask what the line-of-tops-of-strips tells us. T

> 'If the trolley is moving along without changing its speed at all (at constant velocity) what will the line look like?
> 'If the trolley is speeding up, going faster and faster, what will the top line look like?'

'Acceleration'. We should not expect to elicit the answer: 'If the trolley is accelerating with constant acceleration, the top line will be a slanting straight line whose slope indicates the acceleration.' That is a sophisticated description towards which we are encouraging pupils to work their way. T

Discussion Questions

1. 'Can you describe the way a boy was running if the tops of the strips on the chart make a straight line slanting upwards? T

'Can you make up some words to describe just what he was doing with his running-speed in that case?'

2. 'What does the length of each single strip really tell you? Suppose you took the length of the first strip and added the length of the second strip, and added the length of the next, too? What does the total of these three lengths tell you?

'Look at the chart which has strips on it, and use a pencil to shade strips Nos. 1, 2 and 3 (the ones whose lengths we have just added up). You have now shaded an area. Suppose you had a tape just 1 cm. wide.‡ In that case, the area of a strip would be [length] × [width], and that is [length] × [1], so in fact it would just be plain [length]. In that case, what would the total of the three lengths tell you? In that case, what would the area you have shaded for the first three strips tell you?'

That new idea is unfamiliar and difficult for many pupils. We should not try to teach it in a hurry. We should be wiser to leave that second question without much discussion and without clear answers, as if the teacher himself is worrying about it and not quite sure what the area will be. Then there is some hope that pupils will come round the next day and try to help the teacher to clear up his woolly thoughts.

Many pupils will find this idea of using the area strange. We should offer some different examples where the area under a graph indicates something important.

Examples of Charts or Graphs leading to Useful Areas

a. 'This chart shows the weekly wage paid to a young man who is doing various jobs. T

'Here he starts at 50*s* a week and he works like that for one week, another week and another week (three weeks altogether). Then he does a more difficult job for two weeks and is paid 70*s* a week; then he has two weeks out of work, paid nothing. Then two weeks on half-time of a £4 a week job, so he gets 40*s* each of these

‡ Or we could have narrow tapes pasted with their centre lines just 1 cm or 1 inch apart. That would be like having tape 1 cm (or 1 inch) wide.

weeks. There is a chart for 8 weeks. How much money does he get altogether in these two months?

'Now let's draw the chart on squared paper so that each square sideways means one week and each square upwards means 10*s* a week. Then the first week is 1 square wide and 5 squares high, and in that week he gets 5 lots of 10*s* and there are 5 squares on the chart. There is the same kind of story for later weeks. What can you do with the squares on the chart to find out how much he was paid in the whole eight weeks?'

b. 'Electric power stations keep very careful track of the power load from hour to hour through the day; because they want to be able to predict the big demand, so that they can get turbines and generators going beforehand. The energy running out from the power station is measured by instruments like an "electric light meter" graduated in "kilowatt.hours" of energy. (A kilowatt. hour is just a large package of energy, a little more than $3\frac{1}{2}$ million joules.) But power stations also have power metres that tell them how fast energy is flowing out to the power lines constructed. The power meter shows the rate-of-energy-going-out in kilowatts. (A kilowatt means an outflow of 1,000 joules every second.)

'Suppose the power station finds it is delivering 2,000 kilowatts from 8 a.m.–9 a.m.; 2,000 kilowatts from 9 a.m.–10 a.m.; 1,000 kilowatts from 10 a.m.–11 a.m. and 11 a.m.–12 noon; 3,000 kilowatts from 12 noon–1 p.m. (lunch is being cooked). Make a chart for that, with 1 square upwards for every 100 kilowatts and 1 square along for every hour. What does one single square on this chart mean? It would mean 100 kilowatts for one hour, and we call that 100 kilowatt.hours. That is all "kilowatt.hours" means. The word means that number of kilowatts running out all the time for one hour; or some other number of kilowatts multiplied by some other number of hours to give that value. "Kilowatt.hours" are like "man.hours" in those arithmetic problems about men digging ditches. How many kilowatt.hours did that power station deliver between 8 a.m. and 1 p.m.?'

c. 'A man running an orange–juice stall buys 5 dozen oranges at 6*s* a dozen, then 10 dozen oranges at 4*s* a dozen, then 3 dozen oranges at 6*s* a dozen, and another lot of 3 dozen oranges at 6*s* a dozen. Make a chart of each purchase showing the price upwards with 1 square for 1*s* per dozen, and the quantity of oranges along; 1 square for every dozen. What does the area on your chart tell you?'

Now return to the tickertape chart. Again ask what the area tells and again leave the question to brew.

Looking Ahead to Year IV. (We have some developments of this ahead of us, so it is better to let pupils enjoy pursuing it rather than hurry them into quick learning that carries doubts with it.

By Year IV, we shall draw a graph with speed plotted upwards and time plotted along – which is a refined form of this tickertape chart. Then taking the case of constant acceleration, we shall arrive geometrically at formulae such as $s = v_0t+\frac{1}{2}at^2$. That is much better than the simple algebraic method which takes $\frac{1}{2}$ the sum of first and last speeds, where the $\frac{1}{2}$ comes from a concealed assumption of uniform acceleration. Later still in Year IV we shall plot a strange graph, with [velocity] along the horizontal axis and [mass] $\times$ [velocity] upwards. That will give us an area which represents energy; and next Year we must prepare for that very carefully.)

Area of Circle (*optional: for able group*). Since there are several places ahead where we shall use the area of a triangle under a graph to tell us something important, we might prepare the ground, with an able group, by offering to show pupils how to prove themselves that the area of a circle is πr^2.

We first tell them the 'definition' of π, as the number that we multiply the diameter of a circle, or a cylinder, by to obtain its circumference. And we show them that one can obtain a rough value for π by direct measurement. We put a tape measure round a tree or a large beaker or a fat boy, undo it and read the circumference. Then we divide that by the diameter. Having established that π is just an important number, a little larger than 3 – an old story learnt by rote in arithmetic class long ago but a surprise to many now as a thing to be understood – we ask, 'How do you know that the area of a circle is πr^2?' We draw a circle of radius R. Then with the same centre we draw a smaller circle with radius r. We plot a graph of circumference (upward) against radius (along), as radius grows from 0 to R. It is a slanting line through the origin that looks quite reasonable, until we re-label the axes $2\pi r$ and r. Then some pupils will complain that this is a silly graph, automatically straight because we are really plotting the same thing along and upward; although we have magnified the upward distances by a factor a little more than 6. We reply, honestly, that it *is* an artificial graph. It is not a graph like a chart of some natural motion or the stretching of a real spring. But it may be useful.

We mark the value of r for the smaller circle on the graph. We ask what the height of the graph shows there – it shows $2\pi r$, the circumference of the smaller circle. We draw a vertical line at that place to represent that circumference. Then we go a very small distance w farther along the graph, representing a move to a slightly bigger circle, and we draw a vertical line to represent the circumference of that. Between those lines we have a narrow pillar whose height is circumference and whose width w is the distance between the two circles (difference of radii). We draw the slightly bigger circle and shade the ring of area between these two neighbouring circles. We also shade the pillar under our graph, between the two vertical lines. We ask what the area of the pillar tells us. ...

Then, of course, we draw a whole series of pillars from the origin right up to the outer radius R. The area of the triangle made up of those pillars is $\frac{1}{2}(2\pi R)r$, that is πr^2. The age at which seeing this becomes a delight rather than a pointless muddle depends both on the ability of pupils and on the way in which we present it. If, somehow, we can offer it in a light-hearted way, 'I bet I can show you ...', with a hint that a pupil can beat his older brother by a challenge to do it, we may succeed this Year. If not, we shall need the help of such demonstrations next Year.

More Tickertape Measurements *(optional extra)*

An Acceleration Chart. With a very fast group, the teacher can suggest that since the length of each strip shows the speed, the *change* of length (the *growth* of height from one strip to the next) shows the growth of speed. And the growth from one strip to the next occurs in the same time interval for each successive change from strip to strip. So, if we make a new chart, not with strip-lengths but with increases of strip-lengths, we should have a chart of acceleration plotted against time. This is a difficult idea, only to be tried by those who find it clear. With a supply of spare tape children cut pieces of tape equal to the increases of strip-height from strip to strip and paste these side by side to make a chart. T

Free Fall and Diluted Gravity

Free Fall. Pupils let a stone, or a piece of brick or a block of wood, fall to the floor and watch its motion carefully. Ask whether the falling thing does go faster and faster. When they say 'yes', ask whether they really saw it moving faster and faster, whether they really know that or think they ought to say so. One might argue from the fact that the object was at rest originally and later was moving fast, that it *must* have changed to faster motion; but an ordinary observer cannot make much of the acceleration during the later stages. T

Ask pupils how they can find out what the motion is like in detail, whether the thing goes faster for a short time and then runs at a steady speed or what. Elicit the suggestion that the tickertape and vibrator could tell us.

As a class experiment, let children attach a falling object to tickertape and let it drag the tape over the edge of the table while the vibrator records on the tape. Results will be somewhat inconsistent, partly because the acceleration is so great, partly because of friction troubles. Yet the experiment is worth doing because it does indicate that we are dealing with a large acceleration and it shows that this acceleration has something about it which we have not seen before. C48

Diluted Gravity. How can we improve the free fall experiment so that the acceleration can be studied carefully? If possible leave this as a question to brew in pupils' minds and do not at once give Galileo's solution. Faced with this problem, most classes sooner or later offer Galileo's idea: use a sloping hill, and deal with a 'diluted' form of gravity fall. Waiting for the suggestion is well worth while, because then pupils will feel the class experiment that follows is their own. T

Then as a class experiment, pupils should arrange the runway for their trolley to have a good slope and let the trolley pull a length of tickertape behind it under the vibrator.

This is a case where the teacher might also have his own demonstration set already arranged, to help the children set up their plank at a reasonable slope, etc. Then pupils should set up their apparatus and take several runs, so that each pupil has his own tape. C/D 49

Then each pupil should make his own chart and look at it carefully. The teacher should not suggest what the result should be or what the actual result means: this should be an interesting discovery for pupils, even though they do not know quite how to describe the result that they see.

Some pupils will see clearly that they have 'constant acceleration', in the sense that the speed increases by the same amount from each time interval to the next. To others, the straight slanting line of the tops of strips will merely mean that there is something interesting about the motion – and for them we should leave it like that.

A Strong Plea to Teachers. Many teachers, particularly if the class is a fast group, will feel tempted at this point to change from pasted-up charts of tickertape to a graph plotted from measurements of the tape. We urge teachers *not* to make that change yet. The pasted tapes have a strange virtue for beginners, of insisting on the physical nature of the chart. Graphs plotted quickly and skilfully may look neater and take less time but at this stage they somehow let pupils lose contact with reality. * * * * * * * *

A Different Investigation of Diluted Fall (*optional*). Ask pupils to take a new tape record of the same thing: a trolley running down an inclined runway. C50 OPT

> 'This time, turn off the vibrator until you are ready to start, and start the vibrator at exactly‡ the instant you release the trolley. Then you know the recording starts from the instant when the trolley starts. After the run, mark your tape at the starting point, and mark it after 10 ticks, and after another 10 ticks, and after another 10 ticks, and so on. Put a pencil mark on the tape every 10 ticks.
>
> 'Take some more tape and cut off a piece of the new tape just equal to the distance the trolley travelled in those first 10 ticks. Then cut another piece of new tape equal to the distance your trolley travelled in the first twenty ticks from rest. And now make another piece of tape for your trolley's distance covered in the first thirty ticks from rest: and so on. Look at these new pieces of tape and see if you can find anything very interesting about their lengths. There is a secret of numbers among those lengths.'

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

This is a difficult problem, one to be offered but not pushed at this stage. Most pupils will find Galileo's answer, that the successive tapes grow by equal jumps (3 ... 5 ... 7 ... etc.). Few will discover that the tape lengths themselves run as the squares of integers (1 ... 4 ... 9 ... 16 ... etc.). (If some pupils see the second answer, give praise and suggest the following experiment.) T

‡ If the vibrator is started beforehand, the record will still give the time we want – because while the trolley is at rest the dots fall on top of each other.

'If you are right, you could *imagine* a different kind of experiment with your tape. Instead of having the vibrator and tape, you could use string and tie a knot in it at a certain distance from the starting point, and another knot at four times that distance. Then if you put your finger at the starting point and felt the knots go bump under your fingers as the trolley ran downhill, how would those bumps feel to you? ... Yes, you would feel ...

'Well, in that case could you try the same thing with something falling freely instead of this diluted motion down a hill? ... Yes, you could have string with knots in it and feel them. You can try that if you want to ... or you can try tying a small stone to a string instead of a knot. Then you could have a tall string, with H51
a brick on the floor to anchor the bottom end, and stones tied on at the right places so that when you let the top of the string go you would hear the stones arrive at the floor (instead of knots hitting your hand). You could try that.

'You could try it with stones tied on to the string with small side strings, or with ping-pong balls attached with Sellotape, or best of all with small lead beads that fishing tackle shops sell for weighting lines.'

Give encouragement, but do not do the planning for these bright pupils.

Acceleration on Uphill Trip (*optional buffer experiment*). Ask C52
pupils what happens to a trolley that runs *uphill*, after being given a OPT
push. If possible, let them try a class experiment with tickertape with the same hill.

Then ask what would happen to a trolley which is allowed to run T
downhill, and then along the level, and then meets an uphill slope.

NEWTON'S FIRST LAW AND INERTIA. INFORMAL TREATMENT

The Downhill-and-Uphill Demonstration

Everyone knows the qualitative answer to the last question, but T
what about the quantitative answer? Will the trolley run up the other hill to the same height as its starting point?

Show a demonstration with a steel ball rolling down a hill of a D53a
curtain rail and up an opposite hill. This must be arranged with the rail very firmly supported on wooden planks in all sections – not

just held in mid-air by isolated clamps – or the energy loss will be too serious.

Show this with several different slopes, also with a horizontal section between the downhill and uphill parts.

In each case pupils should watch the height to which the ball climbs on the ascending side. They will 'explain' the failure to reach the original height as 'due to friction'.

Some may even bring an energy argument to it from Year II and *
point out that the potential energy that turns into kinetic energy *
should go back into the same amount of potential energy – but for *
friction – so that the ball should (or 'must') rise to the same level. *
That argument seems to beg the question, though it would be *
sound if one could be assured by some *other* means of the con- *
servation of energy. In fact, our belief in conservation of [P.E. + *
K.E.] is derived, on certain assumptions, from Newton's Laws of *
Motion. That provides us with $\frac{1}{2}mv^2$ for K.E. –Laws which Newton *
in turn derived from Galileo's thinking and experimenting with *
motion down one incline and up another. So, logically, motion on *
inclines, Newton's Laws, and energy conservation are inter- *
connected and we must be careful not to 'explain in a circle'. *
Nevertheless, children who point out any connection here deserve *
high praise and should not be worried with the ultimate logic. *

Galileo's Pin-and-Pendulum Experiment. Friction spoils the downhill-and-uphill experiment and makes it unconvincing. Now is the time to show Galileo's practically frictionless version of it as a demonstration or, better, as a class experiment. This should not be shown as a set piece that is taken out of a cupboard ready made, but should be something that pupils or teacher can rig up when it is needed. Hang a pendulum from a *very* firm and massive support and, as it swings, interpose a firmly supported rod some distance above the bob's lowest point, so that the string swings against it and the pendulum continues in an arc of much shorter radius. Pupils should watch carefully to see whether the bob climbs the 'steeper hill' to the same height as its starting point of the shallower hill. This experiment needs very firm supports for the pendulum and for the peg that is interposed, or it will be spoiled by energy leakage. Of course, children will try reversing it. That is good science. C/D53

Newton's First Law

Galileo carried out a thought experiment: he thought about a ball rolling down a hill and up an opposite hill which had no slope at all – a horizontal road. He imagined the ball going on and on along that 'opposite hill', which was just a level plane, and never stopping because it could never reach its original height! See whether pupils can arrive at that by giving them the original problem and a little help: T

> 'Suppose a ball rolled downhill and up an opposite hill, as in this picture, without any friction. How high would you expect it to rise? Now suppose the opposite hill does not slant up so steeply but is like this. What would happen? ... And now suppose ...'

Remember that the joy of making one's own theoretical discovery in a matter like this is well worth the time taken and we hope teachers will accept the sorrow of having to leave the question unanswered for many pupils.

Demonstrations of Frictionless Motion, using solid carbon dioxide, are so important that we hope they will be shown at this point and at several later times in the course. T

It is possible to manufacture small quantities of solid CO_2 with a cylinder of carbon dioxide, like a fire extinguisher. In such a cylinder the carbon dioxide is liquid at room temperature and unless it is a special one with a siphon, should be inverted. The valve is opened *fully* for five or ten seconds, and a blast of CO_2 driven into a piece of closely woven cloth, folded to form a bag. The latent heat that is taken from the vaporizing liquid cools some of it to freeze it into a solid. Unless one releases the CO_2 in a copious blast, too little solid CO_2 will be formed; but a large blast will produce sufficient for these experiments. Therefore it is essential for schools using this method to have a spare cylinder as well as the one in use.

But to do justice to the first demonstration suggested (and to some others this Year and next) a larger supply of solid CO_2 is necessary. The manufacturers now have good containers and excellent arrangements for sending one or more 25-lb blocks by rail to any school. We hope that schools will experiment with large blocks.

Some suggestions for demonstrations are given below but teachers should remember that a fuller treatment of Newton's Laws of Motion will be given in Year IV, so most of these demonstrations can be postponed if time is short. Nevertheless, where a class has the time, early preparation will yield good fruit in Year IV and will enable the other work in Year IV to have the full time that it deserves. Year IV proves to be a full year of physics.

The Large Block. Best of all, if it is available, is a block of 'dry ice', solid CO_2, say about 6 inches $\times$ 6 inches $\times$ 4 inches, or even larger, coasting on a large sheet of glass. The glass must be carefully levelled, then carefully cleaned with window-cleaning fluid. The bottom surface of the block of CO_2 must be polished by ironing it to and fro on a sheet of metal. Then the block will coast on a flat glass sheet with a marvellously constant motion. D54a

Ring Magnets. A metal ring covered by a lid, with a little solid CO_2 under the lid, coasts along a smooth table with practically no friction. The ring may be a ring magnet, to be used later for collisions. The CO_2 snow is placed in the centre of the ring and the ring is given a push. As the CO_2 evaporates a stream of gas runs out under the edges of the ring keeping it supported and allowing it to move freely with practically no friction. D54b

As a much poorer alternative, a small metal disc will move with little friction on a glass sheet covered with tiny polystyrene balls.‡ D54c

Demonstration (*optional*). As a puzzle, photograph a collision of ring magnets coasting on a sheet of glass, and ask pupils what they can find out from the clues in the picture. D54d OPT

It is essential to show pupils at least one of these demonstrations and not just to talk about it. This is an exhibit of Newton's First Law of Motion. Although in this age of satellites pupils may have heard about motion going on and on, it is still a strange idea to many. Blatt – in one of the lectures to physics teachers in Australia (edited by Messel)‡‡ – puts the first 'commonsense' law of motion thus:

> 'A body with no force acting on it either maintains its state of rest or comes to rest very quickly if it was moving initially.'

‡ *Other Pucks.* Larger forms of puck have been suggested and tried. A copper ball can be filled with chunks of solid CO_2 or even liquid air, and the gas developed carried by a pipe through to the bottom of a massive base. In another form a metal canister is pumped up with a bicycle pump. These devices work well but seem unnecessarily complicated for our direct demonstrations.

‡‡ H. Messel, ed., *Selected Lectures in Modern Physics*, Macmillan, 1960.

That is just what an intelligent person would think if he watched what happens in ordinary life. Friction is all around us. No wonder the Greeks studied motion with friction and arrived at quite intelligent laws for the motion controlled by friction.

Newton's First Law of Motion applies to cases where there is *no* *
force. That either means no force at all (including no friction), as *
in the case of a moving object far away out into space; or it means *
motion with no *resultant* force. Putting in that word 'resultant' *
makes Newton's First Law sound more sensible. When we have *
some object coasting along the level table at constant velocity, *
with no friction, it is not true that there is no force on that body: *
there is its full weight, gravity pulling on it as much as ever, but *
that is balanced by a push up from the table. Again, we could have *
an object moving along such a table with plenty of friction dragging *
on it and still have a case of Newton's Law I if we kept pulling the *
object forward with a force that just balanced friction. *

We must be careful not to give pupils the idea, now or later, *
that Newton's First Law of Motion applies only to cases where *
there is no friction! It applies to any case where all forces balance *
out to zero resultant. *

Many a physicist reverses that statement and says that when he sees *
motion continuing constantly he knows that there must be zero *
resultant force – in fact that might be taken as a definition of zero *
resultant force. *

Inertia

Instead of just thinking of *motion* continuing when there is no force, *
we might concentrate on the idea of a *solid body* continuing to move *
when there is no force. Then we think of the solid body as having *
some property in it of wanting to continue to move, of being *
difficult to stop moving. It is the property that we call *inertia* – *
though giving it that obscure name is no help whatever towards *
pupils understanding the idea of mass. *

We can develop a feeling for inertia by asking pupils about moving T
things:

> 'Can you stop a moving goods wagon that is running along a line smoothly after being shunted? ... Yes, but can you stop it easily or at once? Can you stop the moving object in the frictionless demonstration you saw, immediately, with no trouble?'

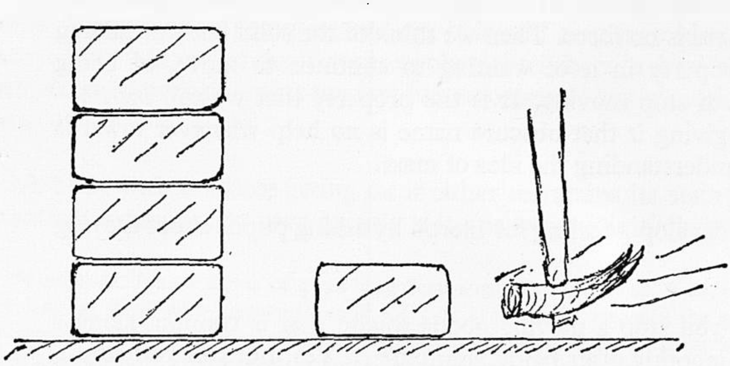
A very useful demonstration consists of two tin cans hung by long strings as pendulums side by side. One tin can is full of sand, the other is empty. Let the pupils try pushing each to start it moving. And let them try stopping a can when it is moving. Then ask why safety belts are worn in cars, and continue that by asking what happens to the non-belted passenger on the back seat when a car suddenly starts, stops, goes round a sharp corner. Later that could lead to a discussion of motion in a circle; but we should not embark on that now or we shall get seriously entangled with centrifugal force. D 56

There are some traditional experiments that illustrate inertia, such as the following:

a. A coin on a card on a tumbler. The card is whipped away and the coin falls into the tumbler. D 57a

b. A thread hung from the bottom of a weight which is itself hung on a thread – so that a steady pull on the lower thread breaks the upper one, while a sudden snatch on the lower thread breaks the lower one. To make the paradox underlying this demonstration specially clear, use the same kind of thread throughout, but have a single thread for the upper one and two or three strands in parallel for the lower thread. D 57b

c. A very small weight (1 gram) tied to the end of a thread and placed on the table. Although the breaking strength of that thread is many hundreds of grams and it carries only one gram loose on the end, it can be broken by a sufficiently sudden jerk of the other end. (Strong sewing thread needs 5 or 10 grams for this to succeed.) D 57c



D57d

d. As a reverse form of (*a*), we can push a wooden brick in at the bottom of a pile of similar bricks. The bricks should be smooth blocks of wood, say 4 inches × 3 inches × 2 inches with their edges and corners rounded. We build a pile of 4 bricks, then push a fifth brick quickly at the bottom brick of the pile. The fifth brick goes in and the bottom brick goes out. This is most dramatic if the fifth brick is projected along the table towards the pile by a 'croquet hit' from a small mallet.

To children these are delightful tricks rather than exhibits of the effects of inertia; therefore it is probably better to leave such tricks for a later stage.

These inertia tricks do involve a true inertia property, that if a force acts on an object for a short time, the object does not acquire much motion or move far; but they also involve properties of friction. The simplest form is the trick of pulling one book out from the middle of a pile of books. The book that the operator snatches out exerts a force by means of friction on the books which are above it.

If the operator snatches the book with sufficiently big acceleration, the force that would be needed to give the books above the *same* acceleration is bigger than limiting friction; so there is slipping and the pile above does not manage to follow the book that is being snatched. However, it does not completely fail to follow; there is friction between the surfaces in relative motion (and unless the operator was skilful at the start, he probably began snatching with too small an acceleration, in which case there was a short time in which static friction accelerated the pile of books above).

Therefore, the pile above the snatched book does get going, though not so fast as the snatched book. When the snatched book is out, clear of the books above, the latter can fall; so they follow a little farther still, while they are falling through one book thickness.

If we are prepared to spoil the fun of the trick by going into details, we can point to the final position of the 'upper books', a short distance ahead of the 'lower books', and we can make this a good demonstration of inertia. Unfortunately, we cannot increase the inertia of the 'upper books' without also increasing the friction forces, so that the critical acceleration for success has to be increased. All this makes a good discussion for advanced physicists but throws some doubt on the use of these tricks here.

Rocket Ship Propulsion? We should ask what keeps a space ship going once the rocket is in orbit and the rocket motors are turned off. Here again we should discuss the motion continuing and avoid any discussion of central forces at this stage. T

Then we say:

> 'Suppose a space ship has its rocket motor turned off far out in space, well away from the gravitational pulls of the Earth and the Sun and the other stars, will it keep going? Why?'

Perhaps the right question to ask is 'What is there to stop it continuing in motion?' Once that leading question has been asked then the First Law seems more acceptable.

FORCE AND MOTION: INFORMAL TREATMENT

Although we do not intend to carry pupils through a formal study of Newton's Laws, we do want them to acquire a feeling for the relationship between force and motion. A few simple experiments should be tried with a trolley and tickertape: but the full investigation with that should wait till Year IV. * * * * *

Trolleys and Tickertape

Now that pupils have had some experience with trolleys and timing, they will be ready to pull a trolley with various forces and measure its acceleration in centimetres/tentick per tentick. The following experiments should be done quickly. T

The pulling is done by a pupil holding a length of rubber thread at constant stretch, or a long thin rubber band. (A spiral spring would be better behaved, but it is too easily tangled in this exciting game.) The rubber thread should be 6 to 8 inches long, stretched to a total length of about 12 inches when in action. To maintain the stretch, the pupil uses the length of the trolley as a guide. He attaches one end of the thread to a post at the rear of the trolley and holds the other end just above the front of the trolley so that the rubber is stretched to the full length of the trolley. Then he walks along beside the trolley, keeping the thread stretched to same length. At first this seems hopelessly rough, but pupils can learn considerable skill in a short time. Meantime, a partner takes charge of the vibrator and tape. At the start he holds the trolley still and gives a signal to the first pupil when he releases it. C58a

In analysing the tape by making a 'chart' – *not* a plotted graph at this stage – pupils should use only that region of the tape for which they consider the pulling force was kept fairly constant. Each pupil should make his own tape and cut it up for a chart.

The question of friction will at once crop up. Measuring friction and making allowances would be too complicated. It seems better to discuss with pupils the possibility of 'compensating for friction' – paying for it by some automatic scheme: T

> 'What could you do to your whole experiment to make it behave as if it were frictionless; not with any magic oil or special wheels, or compressed air to support it like hovercraft, but just a clever simple change of your present apparatus?'

We are trying to elicit the suggestion that the runway, the plank on which the trolley runs, should be given a slope; just enough for the trolley to run down it at a constant speed. The teacher should help pupils to arrange, and test, this slope. (With good trolleys it may be as low as 1°.)

The pupil who notices that even when several bricks are added to increase the general mass the slope needed to pay for friction is about the same, should receive high praise.

With '*friction-compensated*' runways, pupils should try making a chart for the motion with a pull of one stretched thread, two stretched threads in parallel and perhaps more. This experiment should not drag on until it is worrying or tedious. It should only go on as long as it is fun. Having the tape-chart to take home will probably maintain enthusiasm. C58b

Changing the Mass ***(buffer option for fast groups; better postponed for Year IV for average or slow groups)***
We ask what would happen if we had to accelerate two trolleys instead of one. Provide a second trolley to be placed on top of the moving one and let pupils find out what they can. This is an exploration of the principal meaning of mass. We should do better at this time if we let pupils keep anything they find out as something to think about, than if we give a lecture to explain the meaning of mass. C59

Experiments with Large Trolleys (*optional extra demonstrations*). If large 'playground' trolleys are available, these may be used to supplement class experiments, but not to replace them. If done, they should follow, not precede, the class experiments with tickertape. We hope that in the long run teachers will add some D60a OPT large homemade trolleys to their equipment for this purpose. If the school already has large trolleys, some of the experiments below should be tried. However, we do not advise buying a large trolley now when equipment for class experiments is so much more important.

These need to be robust, with sturdy rubber-tyred wheels – or, if the floor is very hard and smooth, roller-skates may be used. The design and use of these trolleys is described in the Ministry of Education pamphlet No. 38, *Science in Secondary Schools*, H.M.S.O., 1960.

The large trolley should be equipped with a bicycle speedometer. We ask pupils to pull a loaded trolley with a spring balance, maintaining a constant pull. This is not easy. It can be made easier by a trick: interpose a *long* piece of sturdy spiral spring between the pulling pupil and the spring balance, or between the spring balance and the trolley. This acts as a 'force regulator' or an extendible buffer that smooths out jerks in the motion and makes it easier to keep the spring balance reading steady. The forces and masses used must depend upon the actual trolleys and local circumstances. We suggest *some* of the following:

1. A pupil pulls the trolley with a force of several pounds-weight (a few kgm-wt or a few dozen newtons), keeping the pull fairly constant. Pupils watch the speedometer and take its reading at regular intervals of time; they plot a very rough graph.

2. Pupils measure the total time to cover some standard distance, from rest, with that pull or, instead, a pupil sitting on the trolley makes chalk marks or drops cards on the ground at regular time intervals as the trolley is dragged along. Subsequent measurement provides a record of the motion.

3. Two pupils pull in parallel, each with the same force as in (1). Measurements of (1) and (2) repeated.

4. If time permits repeat (3) with three pulls in parallel, etc.

5. Try changing the mass by adding pupils as riders. (We do not discuss mass deeply. So far, it just *is* the total stuff, trolley+riders.)

6. Install a simple spring balance preferably on the trolley and double and treble the pull by maintaining a different pointer reading.

In all these cases, the pulls must be so big, compared to friction, that friction does not obscure the whole story.

Optional Extra Demonstration. There is a good but complicated scheme for 'allowing for friction' if the experiment is done indoors, the trolley has very good wheels, and the floor is smooth and unyielding. In addition to pulling the trolley by hand, we pull the trolley with a string which runs along to a pulley fixed on the wall, up to the ceiling, and over a pulley to a small load hung on it. We make that load just enough to keep the trolley moving steadily and we assert: D 60b

> 'That is a pull to allow for friction. That pull is opposite to the drag of friction and we shall reckon that they just cancel out.'

Note that we do not use the misleading phrase 'overcome friction'.

Experimental Troubles. Friction. The rough observations of these experiments will raise two matters in discussion: the obvious difficulty of keeping the pull constant while running; and the question of friction.

We cannot make the pull steady unless we change from a pulling human hand to something like a sandbag pulling on a thread that runs over a pulley to pull the moving trolley. If we do that, the motion is smooth and the force is steady, but we have great troubles with argument about weight, and refinements of argument about that fraction of the sandbag's weight which is used to accelerate the sandbag itself. Therefore we advise strongly against using that device. It seems better to use the pulls of springs and rubber threads and learn to live with the unevenness.

We might reduce friction by employing clever devices such as a CO_2 puck. But in this preliminary study it seems better to meet friction openly and avoid giving the mistaken impression that Newton's Laws of Motion apply only to some ideal frictionless cases.

To help in facing the problem of friction, we make it worse by adding an extra backward drag. We ask two pupils to pull the playground trolley forward, each with the standard force, while one pupil pulls it backward (while himself progressing forward with the trolley) with the standard force. D 60b

After variations of that, we return to the case of no pupil pulling backward and suggest we might make a guess at the force of the friction's concealed backward pull.

We can test that guess by pulling with a spring balance and using just enough force to maintain a constant speed. This shows the advantage of using a spring balance with a scale of forces here. We can then subtract an allowance for friction.

The teacher might be tempted to start with a discussion of friction *
and methods of eliminating it or allowing for it; but pupils, to *
whom this is quite new, will find the practical difficulties of fric- *
tion and the theoretical difficulties of argument together obscure *
the story which they are trying to explore. It is better to let pupils *
find the difficulty by obtaining unsatisfactory results and then start *
all over again with an attempt to allow for friction. *

Therefore pupils should now repeat (1), (2), (3), etc., this time D60b
measuring the friction allowance first and adding an extra pupil pulling just enough to 'pay for that'.

We then hold a general discussion with pupils, asking whether, T
when there is force – in excess of the amount needed to balance friction – there is *constant velocity* or *acceleration.*

And is that acceleration constant as the motion goes on? Is it bigger with a bigger resultant force? Those questions deserve some measurements with trolleys and tickertape; but those should be brief and simple.

Force, Mass and Motion

This is the point at which we should leave the experiments, with *
only general ideas: that a constant force produces constant accelera- *
tion and doubling the force doubles that acceleration; and perhaps *
that two trolleys need twice as much force as one for the same *
acceleration. *

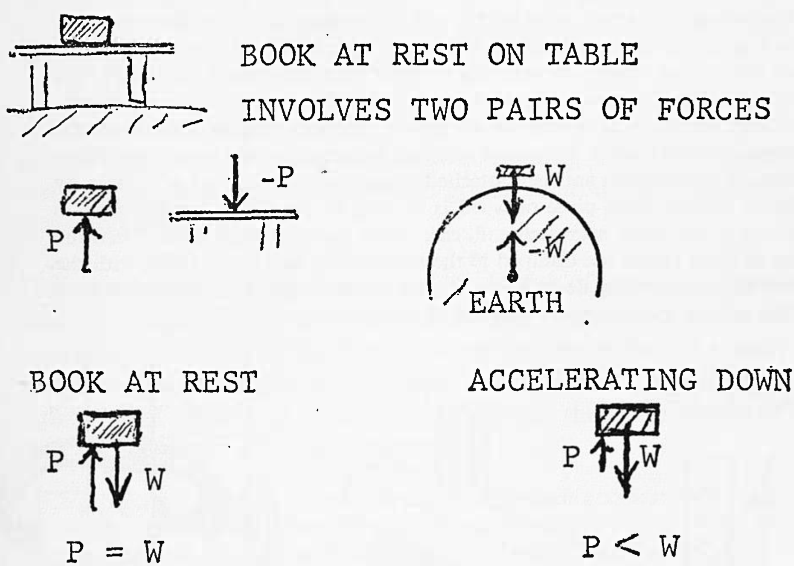
We might ask pupils about rockets and putting on an extra payload. *
We tell pupils that the electrons in a TV tube come out of the gun *
at a fantastic speed, and we ask what that suggests about electrons. *
(Of course it suggests nothing, in terms of proper scientific argu- *
ment. However, the rough suggestion that electrons have very *
small mass is true in the sense that they have an enormous e/m; *
in effect they have a huge charge that is pulled by common electric *
fields with an enormous force compared with the pull of common *
gravity on their mass.) *

NEWTON'S THIRD LAW OF MOTION

We make only two informal beginnings:

1. A very brief demonstration: the teacher offers a pupil the other end of a meter rule and says 'Pull.' Then he says 'Which way am I pulling you? Which way are you pulling me? Is it possible for me to pull you without you pulling me?' D 61

Note to Teachers on Newton's Third Law. We should be very careful, in talking about Newton's Third Law of Motion, always to give genuine action-and-reaction pairs. If I leave a book on the table it does not stay at rest because of Newton's Third Law. There are two forces on the book and they *happen to balance*, owing to the elastic properties of tables. The table is squashed (almost imperceptibly) by the book until it exerts an elastic force just sufficient to hold the book in equilibrium. One force is the downward pull of the Earth on the book and the other is the upward push of the table. If the table were in an accelerating lift, an outside observer would see that those two forces were unequal. The resultant difference between them would be just sufficient to give the book the proper acceleration.



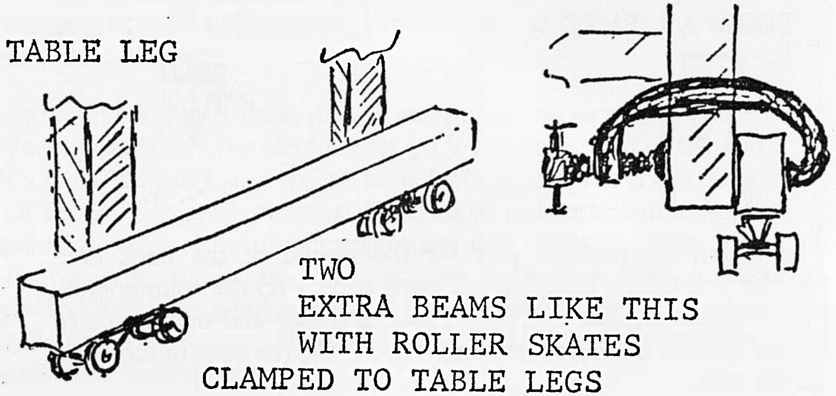
The action-and-reaction pair for the weight of the book are: (A) the pull of the Earth on the book and (−A) the counter-pull of the book on the Earth. There is another action-and-reaction pair: (B) the push of the table on the book and (−B) the push of the book on the table.

Discussing these matters with young pupils is apt to confuse them. Newton's Third Law of Motion – which Poincaré considered purely a convention, an account-keeping rule – is best taken for granted until we come to momentum conservation in Year IV. * * * *

2. As an optional class demonstration, for a fast group, we put some pupils on a table on wheels, and give them a rope with which to pull another loaded table on wheels. (If a school has 'playground trolleys' the teacher may be tempted to use them for this; but we fear damage and advise using tables as described. Unless tables with strong wheels are available, we suggest installing roller-skates, temporarily on two ordinary tables. This is easily done as described in the note below.‡ D/C62

We ask them to pull until the trolleys meet with a bang. The first time we let only one lot of pupils pull; the second time only the other lot pull; the third time both lots pull. If the trolleys have good wheels, and we are careful to start them from the same position each time, the collision will occur at the same place however the pulling is done. We will not draw a moral from this but let pupils think about it.

‡ Any robust tables with good wheels will suffice for this, but on most types of floor a good demonstration needs either large wheels with hard rubber tyres or good roller-skate wheels. In planning to make such tables for a laboratory, one thinks of roller-skates as being much more difficult to install than large wheels. However, where the laboratory already has strong massive tables without wheels, roller-skates make much the easiest solution, because they can be screwed on to beams of wood which are then attached temporarily to the legs of a table by large G clamps. Each piece of wood is as long as the table. A roller-skate is screwed to the beam near each end, care being taken to align them. Then the sides of these beams are clamped to the sides of the legs of the table, with the roller-skates projecting down below the feet of the legs. The tables also need buffer pads at the top where they hit in collision.



Multiflash Pictures (*optional extra*). If the school has equipment for taking 'multiflash' pictures (a camera used with motor strobe or with Xenon flasher) now is the time to take a picture. That will provide useful information for our discussion of falling bodies, and a first taste of a method that will become very important next Year. We do not suggest using this technique much during this year; but schools which are equipped for Year IV will have the necessary apparatus and we think teachers and pupils will enjoy one or two specimen demonstrations.

D/C63 OPT

If a picture is taken (see Note on Stroboscopes and Multiflash in General Introduction) it should be of a freely falling object with a considerable number of exposures on the picture. The teacher should project the picture and show how it can be analysed, or, much better, produce copies§ so that each pupil has a copy to analyse as a class experiment. The flash images show positions at regularly spaced instants of time. Therefore distances from image to image can be used in the way that tentick strips of tape were used. We suggest taking a picture of the freely falling body, or, still more useful for analysis, a picture of two bodies released simultaneously, one to fall freely vertically the other thrown out horizontally. The latter would afford the analysis discussed for the stream of water drops (Experiment D 67).

We can expect pupils to use common sense in measuring and magnifying their measurements and converting them to a 'tape chart'. That is better for them than giving them detailed instructions and warnings.

If the multiflash method that we use has flashes of very short duration the images will be sharp. But if the flashes last some time – an appreciable fraction of the time between successive flashes – each image will be drawn out; and the length of the 'blur' gives a direct indication of velocity. Although these blurs are difficult to measure they do offer very valuable indications.

§ A teacher in trials suggests a convenient way of producing copies which pupils can analyse themselves: 'Place the photograph on a small pad of paper and prick through the centre of each dot or blur with a sharp pin. Copies, up to a dozen at a time, can then be torn off and the distances measured. The results turn out well. After doing the demonstration D 67, he reported: 'Again the pin and pad were used. Care must be taken to lay the photograph squarely on the paper. The pupils can then draw lines parallel to the edges of the paper, to go through the dots – one set of lines at right angles to the other. One set turns out to have equal separations and the other set gives the 1 : 4 : 9 : 16 : ... relationship quite closely, if the picture is squarely on the pad.'

Multiflash Results: Acceleration; 'g'; Avoiding Formulae. It is tempting to say, 'You have seen that acceleration of something falling is a *constant* acceleration. I can give you a formula which will enable you to measure that acceleration.'

Giving a formula at this point would indeed spoil our approach – except for extremely fast groups who have pursued tape charts into acceleration graphs and then used the idea of those graphs for Galileo's geometrical proof of $s = \frac{1}{2}at^2$ for constant acceleration. For all others, that should wait till Year IV.

The urge to measure 'g' is strong in most well-trained physicists. 'g' is an interesting thing connected with the Earth's gravitational field; but the importance we attach to it is probably connected with our use of 'g' in converting weights to absolute units. It gives us the field-strength. Perhaps 'g' is interesting to children; however, spending much time and trouble in trying to measure 'g' precisely does not add to its lustre but gives it a strange reputation of being considered by us to be very important.

Falling Bodies of Different Masses. We ask all pupils to try releasing a big stone and a small one side by side in the classroom and, if possible, from somewhere much higher. We should preface this experiment by asking what will happen. For once in the way, it is safe and fair to start with a strong incorrect impression, that we expect the heavier stone to fall faster – as the medieval Aristotelians taught. (They were, perhaps, foolish in their rigid unthinking repetition of Aristotle's statements – teaching by book instead of by real nature. Aristotle himself was a very wise man, almost certainly writing about objects falling against air resistance, with terminal velocity.) After discussion and votes about what will happen, pupils should try dropping a variety of things. C64

Many pupils will be surprised at things falling with the same motion irrespective of weight; but all will suggest the explanation of ping-pong balls and scraps of paper, etc., failing to keep up with the rest. We should comment on 'g' being the same for all: T

> 'This is very strange. Why doesn't the heavy thing fall faster? I can feel the Earth pulling it with a bigger force. That must be because the heavy thing also has a lot of stuff in it that needs more force to keep it going faster and faster. The bigger thing has more weight (the Earth pulls more on it) and more mass – more stuff to be moved!

At all costs, we should avoid, now and later, the phrase 'overcoming inertia'. Inertia is never beaten: it is always there.

Galileo

'There is a fable, unfortunately untrue, that the great Italian physicist Galileo, who wrote about force and motion three and a half centuries ago, gave a wonderful demonstration. The story says he climbed to the top of the Leaning Tower of Pisa and dropped a little iron ball and a big cannon ball side by side. Everyone was astonished, and some even angry, to see they arrived at the ground together, instead of the big ball, which weighed 10 times as much, falling 10 times as fast. (Long ago the Greek scientist Aristotle had said that, but then he was thinking of motion against plenty of friction in air and water.) T

'We know that Galileo did not make that public demonstration. But he certainly knew the wonderful property of falling things that you have just seen, and he taught it to people. He also invented a "thought experiment" to upset people who were teaching Aristotle's statements blindly. Here is his story:

'"Suppose I let three equal bricks fall to the ground, starting together neck and neck. They are all the same. They will all fall with the same accelerated motion, all arrive together." His opponents agreed.

'"Now suppose I repeat the experiment but first chain together two of the bricks with a light invisible chain, so light that it isn't really there. Then, I suppose I have a brick and a double brick. According to Aristotle, the double brick will fall twice as fast. Do you think that likely, just because that little chain is there?" "Ah yes," one of his opponents might say, "one of that pair of bricks gets a little *ahead* and drags the other down faster than the single one." "Oh, I see," Galileo would reply, "one of the pair gets a little *behind* and drags the other backward making it fall slower!" Galileo made his opponents furious by making their arguments look foolish.'

Air Resistance. Galileo suggested that the reason why a wooden ball was left a little behind a steel cannon ball, and a piece of paper fluttered down much more slowly, is that the less dense things are delayed more seriously by air resistance. He had no vacuum to prove that without air all things would fall exactly together, but he was sure that that would be so. In a vacuum, he said, a scrap of lead and a scrap of sheep's wool would both fall with the same full, accelerated, motion. T

We tell pupils this story and say that, soon after Galileo, Newton tried the actual experiment with a golden guinea and a feather.

The Guinea-and-Feather Experiment. Most laboratories have a 'guinea-and-feather demonstration' in the form of a long tube that has been pumped out and sealed. That is certainly something that pupils should see; but it is much better if they see the actual pumping-out done, and better still if they attend to the matter themselves. C65

(Those of us who watched a teacher turning the great tube over and trying several times to get the feather to start without sticking electrostatically, remember a feeling of doubt. We wondered whether it was a great demonstration or rather a swindle. That would never happen in the pupil's own hands: he would have as firm a conviction as that teacher did in earlier days.)

There should be no mystery about a motor-driven vacuum pump or sacred treasuring that discourages frequent use. Those are now more common in physics research laboratories than balances for weighing. They are expensive but quick, capable, robust and long-lived; and maintenance with fresh oil is easy.

Therefore we suggest that the guinea-and-feather experiment should be a class experiment. Pupils should be provided with a fairly short glass tube, only about two feet long, with rubber stoppers (or rounded ends carefully annealed to withstand minor shocks of the falling 'guinea'; and a wide enough side tube to admit specimens).

A piece of metal the size of a sixpence‡ serves as the 'guinea'; a heavy 'guinea' may smash the end of the tube, particularly if it has sharp corners. A brass tube, to which tubing can be attached for pumping, is carried by a rubber stopper in a side tube or by one of the end stoppers. We interpose a short piece of fairly thin-walled rubber tubing between that brass tube and the main pressure-tubing to the pump, so that the pupil can pinch it to close up the apparatus. Pupils bring their tubes to the pump when ready.

Vertical Fall and Parabolic Paths

We want pupils to see and understand the principle that Galileo arrived at – which formed such a very important, perhaps un- T

‡ A halfpenny has been suggested, but this is large enough to spoil the experiment by pushing the feather down with it.

conscious, basis for Newton's treatment of accelerations and forces as vectors that add independently – that a moving body can have several separate motions, which are independent of each other.

A body can have two separate velocities: it can be moving at a certain speed due east, and with another speed due north and having one motion does not interfere with its progress in the other motion. A clockwork toy crawls steadily across a rug, say eastward, while we pull the rug steadily in another direction, say northward. The toy's progress northward, due to our dragging the rug, is quite independent of its crawl eastward. It travels the same distance north in a given time whether it is also crawling or not. To an observer sitting on the rug the motion of the crawling toy is just the same whether the rug is being dragged or not – provided the motions are ones with constant velocity. The progress of the toy across the floor under the rug is the simple geometrical sum (by the parallelogram construction) of the two separate motions.

The final position of the toy on the floor is the same whether one motion happens first and then the other, or the other and then the one, or both motions simultaneously. The two motions do not interact. That seems to us obvious and necessary: it must be so. Yet in fact it is something we have discovered about the world we live in, and generalized, and now take for granted. We learned when we let something roll or slide or drop in a moving railway train or, as Galileo pointed out, when we throw something across the cabin of a ship moving steadily in a smooth sea. If we lived in a different world, a whirling centrifuge or an accelerating rocket, we might not find the velocities obeying that simple rule. (And we now know that even in our ordinary world very large velocities, comparable to the speed of light, do show different properties to an observer.) Young pupils easily take the simple independence and addition property of velocities for granted; and we should encourage that. Accelerations have the same additive properties; they too are 'vectors' that can be added by the parallelogram construction, according to which the effect of two vectors together is the same as first one and then the other applied afterwards. When they are both together one does not disturb the effect of the other.

Forces too are vectors that add geometrically and do not interfere with each other. We have now made a deeper statement about the world we live in, because in professional physics we judge forces by the motion they produce. So we are now saying that when several forces act on a body each produces its own effect on motion, and one force does not interfere with the motion produced

by another force. The total motion is simply the (geometrical) *
sum of all the separate motions that the separate forces would make. *

All this applies to the world of Galilean Relativity, in which forces *
and their effects can be superposed – the world in which Newton *
constructed his mechanics. *

Of course, none of this discussion of vectors and independent *
actions should come into our present teaching. It is only given here *
as a very remote background for our own thinking about our *
teaching. *

A falling stone falls with the same accelerated motion whether it is T
moving horizontally or not. The two motions are completely independent, and that enabled Galileo to examine the *horizontal* motion of projectiles, which is free from any accelerating force. So, in an indirect way, he knew Newton's First Law from experiments with projectiles.

(When air resistance becomes important, as it does for objects of low density and for high speed, this simple story is masked by varying effects of friction.)

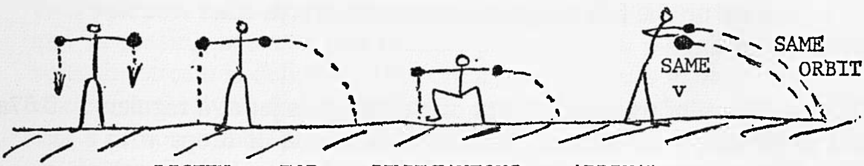
Some laboratories have an ingenious trigger device that releases *
two balls simultaneously, one free to fall vertically, the other pro- *
jected horizontally. Both arrive at the floor together – audibly. *
Moving the apparatus nearer the floor, we find the same simul- *
taneous arrival: at all stages the vertical motion is the same for *
both balls. The device is ingenious and we might demonstrate it *
if we have it or let pupils use it if we have many. Yet, the cruder *
form of this experiment in which the pupil releases the two falling *
objects with his own fingers is more striking to beginners and *
better teaching – there is no gadgetry to divert attention.§ So we *
urge teachers to let pupils do this: *

> 'Hold a stone in your left hand and a stone in your right hand C66a
> and practise letting go to release them simultaneously, and allow both to fall. How can you tell if you let go both at the same instant? ... Go and try it and listen ...
>
> 'Now try the same thing, but throw one of the stones out sideways just as you release both. Now what happens? ... Try doing that at several different heights above the floor, always releasing both

§ 'Done at home and reported in class.'

stones at same time at same height ... Now throw both stones outward with different speeds ... Now try doing it with stones of unequal size. Does the heavier one fare any differently in vertical or horizontal motion from the other?'

This goes very well out of doors.



Satellites. At this point we might diverge to a few questions about satellites, asking what would happen if one threw two stones out horizontally in the same direction; and what would happen if one threw a stone so hard that in falling it only just managed to match the curvature of the earth. 'Suppose the stone falls just as much as the round earth itself *falls away from the tangent.*' The first question leads to the idea that if a man in a satellite reaches out of his window and leaves an empty milk bottle just outside, the milk bottle will travel along in the same orbit. The mass of a moon does not make any difference to its orbit. (Nor does the mass of the Earth matter to its orbit round the Sun. The Moon, much less massive, pursues almost the same yearly orbit round the Sun as the Earth.) * * * * * * * * * * * * *

The second question is Newton's own approach to Earth satellites. However we might leave that at present. * *

Projectiles. The important conclusion is that these two motions, the vertical accelerated motion and the horizontal motion, operate completely independently. T

To investigate the horizontal motion – which we already suspect of being one with uniform velocity, from Galileo's argument or from a solid CO_2 demonstration on a table – we look at projectiles with intermittent illumination. C66b

With a fast group, if multiflash equipment (Year IV) is available, the teacher might take a multiflash picture and provide prints for pupils to analyse.

Or he can set up the following demonstration, which takes trouble but is rewarding:

Drive a stream of water drops out of a small glass jet at a regular rate of 50 drops per second. Shadow this stream of drops with light from a compact source, a very bright filament (or an arc). Interpose a rotating disc with a slit in it to show that shadow by intermittent light, in other words, demonstrate it stroboscopically. To do that well it is best to use a lens to form an image of the filament lamp on the rotating disc. Then all the light rays that go to different parts of the field of view are cut off at the same instant. That light, from a 'point source' at the slit, is directed at the stream of drops which rise and fall in a small parabola. It casts an enlarged shadow of the drops on a white screen which pupils watch. D67a

The pulsing of the water drops is done as follows: the water is fed from a constant-pressure supply to the jet through a thin walled rubber tube which is squeezed under the blade of one of the tuned vibrators used for marking tickertape. The vibrator, driven by a.c., squeezes the feed-pipe at a rate of 50 pulses per second and that makes surface tension form the drops regularly at that rate, as the water emerges from the glass jet. The constant-head tank must be high up, so that it provides more pressure than is needed. Then the flow is adjusted by a screw clip placed on the rubber tube, just *before* the vibrator. The flow should be restricted by a clip placed there so that the vibrator pumps the water forward to the glass jet, rather than backwards to the reservoir.

With a synchronous motor driving a light cardboard disc with the right number of slits in it (5 for a motor running at 300 r.p.m.) the pattern of drops is 'frozen'. A finger placed on the edge of the disc will make the phase shift so that the pattern moves. With a non-synchronous motor, we can make the pattern move slowly or freeze it at will.

This is such a beautiful experiment that it is worth the trouble of constructing it. It can be shown as a delightful sight of 'pearls in air'; it can be used for showing that the horizontal motion is uniform; it can be used for measurements of vertical motion to show constant acceleration and even to measure 'g', though that is difficult. *

And it could be used in Year IV to show a model of electrons passing across an electric field. (In that illustration of a cathode ray oscilloscope we arrange to charge the drops as they leave the jet; and in passing between two parallel plates with a p.d. of 5,000 volts the stream is deflected. One can arrange mirrors to view the stream vertically so that the effect of gravity is concealed and one sees a demonstration of charged 'particles' moving freely through an electric field.) *

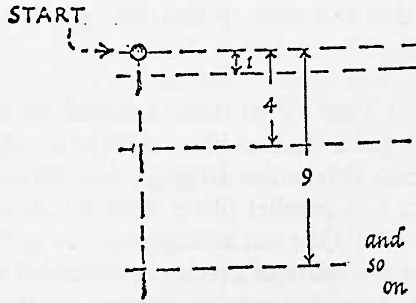
Uniform Horizontal Velocity. Looking at this stream of 'pearls', pupils can see that the vertical motion is accelerated but they can only guess that the horizontal motion may have constant velocity. To demonstrate that we impose a grid of vertical wires to mark the picture or we project a shadow on a screen with vertical lines. T D 67b

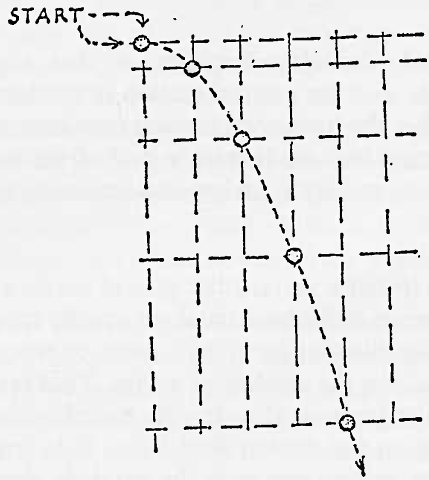
The easiest way is to install a rectangular grid of wires, a vertical set spaced say 1 inch apart and a horizontal set equally spaced. We can adjust the jet so that the shadow of each drop, or every second drop or third drop, falls on the shadow of a wire. That is done by changing the tilt of the jet and adjusting its muzzle velocity by means of a screw clip on the rubber feed tube. It is found that drop after drop all the way up and over the parabola shows even spacing horizontally. Here is Newton's First Law in a new form.

We expect it to be obvious that the drops are moving horizontally with constant velocity. And that will be obvious to adult physicists, once the adjustment is made; but curiously enough some pupils have to be coaxed into seeing what is happening and understanding what it means.

Vertical Acceleration (*buffer option, for fast pupils*). With a fast group who have pushed their studies further and know that for motion with constant acceleration, when the times run 1, 2, 3, etc., the distances run 1, 4, 9, etc., we can draw a very interesting picture. We draw a horizontal line as a starting line for a projectile thrown out horizontally. We draw a line one span below that, another line 4 spans below the top, another line 9 spans below the top and so on. D 68a OPT

We draw a vertical line at the left of our diagram, another vertical line one span from it, and more vertical lines spaced a span apart right across.





We think about two separate motions which (as we have discovered) will continue independently: a vertical motion that carries a projectile 1, 4, 9, ... spans down from its start in 1, 2, 3, ticks of time from the start; and a horizontal motion which carries the projectile one span across in every tick of time. Then starting at the left hand corner we mark diagonal corners in succession (in coordinate nomenclature, we mark the points (0,0) (1,1) (2,4) (3,9)).

We draw the curve that we have thus 'predicted' from our newly gained knowledge. And we ask a question:

> 'Will a real projectile follow the curve? Of course it will not if you throw it with the wrong speed at the start. But if you start it properly, will it follow that curve?'

We let pupils try throwing a small stone or a piece of chalk. The game is still more interesting if one constructs the whole parabola instead of just the half from the horizontal vertex. Again, if a pupil throws a piece of chalk upwards at the right speed along one leg, it will follow the whole curve.

We can demonstrate projectiles following such a constructed para- D 68b
bola with a stream of water drops instead; but that is much less valuable for young pupils. (To make the stream tractable, it is wise to pulse it with an a.c. electromagnet as already described.)

This parabola constructing is too hard for most pupils because it *
draws upon future material. We should place it in Year IV. *

Independent Motions

Now pupils should know that the two motions of the projectile – its *
constant horizontal velocity and its accelerated vertical motion – *
are quite independent of each other. Giving a falling body some *
horizontal motion does not affect its accelerated vertical fall. Nor *
would some sudden change of gravity (such as could be simulated *
by an extra magnetic pull) affect the horizontal motion. Suppose *
instead of giving a projectile a horizontal initial velocity, we fire it *
in any tilted direction, so that its initial velocity has a *vertical com-* *
ponent and a *horizontal component*. We expect to find the horizontal *
component continuing quite independently of the changes of *
vertical motion due to gravity. But what happens to the vertical *
component? We find in fact that that also continues unchanged, *
except for friction, the changes due to gravity simply being added *
to it. Thus, *horizontal component*, *vertical component* and *gains of* *
vertical velocity due to gravity all add together as vectors. That is a *
difficult comprehensive story for pupils to understand at this stage; *
and they do not need to grasp it fully. But we should show them the *
following two amusing illustrations. *

1. **The Monkey and Hunter Demonstration.** We should show D 69a
this, if only for delightful entertainment. We tell pupils the story:

> 'Suppose a stupid hunter fires his gun at an intelligent monkey. The hunter does not know that a rifle bullet falls with gravity motion however fast it comes out of the barrel, so he aims straight at the monkey who is hanging by one hand from the high branch of a tree. In fact, the hunter aims by taking the cartridge out and looking through the barrel of his rifle at the monkey. The hunter fires; but the monkey, knowing the danger, lets go at the instant the gun is fired. Will the bullet hit the monkey?'

For our demonstration, we use a simple spring gun (or compressed air gun) to shoot a steel ball. A trolley with its buffer spring does well. The monkey is made of iron so that it can be held suspended by an electromagnet. (A small tin can will do, inverted with the centre of its base held by a small electromagnet.) Just as the bullet emerges from the 'gun' it cuts through a thin strip of metal and thus breaks the electromagnet circuit. In showing the demonstration, we must try each part separately first: show that if the circuit is broken the monkey falls; show that when the bullet is fired the circuit is broken; and show that the gun is aimed fairly at the suspended monkey. Then we try the full experiment.

This experiment is a delight to pupils and a temptation to ingenious designers: special triggers, beams of lights with photoelectric cells, and other gadgets come in to make this easier for the operator, but more complicated for the audience. We hope it will be kept quite simple. It is far more important for pupils to enjoy its essential message about projectile motion than to follow the ingenuity of special apparatus.

It is tempting to discuss the experiment fully and make sure that *
pupils understand that it has shown the independence of motion, *
that the bullet hits the monkey because it falls on its original *
straight slanting path the same distance as the monkey falls in free *
vertical fall. That will spoil the glamour of the experiment; and in *
this particular case we suggest that the glamour will turn out to be a *
valuable part of our teaching. Leave pupils to think the matter out *
for themselves and if many fail to arrive at a clear conclusion we *
may be wise to be content and say nothing. There is still a chance *
that we have given them a delight in physics that will bear fruit. *
Remember that this is still a Year of seeing and doing: formalities *
will come in later Years. *

2. **Water Stream through Hoops** (*optional, not easy to set up, but rewarding*). A jet of water (pulsed to make it behave well) is fired from a tilted glass tube which has a long straight pole attached to it to act as a tangent to the initial emergent jet. From that pole at one foot, two feet, three feet, four feet ... along the pole from the outlet of the jet, are hung rings, each on a thread. The first ring, at one foot, hangs on a thread of length x; the next ring on a thread $4x$; the next ring on a thread of length $9x$, and so on. If the jet is adjusted to pass through all these 'hoops', that circus trick succeeds equally well when the jet and its wooden pole and rings are tilted to other angles. D 69b OPT

Thus the water-drops fall away from their original straight path tilted upwards, by the same amount in a given time whatever the tilt. (In the demonstration we must keep the muzzle velocity constant because we have hung the rings by threads whose *spacing* and *lengths* are adjusted to fit the combination of gravity-falls with that muzzle velocity. Therefore a constant-pressure head is essential.)

This demonstration now shows the essential property of projectile paths: that the vertial drop from any straight-line path along which the projectile is originally fired is the same in a given time, whatever the tilt of that path. In a way, this is a preparatory experiment. for the 'monkey and hunter' experiment above. Pupils who have seen this experiment will expect the hunter's bullets to hit the monkey, whatever the tilt of his gun – as long as it is aimed straight at the monkey. However, that is more an experiment for delight at this stage than a matter of careful exploration of projectile properties. So, if the water stream experiment is omitted, the monkey and hunter should still have full play.

Gravitational Field

In Year IV, we shall use the idea of the Earth's gravitational field and take g as a measure of it. This is probably a difficult idea for Year III, but it is so important that we suggest it should be introduced now.

We speak of the Earth having a 'gravitational field', something that is ready to grab on any piece of matter we place in the field and pull it with a force towards the centre of the Earth, a force that we call weight.

We know that the pull of the Earth on three equal bricks is three times as big as the pull of the Earth on one brick. Galileo's fabulous experiment with the Leaning Tower suggests that we can extend the idea of [weight] being proportional to [mass] from the simple case of several equal bricks, to all bodies. The bigger the body, the bigger the pull-of-the-Earth on it but also the more stuff there is to be accelerated. The experiment shows us that the Earth's pull gives all bodies the same acceleration. So we think of the Earth's field as ready to pull in proportion to the amount of stuff that we put there to be pulled on.

We can specify the pulling *strength* of the Earth's field by saying how much it pulls on each kilogram of stuff. We measure the pull in newtons. If we have a newton balance (fortunately calibrated by the manufacturer) we can hang a kilogram on it and measure the Earth's field strength in the laboratory. We find it is 9·8 newtons per kilogram. That means the Earth, here in the laboratory, pulls with a force of 9·8 newtons (about 2·2 pounds-weight) on every kilogram of matter, whether it is one substance or another, whether it is part of a big lump or a small one, whether there is other material between it and the Earth or not. If we hang 2 kilograms on a newton balance it reads 19·6 newtons. Again the Earth's field strength is 19·6/2 newtons per kilogram.

This scheme of describing g as a field strength is very useful. At a later stage it prevents young physicists from being confused when they convert forces in 'bad' units such as kg-wt into absolute units such as newtons; and it keeps young engineers on the right lines. (For example, suppose we attach a 10 kilogram lump of metal to a string and use the pull of the Earth on that lump to make some machinery go. The force is 10 kg-wt, meaning 'the pull of the Earth on 10 kilograms of stuff'. We want the force in newtons. We simply multiply the mass of matter, 10 kilograms, by the Earth's field strength [9·8 newtons/kg] × [10 kg]. The force is 98 newtons; and there is no danger of dividing by g instead by mistake. Nor is there any danger of multiplying the 10 kilograms by a nonsensical *acceleration* of 9·8 metres/second^2, which certainly does not describe the motion of that load when it is hanging on a string.

We should give pupils a qualitative idea of gravitational fields, pointing out that they extend from all bodies; but only have appreciable strength outside big things like the planets and bigger things like the Sun. We should point out that gravitational fields are rather like magnetic and electric fields, but they pull on all matter, proportionally to mass – whereas electric fields pull on electric charges, proportionally to charge. And gravitational forces are always attractive. (We know of nothing equivalent to negative mass in the real world at present.)

We should give pupils the name 'gravitational field strength' and C/D70
show them a spring balance being used to measure it. We might ask what the balance would show with the same kilogram of matter on the Moon, or 4,000 miles up from the Earth's surface, or far out in space, or at the very centre of the Earth. These are meant to be intriguing questions to stimulate thinking. We should not give away the answers now or argue them out for pupils.

It is unusual, but not dishonest, to measure the Earth's field *
strength by hanging a kilogram on a spring balance calibrated in *
newtons. *

We can, at least in principle, calibrate that balance without any *
appeal to gravity: we use it to pull a 10 kilogram trolley along the *
level on frictionless wheels (or along a friction-compensated *
runway); we measure the acceleration and, as we shall see in Year *
IV, we multiply [mass in kilograms] by [acceleration in metres/ *
second per second] to calculate the force in newtons. However, *
since that would require the use of $F = ma$ and a discussion of *
absolute units it would be quite out of place here. There is a *
good place for it in Year IV. *

Chapter 4

MOLECULES IN MOTION

Molecule Models, Behaviour of Gases

A serious study of kinetic theory, with a prediction for the pressure by considering momentum-changes, will come in Year IV. Here we are preparing for that by revising some qualitative ideas from Year I and we shall do some experiments on pressure, volume and temperature behaviour of gases. * * * * *

REVISION†

Models

Pupils should see models of gas molecules in motion, to help their thinking about pressure, collisions, random movement, and the Brownian motion. We show a three-dimensional model. This may D71a
be a handful of plastic beads or metal balls kept in motion by a vibrating membrane at the bottom of a tall, wide transparent tube. The membrane is driven by a cam on a small electric motor. We can keep the 'molecules' at various temperatures by adjusting the supply to the motor.

We say that we think gas pressure is simply the effect of elastic bombardments by moleclues.

> 'They must be elastic, they must bounce back without loss of motion energy, on the average; otherwise if they lost ever so little at each collision they would soon be "dead" at the bottom of the box.'

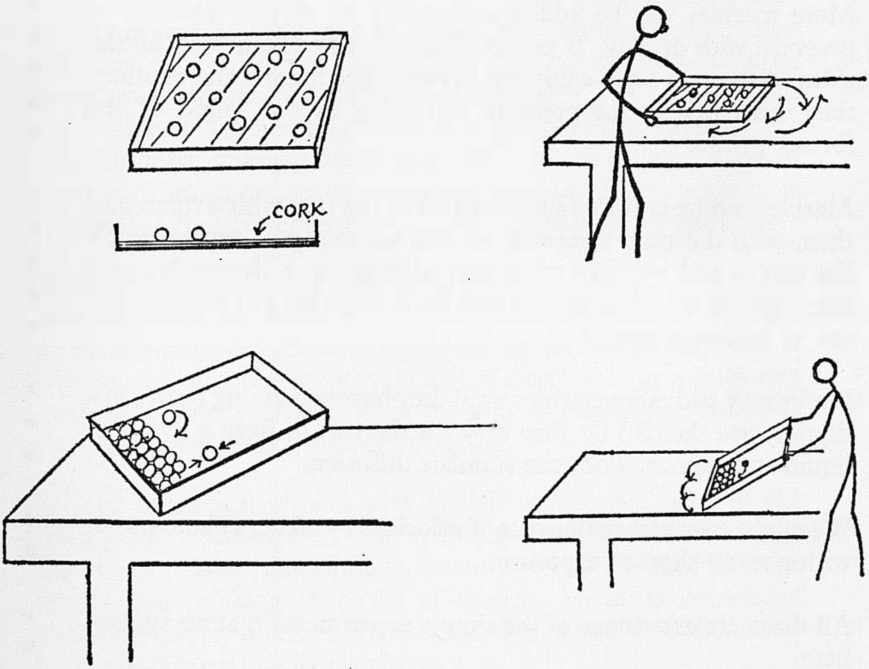
We face boldly the comment that there are fewer molecules in the higher reaches of the model.

> 'Of course there are. Why don't all the molecules fall down crash to the bottom, moving or not moving, since gravity is always there? A molecule falling downwards must be meeting greater chances of a collision to knock it back towards the top than a molecule moving upwards has chances of collisions that knock it towards the bottom. So the molecules will have to be more crowded near the bottom.'

We say that that is a good model of our real atmosphere (and pupils will be able to imitate that in their class experiment).

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 fast.

Like the two-dimensional model, this model, which was used in Years I and II, will be used again to illustrate further aspects of gas behaviour in Year IV.



Two-dimensional Model of Gas Molecules in Motion

As a class experiment, give pupils a tray of marbles which they keep D71b
in constant agitation by pushing the tray about irregularly on the table by hand. 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, rotatory motion. The noise is reduced if a thin sheet of cork is placed in the tray as a carpet; 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 collec- *
tion. *

More marbles can be added to the tray to suggest increase of *
pressure with density. If pupils distinguish by ear impacts on the *
sides of the tray from collisions between one marble and another, *
they can listen to the pressure increasing as the sound of the *
former grows. *

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. They can simulate diffusion. *

We might even gather statistics of velocities by taking a photograph *
with not-too-short an exposure. *

All those are extensions of the simple experiments that we suggest *
here. *

We give a tray and two dozen marbles to each pair or quartette of children, and ask them to keep the tray on the table but agitate it by rapid irregular motion, and watch what happens. D71b

Pupils may imitate the atmosphere by giving the tray a very slight tilt and then keeping it tilted while agitating it.

We provide one or two larger marbles to be put among the rest in the tray, to illustrate Brownian motion. We tell pupils that the large marbles represent small specks of smoke-ash that they can watch under a microscope in air. This model should probably be shown both before and after the real experiment with a microscope. D71b

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 $\times$ 8 inches with edges about $\frac{3}{4}$ inch high, does well *provided the edges are vertical.* Most ironmongers stock trays with edges that slope outward (and marbles do not rebound well from H71b them) but from time to time a line of trays appears with vertical sides, costing less than 2*s* each. A packet of two dozen glass marbles from a toy shop for 9*d* is the only other thing that is needed.

Note to Teachers on Models. We should show models, preferably in several forms; but we should also murmur gentle warnings that a model is not the real thing, in many cases not even meant to show what we think the real thing is like. This kind of reservation is discouraging when young people first meet it; but they can learn to enjoy devising models and thinking in terms of them with much greater freedom and skill and imagination once they realize the greater scope of scientific models as we use them.

We might contrast a tray of marbles as a model simply to help our thinking about gas molecules – to suggest a line of investigation, or to illustrate a technical term such as the mean-free path – with our use of a tiny wooden model of a cyclotron or a huge wax model of a flower. The last two are used to aid people in visualizing; the first is used for constructive thinking.

All our theoretical physics uses models as essential parts of the framework of knowledge – but with great care to remember that the words, phrases, descriptions, are only parts of models. Without imaginative thinking in terms of models, scientific knowledge would be merely a pile of facts, codified here and there in laws – little more than a handbook of data.

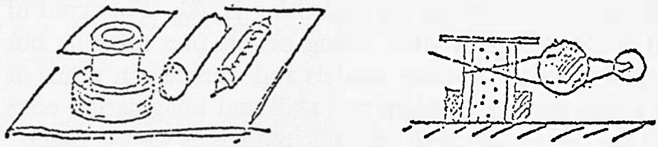
We cannot put this to our young pupils at this stage; and we should not be wise even to try; but we should think about our own picture of science and the part played by models in it when we use demonstration models as part of our teaching skill.

Brownian Motion

The Brownian motion is not conclusive evidence for the existence C72
of rapidly moving air molecules, but it is a strong illustration. This individual look at the Brownian motion – utterly different as an experience from just seeing a film, or even from being shown a demonstration at the hands of an expert teacher – plays a very important part in our building up of confident and cautious knowledge of atoms and molecules.

This is so important that we feel all pupils should see the Brownian motion again now, whether they have seen it before or not. Teachers will find that pupils who saw it in Year I are pleased to see it again now that they know so much more – they will enjoy showing it to any others who have missed it.

Therefore schools must have smoke cells and microscopes if they are to do justice to our programmes. Schools which teach our Year I will have smoke cells already; and schools which do not teach Year I will now need to obtain smoke cells – it should be the Whitley Bay form because that is much the best for a clear view.



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 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.)

Microscopes will be needed for viewing the smoke cells, *at least one for every four pupils*. That is not an unnecessary luxury, since we want pupils to see the Brownian motion for themselves. Joining in a queue to use one demonstration microscope would lessen that feeling of being personally involved as an observer, so seriously that it would harm our programme (and replacing this experiment by a film would be worse still, even more indirect and undesirable). Eight microscopes per class make a very large demand on the provision of equipment. We hope that by this stage, the physics class will be able to borrow enough microscopes from the Biology department – the authorities there may be more willing to lend their microscopes to pupils at this age than in Year I. If not, we are sure that microscopes should be bought. Those need not be elaborate instruments, but must have an objective with a large aperture to take in plenty of light for pupils to see the motion of the smoke particles clearly. (A microscope with a tiny aperture may suffice for an adult physicist; but pupils, to whom the use of a microscope is strange and the thing they are looking for is stranger still, need better illumination.) A high-power objective is not needed – not even suitable. Any focal length between 15 and 30 mm will suffice.

We need to warn pupils that there are convection currents ('breezes of warm air') which carry the whole army of particles drifting across the field of view; and that the drifting motion is not what we are looking for. We must also explain that particles out of focus make large, round patches of light. These characteristics seem simple enough to us but can spoil the experiment if pupils are worried by them.

(The demonstration of Brownian motion in a liquid is also good to see; but it should *not* take the place of this essential look at smoke in air. A little Indian ink added to water provides carbon particles small enough to show appreciable Brownian motion with a high-power microscope objective, preferably used as a water immersion lens.) T

Diffusion

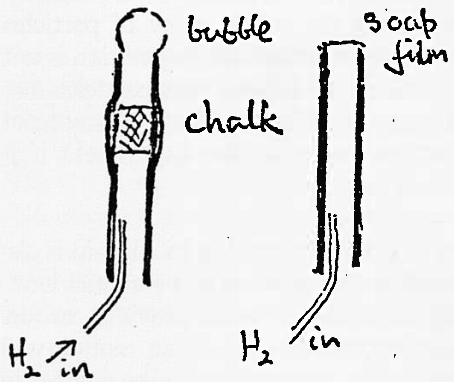
Diffusion fits in with our picture of gas molecules in constant motion in a vast open space. We may show some diffusion experiments. D73

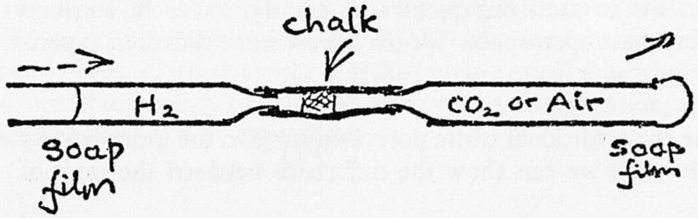
If we use the traditional white porcelain jar (like the inner jar of a Leclanché cell) we can show the difference between the rates of air diffusing through the jar and some other gas, such as carbon dioxide or hydrogen, diffusing through.

Hold the porous jar, mouth downwards, with the mouth closed with a bung which carries a long glass tube. Surround it with hydrogen by pushing it up into a bell jar of hydrogen (with its mouth downward). The glass tube projects down into a beaker of water. Hydrogen surrounding the jar seeps in faster than air seeps out by diffusion, so the pressure increases and the glass tube blows bubbles in the beaker.

Or, turning the jar mouth upward, place it in a large open beaker of carbon dioxide, and bend the glass tube over and down into a beaker of water. As air seeps out faster than carbon dioxide seeps in, the pressure in the jar is reduced and water rises up the tube from the beaker.

We suggest an ingenious diffusion demonstration which uses *soft* blackboard chalk. A short piece of chalk is pushed an inch or two into a 6 inch length of plastic tubing which has been warmed to make it easy to stretch. The plastic tube is held in a vertical position and filled with hydrogen by a thin feeding tube from





below. A soap film is spread across the top of the plastic tube. As hydrogen diffuses up through the chalk faster than air diffuses down, the pressure above the chalk increases and blows a soap bubble. In response to the obvious criticism, we try a 'blank test' of a similar piece of plastic tube, filled with hydrogen but without any chalk, and find that the buoyancy of the hydrogen is unable to blow a soap bubble!

Such diffusion experiments may be shown now as illustrations of *
the molecular story; or teachers may want to defer them until *
Year IV when much clearer descriptions and predictions of diffu- *
sion can be made. *

Bromine offers a chance to make diffusion visible. We should not at this stage show bromine spreading in a vacuum – that comes properly after the astonishing calculation of the high speed of gas molecules in Year IV – but we can release some bromine in a tall D 74
tube of air and ask why, if its molecules are moving fast, it does not spread all the way through the tube at once. The answer to this question is worth waiting a long time for. It is not obvious to chil- T
dren that if gas molecules had no size at all but were just points, they would spread right through the tube at the full speed of molecular motion. It is not obvious that the slow spreading of the brown bromine through air shows that one kind of molecule or the other or both must have some considerable size. After this question has rested in pupils' minds for a time, we can ask questions that lead to the answer, such as:

> 'Suppose I throw this piece of chalk straight out among you past your heads. Do I stand a chance of hitting someone's head? Suppose you were all pinheads with practically no head at all, each head the size of a ping-pong ball, would I stand the same chance of hitting a head?'
>
> Or 'Imagine you are trying to cross a room which is crowded with people. What will happen to you? What happens to the other people?'

We do not pursue that now but we promise that in the following *
Year we shall use the diffusion of bromine to make an actual esti- *
mate of molecule size. *

Note to Teachers: Data for Air Molecules

We should not give pupils numerical data for gas molecules because we can offer them no evidence for the data at present, but teachers might find it useful to have the following in mind: *

Speed. In air at atmospheric pressure and room temperature, the molecules have an average speed about 500 metres per second (about 1,650 feet per second). Compare that with the speed of sound, 1,100 feet per second. *

Size. An air molecule is not a round object, and not a hard solid one like a billiard ball, but if we estimate an average diameter for an air molecule, using the rather gentle collisions that molecules make at ordinary temperatures, we find a diameter between 3 and 4×10^{-10} metres. *

Spacing Apart in Air. When we know the 'Avogadro number' (from measurements in a later Year), we can divide the volume occupied by a sample of gas by the number of molecules in it: find the average volume occupied by one molecule: and take the cube root of that to find the average distance apart of molecules. We find it is about ten molecule diameters, about 35×10^{-10} metres. *

Mean Free Path. When we calculate the mean free path of a molecule, the average distance that one molecule travels before it hits another, we find it is about $1{,}000 \times 10^{-10}$ metres in atmospheric air. *

So air molecules are about 3·5 Ångström units in diameter, about 35 A.U. apart, and travel about 1,000 A.U. between one collision and the next. *

Temperature

We have a picture of gas molecules flying about with random motion, making collisions from time to time, but only after a long trip compared with their own size or even their average distance from a neighbour. What happens, in such a picture, when we make a gas hotter? Pupils know that if one heats a tin can sealed up full of air the pressure in it will grow bigger and it may even burst. T

Pupils should see a gentler test of that with a glass flask of air, connected to a Bourdon pressure-gauge, plunged in hot water. (It would be good to have a more violent demonstration in which we heat a closed tin over a Bunsen until its lid is thrown off. A paint-tin or a Nescafé tin with a well-fitting, push-in lid will probably do this.) D75 D76 OPT

We ask pupils to speculate on the behaviour of gas molecules when we heat a gas in a closed container. How can the molecules make a bigger pressure? There are just as many as before – we doubt if the heating manufactures extra molecules. So the molecules that are there must bombard the walls more often, or more violently at each collision. If more often, the molecules must be moving faster. If more violently, what must have changed to make the collision more violent? T

We suggest a human picture, molecules represented by pupils running about at random in the room with chance collisions, like a soccer game; and the container represented by a solid line of vibrating people anchored all round the edge of the room. What can we change about a boy to make his collision with one of the edge people more violent? Only his speed. It seems likely that if a gas molecule makes a more violent collision when it hits a wall that must be because it is moving faster.

So either of our suggestions leads to the idea of molecules moving faster in a hotter gas. Now reverse the story. If molecules move faster, they will make more violent collisions and they will arrive back at a wall for another bang more often: so we might expect an increase of speed to appear twice over in the pressure. We even might expect the pressure to vary as $(\text{speed})^2$. And more careful examination in full kinetic theory shows that this is so.

In our demonstration model of a gas, we can see what corresponds to higher temperature when we increase the amplitude of motion of the driving motor. We have to drive the motor faster so that it bounces the 'molecules' up more violently, with more energy. We suggest that perhaps the motion energy (K.E.) of a gas molecule, which clearly increases with temperature, might be a good measure of temperature itself. We cannot do more than just suggest that at this stage. We shall return to it in Year IV. D71a

The two-dimensional tray model shows this also. C71b

Some pupils may ask why we have to keep on supplying energy to the vibrator in the model, in contrast with a real gas, whose molecules keep going of their own accord. The chief answer is: the walls of the model are 'cold'; but the walls of the gas container are as hot as the gas. Their molecules in violent vibration 'give as good as they get' when the gas molecules hit them. When that question arises we say:

'Why don't we have to shake the walls of this room to keep the air molecules in motion? But the walls of this room *are* in violent motion. A molecule approaching the wall finds the atoms of the wall vibrating violently. From the molecule's point of view the wall is an ocean of atoms bouncing about with a great variety of vibrating motions. Those motions are so violent that a gas molecule arriving at the wall is bounced away again with the same energy, on the average.

'If you leave your tray of marbles on the table and do not keep it agitated, that is like a room with very cold walls. For a model of the air in this room, you must keep the sides of the tray "warm" by continual agitation. You have to provide a continual supply of energy for that, because the marbles waste energy in scraping the floor of the tray and warming the air. Real gas molecules have no such opportunity to give energy away.'

We can talk about supplying energy to water as it turns from liquid T
to vapour; but we must be careful not to suggest that water molecules at, say, 20° C have less *kinetic* energy than vapour molecules at the same temperature.

In escaping through the surface, a water molecule has to pay, from K.E. to P.E., a large tax, demanded by attractive forces of neighbours as the molecule leaves the surface. Only a water molecule that has, by chance at the moment, a much-more-than-average kinetic energy can afford to pay that tax. Any molecule with less kinetic energy will either not escape at all or only get part way out through the surface layers and fall back in again.

It is because evaporation is the escape of molecules which are richer-than-average in kinetic energy that it is a cooling process. The kinetic energy that disappears as the molecule evaporates is stored up in force-fields attached to molecules, and this potential energy can return to kinetic energy when vapour condenses to liquid. Those 'extra-rich' ones that are lucky enough to escape form a vapour of 'impoverished extra-rich' molecules, whose average kinetic energy is much the same as that of molecules in the liquid. However, the mean free path of molecules in liquid is so much shorter that a molecule is aware of its neighbours most of the time. (And thus a molecule in liquid has more negative potential energy in the force-field of neighbours.)

As pupils watch the demonstration model of gas molecules, or play D71a
with their own informal, two-dimensional model with marbles,

some will see clearly that a molecule changes its speed frequently. The whole collection of molecules have a great variety of speeds, all of them changing at each collision. The speeds keep to a statis- C71b
tical distribution around a constant average, characteristic of the temperature. Other pupils will miss that, and think that all molecules have the same speed, for a given 'temperature'. We should draw their attention to the distribution of speeds, but we need not emphasize it at this stage.

Absolute Zero. If there is a close link between the motion energy T
of a gas molecule and temperature, what will happen if we cool a gas instead of heating it? Could we get down to a very cold state at which the gas had no motion at all?

(When, in elementary teaching, we have a choice between a simple description that fits with later knowledge and another description, perhaps even simpler, which conveys a mistaken impression that would have to be rectified in later teaching, we try to choose the former. Of course, we must not sacrifice the simplicity that is essential in early stages and give a complicated story that will puzzle pupils, just in order to be right or modern. But here, for example, we can use a little care and avoid an impression that would prove to be misleading in advanced studies. We need to give pupils a picture of absolute zero, at which an ideal gas would have molecules with no kinetic energy. Yet our present structure of thinking and knowledge about atoms and molecules tell us that at absolute zero materials – all of them solid or liquid then – must still have some residual molecular energy. There is a 'zero-point' energy of vibration which we are now sure will remain there. This is one place where quantum mechanics differs in its picture of the world from both common sense and Newtonian mechanics. The moral of that is not that we must remain silent and say nothing clear or simple about absolute zero: it is only a word of warning about the way we say things.)

> 'If there is a temperature, far down on the scale of the ther- T
> mometer, at which molecules would have for practical purposes no motion, what would the pressure be like at that temperature – assuming that our picture of gas molecules is reliable? ... Yes, the pressure would fall to nothing. Of course, the molecules would also fall down, into a liquid and more probably a solid, before they got down to that temperature. Yet we can think about an "ideal" gas in our imagination; and ask what the temperature would be at which that would collapse to no pressure and no motion.

'We can find out about that by doing an experiment, by watching how the pressure of a gas in a bottle changes as we cool it down. Then we calculate on down to find out the temperature at which the gas would have no pressure, if it continued its behaviour. That is called "extrapolation".'

Extrapolation. 'Extrapolation is a risky business, trusting that something we've observed or measured continues on and on and on. Did the Sun rise in the East this morning? Did it rise in the East yesterday? Did it rise in the East many a morning before that? Are you willing to *extrapolate* those observations, and say that you are sure the Sun will rise in the East tomorrow? Are you *quite* sure? ... Suppose you were not a human being but were an insect that hatched out of a cocoon on a warm day in early summer and flew about from flower to flower, day after day. What would you observe about the weather? A fine day, a fine day, a fine day, ... and so on. You might extrapolate to a prediction that every day would be fine. You would have no foreknowledge of the wintry day that would end your happy flights. T

'Extrapolation is more than risky in thinking of gas molecules for a real gas like air or carbon dioxide. If we cooled any gas on down and down, it would certainly fail to remain a gas. You have seen carbon dioxide jammed together into cold, solid crystals of "dry ice". You will some day see air cooled down and pushed together so that its molecules – with less energy of molecular motion at that low temperature – stay crowded together in a liquid.

'Yet we can carry the extrapolation down in imagination and find quite a useful "absolute zero" as starting point for a grand temperature scale.'

Pressure and Temperature for a Gas

As class experiment (or demonstration) pupils should make measurements with a flask full of dry air: the pressure with a Bourdon gauge, temperature with an ordinary mercury thermometer. They should use as large a range of temperature as possible, taking only a few measurements, since this is a matter of looking for a simple law rather than going into precise detail. C/D77

The Bourdon gauge should be arranged to read *absolute* pressure, so that when it is open to the air it reads atmospheric pressure. That saves us the usual worries about 'remembering to add the atmosphere'. We recommend this experiment with a direct reading * * * * gauge very strongly, instead of the more usual one which involves columns of mercury and an added barometer. * *

With such a gauge, the change of pressure when air is heated from melting ice temperature to boiling water temperature, or even less, will seem disappointingly small. And with a simple dial gauge, the pressure may not be read very precisely. Yet we consider this form of the experiment much the best, and it can yield quite good results – the points on the graph near to a straight line, and the estimate of absolute zero not too far away from $-273°$ C – if it is arranged carefully and pupils are given a warning. The sample of air should be in a round-bottomed flask with a rubber stopper, not a cork. The stopper should be wired in, unless it fits very well indeed, for which a little saliva will help. The tube that connects the flask to the gauge should be as narrow and short as is convenient; but the error introduced by the 'dead space' of air in the tube is likely to be smaller than that due to the dead space in the gauge and both will be trivial compared with the large error that will arise if the neck of the flask is not fully heated. Therefore the flask must be heated in a container of water with the water-level right up to the rubber stopper in the neck. Therefore the flask will have to be held in a firm stand to keep it fully under water. The water in the heating bath must be stirred vigorously. Before each reading, the experimenter must remove the Bunsen burner and stir for some time to bring the air inside the flask to the same temperature as the water outside. T

If melting ice is used for one of the measurements, it is essential to have the flask completely surrounded by it. We suggest putting ice and a little water into the outer container, then pushing the flask down into this sea of icebergs, then adding more ice on top so that the whole flask is surrounded.

Pupils should plot a graph of pressure against temperature, for the temperature range of their measurements. The graph should be straight enough to justify drawing a 'question-asking straight line' which tests whether the plotted points (the true results of the experiment) fit closely an ideal simple law – which is what we would like to find, because it makes our describing of nature easy and simple. T

Pupils should draw a 'best straight line'. Then we discuss the possibility of extrapolating that line. That requires a new graph with its temperature scale extending 300° below the ice point. Even though that crowds the experimental points into a very small T region, pupils should draw that graph. For one thing, it emphasizes the practical risks of losing sight of the behaviour of real gases. However, some pupils will suggest a safeguard against that practical risk: Go back to the first graph with the more limited temperature range and calculate the position of absolute zero from that by working backwards along the slope. If faster pupils suggest calculating back to absolute zero altogether by arithmetic, we should certainly let them do that; though we should encourage them to draw the graph as well. When a young pupil wants to find something very exciting – as absolute zero should be – he can face quite complicated questions of arithmetic or geometry and deal with them successfully.

Liquid Air. If liquid air is available‡ it is very interesting to dip this 'gas thermometer' in liquid air and see what it says about the boiling point of air. This may require a larger container than the usual vacuum flask used for liquid air. In that case, provided enough liquid air is available, we should use a large beaker topped up with liquid air by continual pouring.

We hope that this experiment can be a class experiment. It may be necessary for the teacher to follow it with a demonstration version to clear up doubts and difficulties. In any case pupils should emerge with a clear idea that, *judged by a mercury thermometer*, gas pressure runs down a straight line as temperature falls, a straight line directed towards zero pressure at a temperature somewhere between −250° C and −300°. And we call that 'absolute zero'. We must give pupils the result of accurate measurements, −273° C, their own experiment retaining its full importance as an 'experiment of principle' to enable them to claim they understand the measurement and to boast that, given facilities, they could make an accurate measurement themselves.

‡ It is sad to find this common commodity – as it now is in research – so rarely available for schools. A plea to the nearest university physics department is quite likely to be productive; and we hope that schools will make every effort to beg or buy some liquid air. Pupils should see a demonstration of its properties. We would like some for this experiment here, and we need some for a very important experiment in Year IV.

We hope that such cooperative help from physics departments will lead to liquid air becoming more generally obtainable.

The possibility of a device for home production of small quantities of liquid air in school laboratories is being investigated; but that is unlikely to produce enough for demonstrations of this kind.

We can then make a simplification, by shifting our zero to that 'absolute zero' and reckoning all temperatures from there. We explain that that is not used in giving the temperature of the weather or in giving a boiling point in chemistry; but that it is a remarkably clear, simple temperature system for our general thinking about physics. All we have done is to add 273 to all our Centigrade temperature numbers. We have *not* changed the fundamental nature of the scale. It is still, at this point, a scale that uses a mercury in glass thermometer, although that thermometer would fail in practice over a considerable range of the scale.

[Pressure] varies as [Absolute temperature]. This is one of the 'gas laws', one without an official name. "Charles' Law" states that the [volume] of a sample of gas at constant pressure varies directly as the [Absolute temperature]. That was originally an experimental law arrived at by comparing the behaviour of real gases with readings of a mercury-in-glass thermometer. As such, it is limited and not quite correct; but it gives a fairly good account of the behaviour of most gases, and it serves to suggest the idea of absolute zero.

Charles' Law. Experimentally Charles' Law is difficult to demonstrate accurately and the simpler forms of apparatus given to pupils are not very precise. On the other hand, Charles' Law seems to most beginners a more obvious way of looking at gas behaviour than measuring the pressure. In our programme, however, we look at the pressure changes first because we are talking about pressure in terms of our molecular model and can give a more convincing idea of absolute zero that way – it is easier to picture the pressure collapsing to nothing when there is no bombarding molecular motion than to say there is a special temperature at which the gas will *shrink* to no volume whatever.

Gas Laws: Experimental Summaries or Definitions?

As long as Charles' Law, or the pressure law, which we might call 'X's Law', is an experimental law, it connects gas behaviour with the readings of temperature on a mercury thermometer. If we find that the experimental points, for either set of measurements, lie very close to a straight line we may say that gas volume (or gas pressure) varies directly as absolute temperature on the extended scale *of the mercury thermometer*. And we may suggest using a gas thermometer to extend the mercury thermometer's scale by extrapolation. However, that gas thermometer would only be a secondary servant, like a platinum-resistance thermometer, or a thermocouple thermometer. (The latter has a somewhat curved graph of e.m.f. *v.* mercury-thermometer-temperature, but yet we can use it as a secondary thermometer by calibrating it against a mercury thermometer.) In all this we do not escape from the original lucky choice of the expansion of mercury as our measure of temperature. That was lucky, because mercury-expansion plotted against gas volume, (or gas pressure), gives a graph nearer to a straight line than that of most other liquids. In that sense we can, of course, say that 'mercury expands uniformly' without committing the illogic of a circular argument – but only in that sense.

We may wish to break with older tradition, and start afresh with a new temperature-scale which we consider more universal, because different gases agree closely in providing the scale. Then we must *define* absolute temperature on our gas thermometer scale as directly proportional to either pressure or volume (in each case the other quantity being kept constant). The moment we do that, Charles' Law (or X's Law) becomes *automatically* true: it is simply a definition of what we mean by temperature on our new scale. The experimental law would now be one which says that mercury does expand fairly uniformly when temperature is measured on the gas-thermometer scale.

In modern practice we do adopt the gas thermometer as our ultimate practical standard, for three reasons:

a. Since a widely differing assortment of gases all agree closely in yielding the same scale, some of us have a mystical feeling of satisfaction that we are no longer attaching 'temperature' to a particular liquid metal. That is probably only a relic of a childish seeking of 'the really-true temperature'.

b. As a practical standard, a gas thermometer is more reliable, though it is clumsy and difficult to handle. Mercury thermometers suffer from the bad behaviour of the glass of their bulb. Glass is not a proper solid, but rather a supercooled liquid, which is always complaining about its previous treatment. A mercury thermometer which has recently been heated has a sagging glass bulb that is slowly shrinking back to its earlier volume, meanwhile making the mercury read too low; the tale of such difficulties grows when we try to use a mercury thermometer with great precision over a long period of time. A gas thermometer also has a bulb of glass (or silica), but the vindictive memory of the material has a relatively small effect on the measurements we make with the big volume inside.

c. We go one step further and define a universal scale of tempera- *
ture by considering the efficiency of an ideal heat-engine – in which *
we can, in imagination, use any working material we like, always *
with the same resulting scale of temperature. Then we find, a *
surprising outcome of further reasoning, that our new scale agrees *
with the scale of an ideal gas thermometer. In ordinary temperature *
ranges, real gases differ from the ideal behaviour by small amounts, *
which can be measured. *

We cannot labour any such discussion of the philosophy of temperature measurement with our young pupils. Yet we should not suggest changing to a gas thermometer and then give the impression that we still find Charles' Law and X's Law experimental laws. We should give some hint that we are changing now to a new definition of temperature, enshrined in one or both of those laws.

Volume and Temperature

Pupils should have a demonstration or class experiment on the D/C78
expansion of air at constant pressure. If we take trouble to give a precise demonstration, the details of the apparatus are apt to remain the major items in pupils' memory: and this important case of simple behaviour is not one where we want the apparatus and techniques to take charge.

There is a simple experiment which will teach some of the story and put a pupil in a position to say 'Given enough time and some apparatus of my own choice, I could do that fully and successfully.' A sample of dry air is enclosed in a length of capillary tube, closed at one end and open at the other, by a small bead of mercury that acts as an index. This tube is heated to various temperatures, measured by a mercury thermometer. The length of air sample, from closed end of tube to index, is measured. The mercury thermometer should be strapped to the tube with rubber bands and placed in a large water-bath. With plenty of stirring and patient waiting to avoid big errors due to temperature lag, some success is possible; but the results will always be disappointing because of slow heating through the wall of the glass tube, and because the
index bead of mercury either sticks or allows a little air to leak past. *
A bead of water is worse, because it adds a changing vapour *
pressure. A bead of concentrated sulphuric acid is sometimes *
advocated: this gives the better behaviour of dry air, but is *
dangerous for a class experiment. *

Nevertheless, this simple experiment, with just a few pairs of *
measurements taken, serves to illustrate the idea. From this stage *

on, in our course, pupils should be prepared sometimes to see a rough experiment given as 'an experiment of principle' – to show what could be done rather than to carry out a precise measurement. * * *

Boyle's Law

At this stage, we ask what will happen if we keep temperature constant but change pressure and volume. It is customary to start with Boyle's Law, but here with our attention on energy it seems easier to treat the effects of temperature change first. We have the advantage now that pupils will not forget that Boyle's Law sums up the behaviour of air at constant temperature. T

Quite precise measurements of volume and pressure of gas can be taken with good apparatus available in schools: so precise that deviations from Boyle's Law can be noticed. Yet at this stage, we are still building acquaintance with nature rather than precision of technique. We should give pupils the best apparatus we can provide without entailing a long subsidiary explanation of the techniques of measuring the pressure or volume. D79

Teachers will differ in their choice here: some will wish to have simple apparatus that shows Boyle's Law quickly; others will prefer to give a careful introduction to apparatus that gives a very satisfying series of constant products. We favour the former strongly for our programme.

A simple form of apparatus has the sample of gas in a wide glass tube with a scale of volume beside it, and measures the pressure on a Bourdon gauge – which of course must be graduated in absolute pressure for the sake of good clear teaching. The pressure has to be changed by driving in oil from a reservoir. There is an air space above the oil in the reservoir and the pressure is increased by pumping more air into that space with a foot pump. Thus the oil serves as a piston confining the gas to a visible volume; and the gauge measures the pressure. This is direct and clear but does not give very precise measurements. We hope that schools will try using this apparatus. T

Where the more usual apparatus with mercury and movable tube is used, we should be careful to explain to students what the aim of the experiment is. T

We may tell pupils the history:

> 'Three hundred years ago the Honourable Robert Boyle reported to the Royal Society of London his discovery "concerning the

spring of air". He was experimenting on a sample of air, as if it were a spring, to see if it fitted with, say, Hooke's Law. Air has quite a different relationship between pressure and volume, and Boyle discovered it, as he said, "not without pleasure and delight". He changed the pressure from four atmospheres to a small fraction of an atmosphere and measured pressure and volume at a number of stages. He kept the temperature constant – or, rather, nature kept it constant, because he did his experiment in a room which did not grow hotter or colder. Try that now. Some of you know what Boyle discovered; and in that case you will be trying your skill against the apparatus, to see whether you agree with the relationship that Boyle found. Other people have carried out the same experiment very carefully and there is no doubt that Boyle's story, a simple one, is followed very closely by gases such as air. So – we must be honest – you are not discovering something unknown, or even adding necessary testimony to something that is still uncertain. But we hope you will enjoy making measurements to see whether what you find fits together in a satisfying way.

'Some of you have not heard of Boyle's discovery. They will have extra fun: they can try to find out what Boyle discovered without knowing the answer. Please don't tell them.'

Boyle's Law: Thinking about Higher Pressures? After the experiment, we make sure that pupils know that [pressure] × [volume] gives a constant value, the same value for one pressure after another. We ask pupils whether they think that will remain true if we add more and more and more pressure. T

'If we made the pressure ten times as big, a hundred times as big, a thousand times as big, a million times as big, would the volume grow smaller by those factors, without limit?'

We do not answer the question, but leave it to prepare for the following Year.

Graphs. Plotting graphs of Boyle's Law behaviour is interesting *
work for neat fingers, but may take more time than we wish to *
spare at the moment. We suggest only simple, quick, crude graphs *
here, or else no graphs but just simple arithmetic. *

Theory and Boyle's Law. A very Simple Theory. We offer a tentative theoretical discussion – to be taken up properly next Year. We say: T

'Think of the picture of a gas made up of little molecules flying about with rapid motion in all directions. Suppose you have a box of gas like that and carefully put more molecules inside (like a collector putting more beetles in his box) until there are twice as many as before in the box. What would that do to the pressure? ... Yes, if there are twice as many molecules to bombard the wall, you might expect the pressure to double ...

'Oh, the molecules will hit each other more often, and get in each other's way. Yes, they will, but does that matter? Think of a molecule that is flying along to hit a wall and contribute to pressure. Suppose it does meet another molecule on its way, head on. They will collide and bounce away in opposite directions. But, in doing that, they have simply exchanged jobs. What would you do if you were driving a car along a very narrow mountain road, too narrow to pass another car, and met another car going the opposite way? Suppose you had to get to your destination urgently. ... You might exchange cars and drive backwards. That's what molecules do in a collision: they exchange jobs. So collisions should not make a noticeable difference to the pressure.

'With twice as many molecules in the box, we should expect double the pressure.'

Note to Teachers. In fact this simple story conceals a very im- *
portant assumption. We are assuming that molecules do not inter- *
act. If in their flight through the box, molecules attract each other, *
or repel each other, for an appreciable fraction of the time, then *
putting in more molecules will give those forces play for a larger *
fraction of the time and we shall see a deviation from this simple *
story. We are also assuming that the molecules have negligible *
volume. Otherwise, putting in more molecules would shorten the *
paths between collisions by the size of molecules themselves and *
thus make the bombardment of the walls slightly more frequent *
and thus make the pressure increase more than we expect from the *
simple story. These are matters that will be discussed in later *
Years. We certainly should not even mention them to pupils now; *
but we should keep them in the back of our mind. *

Simple Theory, continued. 'So, if you could put twice as many molecules in the box you would expect twice the pressure. What would that boxful of twice as many molecules look like to a molecular census-taker, to a spy with eyes small enough to see the population of molecules? It would look twice as crowded as before. Not only twice as many molecules in the box, but twice as many molecules in each cubic centimetre of space in the box. T

'Now there is another way of crowding molecules till there are twice as many to the cubic centimetre. We can put them in a cylinder with a piston and push the piston in until we have halved the volume. Then we have twice as many molecules per cubic centimetre. What do you predict, from the way in which we are now talking about molecules? What will happen to the pressure if we halve the volume of the gas? ... Yes, there is Boyle's Law for you, predicted by simple theory!

'That is the kind of thing we like a theory to do for us. We like it to predict something that we already know, because we think we are on the right lines of making our picture. And then we ask questions of our picture: we try to make further predictions. For example, we could ask this kind of question: Suppose we change from air to a gas whose molecules are much bigger, or a gas whose molecules attract each other when they are quite far apart. How would that change our prediction? What kind of story instead of Boyle's Law would we expect? Actually we find that real gases do not quite fit with Boyle's Law in their behaviour, and with the help of our imaginative thinking we are able to explain their misbehaviour and find out very interesting things such as the size of a molecule.'

Gas Laws

We do not combine our various gas laws to a general law, PV=RT; * but we leave that for colleagues to do that in other sciences where * they need it. At a more advanced stage in physics, we should of * course make very good use of it. At the moment it would seem a * formality rather than a clever combining of separate pieces of know- * ledge; and it might involve us in awkward statements about the * temperature scale used for T. *

Programme: Electromagnetism

We now leave gases and take up the electromagnetic kit for a further series of class experiments with electric currents. See a further note on this Programme, at the end of Chapter 5. * * *

Chapter 5

ELECTROMAGNETISM

Extensive Class Experiments with:
Magnetic Fields, Currents, Forces,
Meters, Motors and
Electromagnetic Induction

† PRELIMINARY WORK WITH ELECTRIC CIRCUITS (FOR PUPILS WHO MISSED YEAR II)

In Year II of our programme we suggested pupils should do a series of class experiments to learn about electric circuits, lamps, switches, ammeters, etc. For pupils entering the programme at Year III some preliminary work may be needed, to take the place of that open-ended experimenting in Year II. How much is needed will, of course, depend on the history of the pupils in earlier science classes.

Whether this preliminary work should be done as class experiments or given as demonstrations must depend upon the time available. If there is time for a series of class experiments, we hope that the school will use the Worcester Circuit Boards and let the pupils do a series of experiments on their own – though they should be hurried to move faster than in the programme for Year II. Teachers will find detailed instructions in the *Guide* for that year. If time is short and demonstrations are given, the teacher should draw upon the normal equipment of the laboratory.

† The preliminary teaching should cover the following:

INTRO. EXPTS. SEE YEAR II EXPTS. C12 to C22

- an electric current is something known only by its effects: heating, magnetic field, and chemical effects;
- a battery provides currents if there is a complete metal circuit; a 'short' circuit can get too hot and do damage.
- several lamps in parallel take more current than a single lamp;
- the more cells in series, the bigger the current the battery drives through, say, one lamp;
- but if one cell is connected backwards among others, that subtracts its push;
- the magnetic effect is used to make an ammeter work, to measure current in amperes (in Year II we offered a simple 'current balance' that pupils could make, as an introduction to ammeters: that might be omitted now, to save time);
- with ammeter (or current balance) pupils find that the current is the *same all the way round* a circuit;
- various materials, tested for conductivity, show that metals, carbon and some solutions conduct current: gases do not conduct unless special measures are taken;
- electrolysis can be put to use in copper plating (but this is done more fully, at an earlier stage in the Nuffield Chemistry programme);
- 'resistance' is looked at informally (without measurements, in fact without a voltmeter);

change of resistance with temperature is seen; and fuses are tried;
with faster groups, a voltmeter is introduced in a special, empirical experiment which suggests that it acts as 'a cell-counter'.

ELECTROMAGNETIC FIELDS

In the work with the Worcester Circuit Board kit in Year II, pupils examined the simple properties of magnets; and by using the simple ammeter or current balance, they established the fact that a force can exist between a magnet and a current-carrying coil. The time has now come to continue this exploration. *

Electromagnetic Kit

All the work with the electromagnetic kit should be done by the pupils themselves, given plenty of time, with the teacher doing his utmost to avoid giving the detailed instructions which would turn these experiments into a drill of following the teacher's physics instead of finding out one's own. A class experiment should *not* be preceded by a demonstration experiment, either with a spare set from the electromagnetic kit or with big demonstration apparatus. *

In some cases, a class experiment may be followed by a demonstration, to clear things up or reinforce what has been learnt, but as far as possible such demonstrations should be placed a considerable time after the class experiment. If a particular class experiment provides some knowledge or skill that is needed for use at a later stage, the demonstration should be postponed until just before that later stage, when it provides excellent revision. Even then it may be better to return to a quick repeating of the class experiment. *

Magnetic Fields

Traditionally, one starts with maps of magnetic fields, of permanent magnets, using iron filings or a small compass needle. However, there is good reason here for introducing this study by the field associated with an electric current. *

A suitable supply (power-pack, or set of accumulators) providing, C80a
say, 8 or 9 amps at about 1 volt, is ideal for this work. If this supply, suitably protected, is short-circuited by a length of thick copper wire, passing vertically through a horizontal sheet of cardboard, the field around that wire can be shown in the traditional way with iron filings. Pupils will see that the lines are concentric circles;

and will themselves comment that the magnetic effect seems to be much weaker further out.§

The Unimportant Rules. The direction of the lines can be related to the direction in which a compass needle, placed on the cardboard, aligns itself. We must remember that this direction is only a convention. In the teaching of this part of physics, the habit has grown up of giving considerable importance to this convention which enables us to put arrows on magnetic lines of force, and to the later rules that enable us to predict the direction of the force on a current-carrying wire in a magnetic field and the direction of induced e.m.f. These rules are tested in examination questions, as a trick way of finding out whether pupils have been taught that material. If the candidate just guesses there is an even bet whether he gets the example on the rule right or wrong, and that does not seem to make the question a very sensible test. Worse still, the rule and the mnemonics used by pupils, take charge and appear to some pupils to be the main substance of electromagnetism.

It seems tragic to have pupils think that by twisting fingers and thumb of their left hand and holding their head upside down they can 'explain' how an electric motor works. Of course those rules have their place: in more advanced training of future physicists one does need some quick rules for directions. Physicists often say that the rules are also essential for pupils who are to become electrical engineers; but we are told that intelligent electrical engineers just turn the current on and see which way the wire moves.

However, there is one exceedingly important aspect of these rules: the directions given by the motor rule and the dynamo rule are related to each other – this relation being one provided by experiment and not just a convention – in a way that is consistent with the conservation of energy. (A reversal of either component in that relation between the rules would suggest the possibility of perpetual motion.)

We suggest that teachers should try the interesting experiment of giving practically no emphasis to any of these rules when they meet an opportunity for them; but should wait until they find the rule is really needed, and then provide the rule at a stage where the pupils themselves see that it is a good idea to have one. Teachers

§ 'Majority of class could explain the pattern of iron filings they obtained. I did not expect them to find it as easy as they obviously did.'

who will try this experiment of waiting for clear need – as felt by pupils as well as teacher – will find it very interesting. * *

The Important Rule. In describing the working of a very simple electric motor with one rectangular coil, we do not need to contort our hand to predict which way each side of the coil will be pushed by the magnetic field: we can just point to one side of the coil and say: T

> 'This side will be pushed up-or-down. Which way will that other side be pushed?'

We hope to elicit the answer 'down-or-up'. The distinction between a push which is vertical (up-or-down) or sideways (left-or-right) or in the third direction (in-or-out) is much more important for a young person's understanding of something like a motor or an ammeter than the distinction between the two senses in each of those choices.

Oersted's Experiment. Pupils should make a quick bow to one of the greatest experiments in the history of electromagnetism, and try Oersted's experiment: hold a compass needle above and below a horizontal wire carrying a big current. If they point out that this is just the previous experiment turned over on its side, give great praise. C80b

Magnetic Field of Current in Coil. Pupils should now try a coil carrying a current. They should wind five or six turns of wire, closely spaced, on a wooden cylinder, then slip the coil into the slots in the hardboard, and look for a magnetic field. They will find an entirely new pattern. C80c

If a bright pupil says that the pattern near the wires is just the same as the previous pattern for the straight wire, give great praise for observation, insight, flexible mind – but do not announce this to the whole class as a thing to look for.

Once again, directions can be assigned by the use of a plotting compass.

Optional Buffer Experiment. Crude Galvanometer. Observations of the reaction of a small compass to the current through the coil can suggest a very simple current-indicating instrument, consisting of a flat coil and a compass needle. As in the galvanometers of the early days of electrical discoveries, this instrument C81 OPT uses the Earth's magnetic field to provide the opposing force that pulls the compass needle one way round while the magnetic field of the coil pulls the compass needle the other way. We do not delay progress with the instrument by giving this discussion of fields here. Curiously enough, young children regard this arrangement as obvious and sensible. The electromagnetic kit contains the necessary bits and pieces for building this very simple galvanometer.

Although this instrument has an honourable ancient history, it is crude and easily disturbed by neighbouring magnets. It has not been used in research or industry for many decades. So unless teachers have a special liking of it we hope they will move pupils quickly on to the use of moving coil galvanometers. Pupils who did electric circuit experiments in our Year II will have used moving coil ammeters; and they are likely to press, quite rightly, for modern instruments again.

Solenoid Field. The next development is, of course, to build up the coil to many turns, thus constructing a 'close-wound solenoid'; and pupils again observe the external pattern with iron filings. C80d

(The name 'solenoid' is a curious one, with an odd history of confusing definitions in dictionaries. We should be wiser at this stage to avoid its air of mystery and just call it a long coil.) * * *

Notebook. Pupils are seeing these shapes of fields, in most cases, for the first time. If we ask them to sketch what they see in their notebooks, it takes so much time that it breaks up the experimenting into short pieces of seeing a real field with long pieces of drawing interposed; and the sketches are apt to be far away from the true shapes. * * * * * *

We suggest that pupils should *not* make sketches of the fields in their notebooks – at least not while doing these class experiments. This should be a time for seeing and learning quickly; and even hurrying on to exciting things like an electric motor. Then when pupils meet that, they will see the sense of knowing about magnetic fields and may be ready to draw some in their notebook. T

We hope that teachers will try the experiment of posting up large sketches and photographs of magnetic fields, *after* pupils have made them and seen them for themselves, and leaving them in the classroom for people to learn the shapes by continual presence, rather than by their own attempts at sketching. D80e * * * *

(Reflect that this is what some artists recommend for developing taste for pictures: they put good reproductions of great pictures on the walls but do not ask young people to try copying the great masters in an art appreciation class.)

Fields. We are, of course, plotting what are known as magnetic fields; and it would be a simplification to introduce the word 'field' at this point. However, it would be unwise to develop the idea of a field further at the moment. There is a modern fashion of saying that if only we teach in terms of fields we shall make our teaching

a. up to date – in line with Relativity and, of course, with 'field theory';

b. clearer and easier for pupils.

Statement (*a*) is certainly true; but statement (*b*) needs to be modified by considering the age and stage of pupils. In our present Year III, using the word field as a short name is helpful, but if we continually say that the thing we thus name has important extensive and intensive properties we are likely to make fields seem rather mysterious to pupils, and even to endow the name itself with too much importance. Freud once wrote 'Words and magic were, in the beginning, one and the same thing.'

Solenoid and Bar Magnet. We ask what the magnetic field is C80f
like inside the tunnel of a solenoid. We ask pupils how they could find out. We encourage them to suggest making an 'open solenoid' of just a few turns, well spaced apart, so that one can see the magnetic field inside. When they use a solenoid to magnetize bars of steel, they should know that there is a strong uniform field inside.

Pupils should then look at the field of a bar magnet. We hope that C80g
they will notice the similarity of its pattern to the external pattern of a solenoid carrying a current. To promote that intelligent observation, we should take considerable trouble to have the bar magnet and the closely wound solenoid of the same size and shape. That is better than telling pupils what to look for, or pointing out afterwards what they should have noticed – which may well be necessitated if the shapes or sizes are different.

If pupils ask about the field inside a bar magnet, we should be cautious and say 'Ah, that is a difficult question. How would you get in among the atoms and find out?' T

† **Simple Experiments with Magnets.** If pupils have not played with bar magnets in earlier Years we should offer them iron filings, nails, loops of thread to suspend the magnet, and at least two bar magnets each, to 'find out all they can'. We hope that they will find forces between poles and perhaps extract rules for those forces. And they will find that a suspended magnet tends to point in some standard direction. T

Even at this more mature stage, we should follow the practice advocated for earlier Years and avoid telling pupils what to look for or dictating conclusions after the experiment. It is their experiment – as we must often tell them when they ask us to do things or make decisions for them – and we shall not build understanding and delight if we insist on offering right answers.

However, we should suggest things to try; and we should ask pupils to make short notes of what they find.§ With the small bar magnets (Ticonal) pupils should feel the forces when they hold
two magnets; then suspend one magnet in a stirrup of loops of C80h
thread, and watch what it does when left alone and when another C80i
magnet is brought near. They may try using a small compass C80j
instead of the suspended magnet. They should also play with the
slab shaped magnets (Magnadur) that are provided in the kit – we C80k
should not tell pupils the position of the poles on these but leave that to be discovered.

Magnets and Electrons. When pupils ask what makes a bar magnet a magnet, there is no reason why we should not say tentatively. 'Perhaps there are electric currents in that also. But if there are, they are not like the currents in a simple electric circuit of wires which continually deliver heat. They must be frictionless electric currents. They cannot be electrons staggering in jolting progress through a forest of atoms. Perhaps they are something much smaller, an electron making a more restricted motion that can continue with no collisions. Can you think what that might be?' We T

§ A teacher with a medium group in a secondary modern school reports: 'Experiments with bar magnets went very well indeed. Class tried various individual experiments but not at all keen to stop and make notes. However, they seem to like the idea of drawing and so I have asked for large drawings – suitable for wall display – instead of notes. I am not sure that notes are of much value anyway.'

do not suggest electrons pursuing planetary orbits round atoms – pupils are not ready for that, and physicists no longer picture that sharply defined form. Nor should we mention spinning electrons which also contribute some of the magnetic properties of materials.

Fields of Bar Magnets. Pupils should now explore magnetic fields of arrangements of short bar magnets, and the magnetic field of a horseshoe magnet – not the traditional one with the legs sloping together but a proper U-shape. Teachers who have a strong feeling for magnetic fields and their shapes, can comment as Faraday did, on the way in which those fields illustrate the forces between the ends of magnets. C80l

The teacher should make a comment on the relationship between these things seen with solenoids and magnets, and the action of the simple homemade current balance. T

There is no harm in talking about magnet poles and the forces between like poles and unlike poles, but we are not likely to need much knowledge of them.

Electromagnets. We suggest to pupils they should try iron filings near a 'C core' of iron. They will find little or no sign of a field. Then we suggest winding two dozen turns of wire round one limb, sending a current through that coil, and looking for a field. They will find they have made a good electromagnet; and if they let it attract another 'C core' they will find it is a very strong magnet. C80m C80n

Optional Extra: Bell. Pupils can make a simple model of an electric bell or buzzer, using a strip of steel and an electromagnet. This might be an optional experiment for pupils who have time to spare or want to take an experiment home. C80o

FORCE ON A WIRE – CARRYING CURRENT ACROSS A MAGNETIC FIELD

We now ask pupils to put together two very simple forms of magnetic field: the field of a wire carrying a big current and a 'uniform' magnetic field, such as that between the poles of a strong horseshoe magnet. The electromagnetic kit provides for this. This experiment should be a pure investigation. We hope that pupils will themselves find that the force on the wire is at right angles to the current and at right angles to the magnetic field; C82 and that a reversal of the current will reverse the direction of the force. This is a difficult but very important discovery; worth devoting at least a complete period to without the teacher 'giving the show away'. Of course, if pupils do not discover the story – and a number will not – we must later on give help.

Catapult Field Demonstration

Then the teacher should give a demonstration of the pattern of the resultant field: the field of current in wire and a uniform magnetic field, combined. This is the pattern sometimes called the 'catapult field' because, if interpreted with the realistic enthusiasm of a Faraday, it shows the wire being pushed – catapulted – by the field. D83

For a clear demonstration the current through the straight wire should be nearer 100 amps than 10. We provide the equivalent of that large current by running the wire several times up through the hardboard sheet carrying each turn up and over far away and down and back to make the next turn. Thus we use a large rectangular coil of 10 or 20 turns. The uniform field is produced by a large U-shaped magnet or by a pair of Helmholtz coils.‡

This is a field pattern that each pupil should look at carefully. In demonstrating it, it is wise to show each component field separately first, then the resultant field.

This might be done as a class experiment, if pupils look for the pattern on a very small scale. For that, they really need to know what to expect; so the demonstration should be shown first. C83

‡ For this demonstration, in which we want to show a uniform magnetic field extending over a wide area, unobstructed by the coil that produces it, a pair of Helmholtz coils is advantageous. These are two coaxial circular coils, separated by one radius from centre to centre along the axis. That arrangement provides a very nearly uniform field over a large region; and here it makes it easy for us to look into that region between the two coils. That is the only place where we really benefit from Helmholtz coils in this course. We shall find them provided in apparatus for deflecting electron streams; but there a single circular coil would make things easier to see and would make the geometry of measurements simpler. The electron stream would be bent into an orbit in the plane of the coil, where its field is quite uniform enough for measurements. Our electron stream experiments do not need Helmholtz coils or justify them. They have somehow come into elementary demonstrations with the intention of increasing accuracy; but our apparatus is liable to other errors that undo that precision. Anyway, we wish to make our e/m experiment a simple estimate rather than a precise measurement.

Motor

Uses of Catapult Forces. The question now arises whether we can put this catapult force to use. Whether, if we could produce rotary motion, we could drive machinery. T

(That is why it seems unwise to give that charming but rather confusing demonstration of the 'barber pole' in which a loose wire carrying a current wraps itself round a bar magnet. Instead we should aim straight at a proper electric motor.) * * * *

The kit provides materials for making a simple electric motor and a model of a moving-coil ammeter. The *Guide to Experiments* gives instructions; but teachers will find it much more interesting and fruitful to try the kit out themselves and develop their own way of giving it to pupils with as little direct help as possible. Then they will be ready to give hints to those who need it. T

Model Ammeter. The model ammeter gives a deflection when d.c. is sent through its coil. If the a.c. supply is used, no deflection will be seen, but the meter will buzz furiously. C84

When pupils have made their model ammeter they should look at and try a ready made instrument, a commercial galvanometer. They should also look at a commercial ammeter, if possible one with the case removed so that they can see how its construction compares with their model.

Electric Motor. Can the ammeter's motion be made to continue? T
It is certainly rotatory, but it ends when the two forces, the restoring force of the springs and the deflecting force produced by the magnetic fields, balance. This leads us to develop the simple motor C85
by modifying the ammeter, adding a commutator to it. That is why it is probably better in this early teaching to make the model ammeter before the motor.

The *Guide to Experiments* gives some details for making the motor but the teacher's own exploration will be more valuable. This motor will run very easily on d.c.: but also on a.c. if it is spun to the synchronous speed to begin with.

It would be a pity to leave the motor at this point; and not see some real motors. Pupils should look at a commercial motor to see whether they can identify corresponding parts – 1/20th H.P. to several H.P. – whatever is available and not completely shrouded. In any case we suggest the equipment for the laboratory should D86 include a fractional horse-power motor, of commercial form and not a toy, to be used in demonstrations.

We hope that many children will want to take their own motor home. They should certainly take it home to show it running; and we wish they could take it home and keep it. The possession of something which, though in some ways only a toy, is in other ways a piece of scientific construction accompanied by knowledge of its working may be so valuable to a young boy or girl that the cost of materials seems trivial. H85

The Nuffield Physics Group would like to say 'by all means let any pupil who wishes keep his motor'. The motor will run on a simple battery – and that the pupil should buy for himself. The only serious cost in the material taken home would be the magnet; so we trust schools will allow the magnets to go home on loan, to be returned or paid for in cash, or – if the teacher considers it worth while – given to the pupil.

ELECTROMAGNETIC INDUCTION

In the history of electrodynamics, which grew up so quickly at the beginning of the last century, the discovery of the motor-force was a great event; but the discovery of the dynamo effect seemed even greater, and a very large jump ahead of other knowledge. Some traces of that historical background remain with us in our teaching; and we are apt to postpone discussion of electromagnetic induction, feeling that it is something that rightly belongs much later. And yet it is not difficult, and it follows the electric motor study very easily. * * * * * * * * *

So we go straight ahead with the electromagnetic kit and ask pupils to try turning their own motor by hand and see what happens when there is no battery there. They must add something to find out what happens; so we suggest, if they do not think of it themselves, adding a commercial galvanometer. Then they will make the great discovery. C87a

Pupils may convert their 'd.c. dynamo' to an a.c. one by installing slip-rings, one at each end of the axle, instead of the commutator. Or they may make a temporary one that will work for a few turns by bringing out a pair of leads of thin wire from the coil and letting those leads twist up as the coil is turned. C87b

We hope strongly that, neither before nor just after this, will pupils' attention be diverted to questions of left-hand or right-hand rules. Those of us who value those rules highly will be willing to postpone discussion if we see the delight of children making rapid progress with the electromagnetic kit as an experimental road for travel, rather than a geography book's description to be learnt.

The dynamo effect is surprising but puzzling. We ask pupils, T

> 'How can we simplify the apparatus to find out what is really happening? When you turn your motor and find you get a current, you have the magnet, the coil, the motion, the electric current; too many things all at once. Try taking the magnet in one hand and the coil in the other. You had better use a straight bar magnet. Then you can poke it in and out of the coil instead of the complicated arrangement of twisting the coil. And you do not need a commutator.'

We ask pupils to wind a coil of 10 to 20 turns, with long leads which are connected to a commercial galvanometer. Then they move this coil relative to one of the permanent magnets from the kit. We must leave pupils for some time to find out what is happening now. It seems clear enough to us, because we have heard of it long ago; but to them the different versions of the same effect take considerable time to disentangle. We want them to enjoy finding out about this dynamo effect; so we do not bother them with rules or explanations – but we do encourage them by pointing out that they are doing the basic research for power stations. C88a

There is no need to go into the mathematical aspects of this work at all; yet it will be apparent that rapid motion produces a larger effect than a slow motion; and that stronger magnets, and more turns of coil and so on, produce different effects. * * * *

Other 'Dynamo' Experiments

After this introduction pupils should try other 'dynamo experiments': they should connect a wire to a commercial galvanometer and try moving the wire across the field of a U-shaped magnet. They wind a coil on one limb of a C core, connect the coil to a galvanometer, and place a magnet across the ends of the core. Then they change that magnet to an electromagnet – they have made a transformer. They try *running* their transformer by switching the current on and off through the electromagnet which serves as primary. C88b C88c C88d C88e

We should also give a demonstration of a commercial electric motor connected to a galvanometer, turned slowly – with and without a separate battery to run its field magnet. D88f

Bicycle Dynamo. One of the simplest generators which has the merit of being commercially available is the generator made for use on bicycles. This has the great advantage that the field moves relative to the coil, in accordance with the standard practice in heavy-current engineering. The field is produced by an 8-pole circular magnet, rotating between the two coils. Of course, such a generator produces alternating current. But this is all to the good, because alternating current is the current that our homes and our schools obtain from the large power station generators. D/C88g

If a bicycle generator of this sort is attached to a gear system, so that it can be driven very slowly and smoothly, the output can be examined on a demonstration moving-coil meter. Pupils should try this. As the speed of rotation is increased, the motion of the meter needle can be followed until the meter simply vibrates over a small range about a zero position. Then we need something that responds more readily to rapidly fluctuating currents. That reminds us of a.c. with an oscilloscope, already put to occasional uses in an earlier Year.

Dynamo and Oscilloscope. We apply the output of the bicycle dynamo, driven slowly, to the Y plates of the oscilloscope; and we arrange for a time base on the X plates. Then we see the traditional wave-form; and this can be compared with the wave-form from a 6- or 12-volt transformer connected to the mains. We should switch from the bicycle generator to the transformer without changing the time base at first, and let pupils themselves raise the problem of a change of frequency. D89a D89b

This experiment with the C.R.O. is our first extensive use of an instrument which is so standard and commonplace in every research laboratory and engineering testing room that we should do our utmost to make this a class experiment. The teacher may find it wise to start with a demonstration, using a 5-inch C.R.O.; but if the class can possibly be provided with oscilloscopes we should arrange for that.

Class Experiments with Oscilloscopes. There are now small oscilloscopes designed for class experiments, with a screen only a few inches across. If they crowd close, pupils see that well, provided there are not other pupils waiting round them; and if we have that C89c small instrument it should be possible to avoid having waiting crowds. Such instruments are not very expensive.

Progress. Class experiments have now carried pupils through remarkable progress – never mind if it has taken weeks – from a simple look at magnetic fields to a first feeling of understanding power stations. That should be a progress of delight, like that of confident bathers swept along by a great river, without being stopped by rocks of note-taking and map-drawing, or stranded on a desert island marked with three-fingered signposts. Yet there are many bathers who are not confident, and even the best of swimmers can lose his head; so here teachers, who know the journey, will need to give encouragement and support to pupils at different stages. Yet we hope that all will arrive with delight and a sense of powerful knowledge. * * * * * * * * * * * *

Transformers ***(probably better postponed)***

This Year is rich in new ideas and experiments; and our pupils are still young and need plenty of time for those. So we suggest that, unless the group is a very fast one, the continuation of electromagnetic studies into transformers should be postponed till Year IV. Even so, some experimenting with transformers will probably move into Year V where there is time available for class experiment with them. * * * * * * *

However, if there is time and if the school has the apparatus (which is required for Year IV) it may be wise to do a simple demonstration or class experiment on transformers: a demountable D/C90a
transformer is assembled and a d.c. supply applied to the primary, with a reversing switch. Then an a.c. supply is applied. In each D/C90b
case the secondary is connected to a galvanometer, a lamp, or some other suitable indicator.

Perhaps the most striking form of this experiment is one in which an open U core is used and there is no secondary coil to begin with. The primary is connected to an a.c. supply. A long piece of flexible D/C90c
insulated wire is connected to a small lamp and then wound, turn by turn, round the other leg of the core. As more and more turns are wound on, the lamp begins to glow and then glows brighter and brighter. This shows very clearly the effect of picking up more and more magnetic flux through the secondary.

CONTINUATION OF PROGRAMME

The work with the electromagnetic kit has been placed at the end of our suggested programme for this Year, so that it can expand to fill whatever time is available.

All should do the class experiments described above in Chapter 5. And any who did not meet a voltmeter informally in Year II as a 'cell-counter' should do that now. After that, the choice of programme depends on time available.

If there is plenty of time

If there is plenty of time, with a very fast group the simple introduction to voltmeters can extend into a more thorough treatment; and this group should make measurements; first of simple things like lamps, and then of power in various parts of the d.c. power line. The use of an oscilloscope may be explored.

If time is short

If the time is short, teachers should keep in mind the programme for Year IV, and consider moving some material ahead to it. In the later part of Year IV, we shall continue with the electromagnetic kit; trying the voltmeter seriously with potential difference defined as energy-transfer (in joules) per coulomb; a simple Ohm's-law experiment, and extension to non-linear cases; possibly a simple experiment with transistors; the d.c. power line if not done before; simple properties of alternating currents; the a.c. power line; and then demonstrations and class experiments with electron streams.

There is some freedom to move experiments from Year III to IV and IV to V. If some of the electromagnetic teaching suggested for Year III is moved to Year IV it will fit in there, though Year IV is a fairly full year. Some of the treatment of alternating currents and electron streams can in turn move into Year V. We suggest in any case offering in Year V experiments with magnetic fields and electron streams, and some class experiments with alternating currents.

So, if class experiments with the Westminster kit, etc., take more time than expected, or for any other reason run short of time at the end of the term or Year, we should probably be wise to postpone some of them to next Year rather than hurrying. When we do postpone them, we should be careful to give the material concerned full dignity of important science by explaining that we are postponing it, and even by giving some hint of what it will deal with – that is a particular help to a pupil who happens to move into another class before meeting that material.

If time is short, it does not *seem wise to condense some of the unfinished material into quick demonstrations. When we have established a tradition of learning electrical things by doing them oneself, a sudden finishing-up by demonstrations can do more damage to the sense of science than it does good by coverage of material. We should reflect that those of our pupils who do no more physics will not retain a clear knowledge of electrical things for many years after a quick lecture process (however efficient it may be for immediate teaching). On the other hand there is some hope that what they do themselves in class experiments will build such a good understanding that they will remain knowledgeable people in electrical matters. And, in particular, it would be a great pity to let Faraday's work on electromagnetic induction be done by demonstrations and notes given to pupils, instead of carried out by pupils themselves following Faraday's footsteps. Pupils should emerge with surprise from some simple play with magnets into a sudden realization that they have a dynamo in their hands.*

Magnetic Theory

At the end of this Year, we suggest a brief return to magnetism to leave pupils with an example of theory. This is an almost unique example of a theoretical treatment that is within the compass of understanding of young people and yet shows the power of theory to build scientific knowledge. We hope that this discussion and test will not be omitted or postponed. It is placed here as an important stage in pupils' learning about theory.

Chapter 6

CELLS AND VOLTAGE

Introduction to Voltmeters, Model Power Line

VOLTAGE

With the idea of a dynamo in a power station in mind, children can see the changes of energy: from chemical energy in fuel to heat to mechanical energy in the driving machinery to electrical form of energy which, as electrons are driven along the wires, is in turn converted into heat and mechanical energy, etc. This raises two important matters for a quick informal treatment now: the voltage that helps us measure energy-transfer; and the properties of electric fields which provide the driving forces on electric charges. T

The bicycle generator driven fast will produce enough power to light a small lamp. But we would hardly expect it to run a mains lamp. This raises the question of measuring the energy which an electric supply is able to transfer. Clearly there is a great difference between the supply that our bicycle generator provides and that provided by the mains socket in a room, or that provided by the grid lines that cross the countryside. Pupils will already be familiar with the use of the word 'volt' in this context. They will know that the label at the bottom of a pylon reads 'Danger: high voltage 132,000 volts', or whatever the number is. They will also know that the electric supply of the mains socket at home is said to have a 'voltage' of 240.

Simple Description of Voltmeter as a 'Cell-Counter'

Here in Year III we may introduce voltmeters as empirical instruments; and in Year IV we shall use them with a clear definition of potential difference in terms of energy-transfer. We can give a hint of the function of voltmeters as follows. (This is the optional class experiment C 23 in Year II.) * * * * *

Give each pair of pupils a voltmeter (or a milliammeter with a suitable high resistance already connected to it so that it will cover a range of 5 or 6 volts). Ask pupils to connect three lamps in series with a battery of three $1\frac{1}{2}$-volt cells in series. With the lamps kept running, pupils connect wires, from the new instrument they have been given, across one lamp, then across two lamps, then across three lamps. Ask: C91

> 'How many cells are needed to run one lamp? How many cells are needed to run two of your lamps together? How many cells are needed to run all three lamps?

'This new instrument is counting something for you. What does it count?'‡

We hope to elicit the idea that the new instrument is a 'cell-counter'. *It counts the number of cells in use for the particular lamp or group of lamps that we apply it to.*

Voltage: Optional Extension
Model Water-Circuit

As an illustration of our talk about current all round the circuit, we should show a simple model of a water circuit. This consists of a small pump (driven by a motor which merely happens to be an electric one) connected to a circuit of glass tubing attached to a vertical board. The tubes are filled with water and the circuit is complete, the water returning to the pump. A tap or a pinch-clip represents a switch. D92a

A section of capillary tubing represents a high resistance wire. An ammeter must be represented by some form of flowmeter.

This model was suggested as a demonstration in Year II; but at that stage it would have been a serious mistake to include a pressure-gauge. Now we should install a gauge to measure the difference of pressure between the ends of a piece of 'high resistance pipe'. That should consist of a small U-tube with mercury in it, and water above the mercury in the pipes connecting it to the appropriate points.

Note on Flowmeter. A simple form fits in the circuit where the water is flowing downward. A funnel is placed to catch the water that emerges and carry it on round the circuit. Thus, there is a pool of water in the funnel; and the faster the flow the higher that pool and the more rapid its motion of swirling round in the funnel. A small piece of cork floating on the water in the funnel acts as an indicator of the rate of swirling, as a measure of the current.

An alternative device is a simple, homemade form of the commercial flowmeter known as a 'rotameter'. This consists of a vertical tapered tube with the wide end at the top, containing a marble or a small spinning-top as indicator. As water flows up the tube it carries the indicator up to a height which depends on the speed of flow.

‡ In a sense, all our measurements in physics are matters of *counting*. Teachers may like to refer back to the commentary and suggestions on this in Year II Teachers' Guide, following experiment C 23.

The faster the flow, the higher the marble's (stationary) position. Commercial rotameters have very carefully made tapered tubes and are expensive. We certainly do not suggest that a school should buy one; but it is easy to make a simple uncalibrated form by drawing out a piece of glass tubing to make a tapered pipe.

Model Power Line

We hope that teachers will be able to use a model power line as a class experiment in the electrical work of this Year. It is done with a d.c. supply and should show clearly some important things about power, voltage and efficiency. The same power line should be used with alternating current in Year IV; but that needs earlier preparation; so it is important to give it a first trial with d.c. in this Year. Pupils do *not* need a clear understanding of potential difference for this – in fact this experiment may serve as the best introduction to the concept, since it shows the practical use of voltage. **C94a**

Pupils are given two wooden dowels and stands, as pylons, to erect on their bench, to carry a pair of 'power cables', consisting of thin Eureka (or other resistance) wire. The resistance of these power cables should be chosen so that when a low voltage lamp is attached to the far ends of that power line, the lamp only glows faintly when a power pack or battery of the right voltage is attached to the other end of the power line. We give pupils two such lamps, one for the 'village at the far end' the other for the 'town where the power station is'. That second lamp is a comparison lamp, so that pupils see that a lamp near the power station does glow at full brightness. If the supply can manage three lamps, we might give pupils one more lamp to add to the village's load.

We suggest the lamps should be 12-volt lamps, 24-watt, run from a 12-volt accumulator. As our programme continues through this year and the next two years, accumulators, which have probably proved useful already, will be necessary for several important jobs. We advise every school following our programme to have at least four 12-volt accumulators (or the equivalent in Nife cells). The cost and care of these may be a considerable burden; but we live in an electrical age where pupils should be able to draw upon supplies of direct current at a few volts.

When we change to a 240-volt supply, the lamps should be of about the same wattage. These should be ordinary bulbs like those the pupils meet in the house at home. Unfortunately, the high-voltage supply likely to be available may not light more than two 15-watt lamps. We suggest that these must be used as the nearest available equivalent of the 24-watt car lamps. (It would not be wise to change to small 6-watt car lamps, because then we could not find high voltage lamps to match.)

We ask pupils to set up the power line and try it. Voltmeters are not required here. The important thing is to see what happens. Pupils use the power line to light one lamp at the power station and one lamp at the remote 'village'. They simply compare the brightness of the lamps.

Then we change to 240 volts. Teachers will want to do that as a demonstration; but it should be done with a power line just like those used by pupils, but with lamps designed for the higher voltage, but with roughly the same wattage. If voltmeter and ammeter are used, they must of course have different ranges.

Thus we can do both the low voltage and the high voltage experi- *
ments without any meters at all and we should do that with *
medium or slower groups. Their importance lies not in the actual *
measurements of power but in the clear change from a highly *
inefficient line to a highly efficient one. Teachers who have not *
tried this experiment will be amused themselves by its impressive *
demonstration. *

With a fast group we may now give some meaning to this rather *
difficult concept, although we shall reserve a further discussion of *
it for Year IV when our studies of energy have progressed further. *

The high voltage line is conveying electric charges which are T
much more energetic than the charges driven by the simple generator. The term '240 volts' or '132,000 volts' simply tells us something about the energy being transferred by each chunk of electricity.

At this point we can say nothing that is good science unless we give pupils some concept of a standard chunk of electricity, such that a current is a flow of those chunks, or at least can be measured in chunks passing per second.

Coulombs

We need to say that '5 amps' means 'a flow of 5 coulombs per T
second past each point, all round the circuit'. We cannot profitably give pupils a rigorous definition of a coulomb at this point. But we can, as with the kilogram or the meter, say that a standard has been agreed on. If pupils ask about coulombs and electrons we can say:

'Yes, a coulomb is a huge bunch of electrons – in those cases where the only travelling things are electrons, as in a copper wire carrying the current. We know from much later experiments that a coulomb is about 6×10^{18} electrons.'

(A coulomb is always 6×10^{18} electron charges, but in many cases – in conducting solutions, in gases, and in some semi-conductors – some of that batch of charges are negative, and are moving one way, and the rest positive, and are moving the other way.) * * * *

Volts ***(buffer option)***

Now we can say what a voltmeter does. At this point we do some simple teaching by assertion, to be backed up by discussion in later Years. We simply say that the voltmeter is a device constructed to measure the energy-transfer,‡ in joules, from electrical form to heat or mechanical form, etc., for every coulomb of charge passing through a certain part of a circuit. We connect the voltmeter wires to the ends of that certain part in which we are interested. Then 5 volts means 5 joules per coulomb. T

Young pupils will not gain much light on the action of a voltmeter by doing class experiments to investigate it; but the teacher should give a short demonstration and talk. He should show a voltmeter applied to successive batteries: one cell, two cells, three cells, in series. If the voltmeter does show energy-transfer per coulomb, and if the imaginary coulomb passing through a battery gains electrical energy at the expense of chemical energy, we should expect three batteries to give each coulomb three times as much electrical energy and we should expect to find the voltmeter across three batteries reading three times as much as across one. This is the cell-counter experiment again, but now with a more sophisticated aim. D 92b

That is a simple overall test. It does not prove that voltmeters measure energy-transfer per coulomb; but a failure of that test would disprove our contention. * * *

‡ If pupils have not followed our treatment of energy in Year I and Year II, the teacher will need to give a considerable amount of teaching, to discussing our method of describing energy changes and our special use of 'work' as a measure of energy-transfer – but not as a name of a form of energy itself. This treatment is described in *Teachers' Guides* for Years I and II, and there are long Notes in the General Introduction on 'Work', 'Conservation of Energy', and 'Perpetual Motion'. As soon as potential difference is described in terms of energy-transfer now or in Year IV, a full discussion of energy is needed.

We could, of course, proceed to test one point on a voltmeter's scale by an absolute measurement. We could send a current through a coil of wire immersed in water, measure the current, measure the time (so that we could calculate the charge passing through, in coulombs) and measure the heat developed in the water. Then if we kept a voltmeter connected across the coil during the experiment, we could compare its reading with the measured energy-transfer (to heat) for every coulomb passing through the coil. That would compare a reading in volts with a measurement in calories per coulomb. We should need an assurance that heat is a form of energy equivalent to mechanical energy, so that our heat in calories is merely measured in different units and is not essentially a different thing. And then we should need to know a conversion rate between calories and joules.

These are important matters that we have only mentioned briefly, and almost guiltily, in passing, in earlier Years; and we wait till Year IV for a sound discussion of the underlying questions. So it would be very unwise to carry out a calorimetric test of a voltmeter now: it would be premature in theory, possibly confusing in practice, and certainly a discouraging experiment – a very rough test like all those calorimetric experiments in which heat leaks away so easily. However, we should keep such tests in mind ourselves; and we should remember that if we propose to carry out the ultimate calibration of a voltmeter by that method we shall need a value of 'J' derived from mechanical measurements and not from the electrical schemes which were used in some of the later and most precise measurements!

With our pupils now we should take a very simple view of a voltmeter:

> 'Here it is, like a stop watch, an instrument designed and manufactured and carefully marked to do an important job. A volt is a joule (of energy-transfer) per coulomb.'

Teachers will find a discussion concerning another question about voltmeters in the Note on 'Logic and Voltmeters' in the General Introduction.

Defining Voltage *(Optional)*

Given an idea of a coulomb as a chunk of electricity – more by assertion than by careful experimental building up of the concept – we can compare different electrical supplies. We say that if one coulomb passes through a part of a circuit and transforms one joule of energy from electrical to other forms we say that we have a voltage of 1 volt. We point out that the word voltage is almost slang, though not quite so bad as the word 'footage' used by the cinema industry. For those who prefer the more formal name, we say potential difference, and shorten that to p.d. pointing out that there would be no harm in thinking of that as shorthand for 'pressure difference'.

We may say that voltage or potential difference is the equivalent, for an electrical circuit, of pressure difference for a water circuit. Some of us enjoy thinking of p.d. as real pressure difference, of something pushing quite hard; of something which, pushing hard enough, hurts us by giving us a bad shock.

A volt then is a joule per coulomb. That is the definition of the word volt. No experiment can possibly prove that one *volt* is one *joule per coulomb* any more than any experiment can prove that one *knot* is one *sea mile per hour*. The short word is simply a dictionary name for the longer phrase.

(And of course we should say the same thing for a watt. A *watt* is a *joule per second* and no experiment can prove that because it is simply a name for one joule per second.)

When we take power from overhead power lines labelled 132,000 volts, we get 132,000 joules for each coulomb that we let the power lines drive through our transformer or other machinery. The ordinary mains at 240 volts supply 240 joules per coulomb; while the bicycle generator provides only two or three joules per coulomb.

We should not labour discussions of potential difference or use of voltmeters at this point. We should rather encourage pupils just to use voltmeters quickly and casually. Full discussion comes next Year. * * * *

Using a Voltmeter (*buffer option*). If there is time, give either a demonstration, or preferably a class experiment, of using a voltmeter to measure the power transferred by a lamp. This is not the time for a series of experiments or even for one careful measurement; but only an opportunity for pupils to see a voltmeter put into the right place in a circuit and used to make an estimate. D/C93

Power Line with Meters (*buffer option for fast groups*). If we have a group who know how to use a voltmeter, they may make rough measurements, after a trial without meters. We ask them to C94a insert an ammeter in the supply line and to use a voltmeter to find out the energy-transfer in joules per coulomb at the village, and at the power station end of the line (excluding the town lamp, which is only put there for comparison). We help them to calculate the 'power used by the village' and 'the power used by (power line + village)'. (Note that the latter is a much easier expression than 'the power supplied by the power station to the power line'.) We ask where the difference has gone. Pupils may be able to measure the voltage between the ends of one wire of the power line and calculate the loss in each wire, and see whether that agrees with their expectations.

Chapter 7

ELECTROSTATICS

Charges, Fields and Forces, Electron Streams

ELECTRIC FIELDS

Pupils may ask what makes the electrons run along the wire. We T
should not quarrel with their wording at this stage, though a more truthful question would be 'What makes the great random motion of electrons in a metal wire keep up a small drifting motion in one direction when a battery is connected?' We can say that the battery has piled up something on its terminals that we call electric charges, plus and minus; and those charges exert forces which extend to the wire and help to drag electrons along the wire. We say that like a magnetic field – but as an entirely different kind of field – there is an electric field around any charges, a state of affairs of readiness to push on other charges.

(**Note to Teachers:** From the Theory of Relativity, we know *
a more complicated story about electric and magnetic fields, but *
we should not raise this with pupils. It is probably better to insist *
that electric fields and magnetic fields are 'entirely different kinds *
of thing'. Yet, in fact, a moving magnetic field generates an electric *
field; and a moving electric field generates a magnetic field. In *
modern relativistic physics, when we carry a small electric charge *
and go exploring among fields, we think that it will see no magnetic *
field due to any other charges that are at rest relative to it. If any *
other charges are moving relative to the test charge we as outside *
experimenters expect to see magnetic fields in the neighbourhood *
of the test charge; but since magnetic fields only exert forces *
on moving charges we may have to think that it is only an outside *
observer who describes the events now in terms of magnetic fields. *

A wise enough observer may be able to describe everything in *
terms of electric charges, electric fields, and relative motion. This *
is certainly not something to take up with pupils. But it makes *
us return now to electric fields as very important things.) *

Charges. If the apparatus is available – it is needed for Years *
II and IV – we can explore electric fields by demonstrations rather *
like those used for magnetic fields. To stress the point that electro- *
static generators produce the same sort of electric charges as the *
power station generators drive round circuits, it is well worth while *
to use the output from a 5 kV power pack (which we state firmly is *
equivalent to a 5,000 volt battery but cheaper) for some electro- *
static experiments. *

Field Patterns. We apply 5 kV to electrodes in a dish of non- D95a
conducting liquid with powdered semolina floating in it, to show

field patterns.‡ The patterns look much the same as the patterns of magnetic fields.

We have now met three kinds of field. Magnetic fields are utilized *
in the simple ammeter and in electric motors, and they play a vital *
part in the working of generators. We have already mentioned *
gravitational fields, with which any chunk of matter offers to pull *
on any other chunk of matter placed near it, exerting the forces *
that we call weight. What about forces in an electrostatic field? As D96
a demonstration, we connect a pair of parallel plates to the E.H.T.
power pack, and put a light, metal-coated ball, hung on a nylon
thread, between them.

In Year IV we shall discuss the Millikan experiment, show a *
model and a film; and perhaps some pupils will see the oil drop *
for themselves. That is a very important experiment in our pro- *
gramme, the only one that gives any real indication that electricity *
comes in small atomic charges. (All the other experiments in elec- *
trostatics and with electric currents and even with electron streams *
in a vacuum, can be understood equally well on the basis of be- *
lieving that electricity is a continuous fluid and the currents are *
continuous streams of some 'juice' – in the case of electrons in *
vacuum it must be 'negative juice'. It is only when we come to *
Millikan's experiment that we are forced to believe in atoms of *
electricity.) So, if we want to do justice to the electrons that we *
have introduced so early and talked about so confidently, we must *
try to do justice to that great experiment, not just showing it as *
an obscure wonder but giving pupils some genuine understanding *
of it. With that ahead in Year IV, it would be wise teaching to T
prepare the ground by showing a large model of the Millikan
arrangement now, a 'macro-Millikan' demonstration. There are
no measurements to be made. This is just a qualitative demonstra-
tion to show the general arrangement. We set up a pair of hori-
zontal metal plates, one above the other, with a small conducting
ball hung in the space between them, with a spring to measure any
extra force on the ball. We establish a large voltage between the D97
plates, to make a strong electric field in the space between. We
give a charge from outside to the small ball.

(In doing that, we must be careful to see that the small ball does *
not suffer from 'image forces' in addition to the force we are trying *
to demonstrate. If that ball carries a large charge and is much *
nearer to one plate than to the other, it induces an opposite charge *

‡ See the Esso-Nuffield film "Electrostatics: A Modern Approach", available on free loan from Esso Petroleum Co.

on that nearer plate which pulls on it with an attractive force. In fact, that force is the force that would be exerted by an equal and opposite charge to that on the ball situated an equal distance beyond that plate, like a 'mirror image'. That effect can be avoided by using a comparatively small charge on the ball or by making sure that the ball is practically midway between the two plates.) * * * * * *

For entertainment, arrange on top of a Van de Graaff machine a pair of parallel plates, enclosed by a cylinder of transparent plastic. Place two or three metallized polystyrene spheres inside this cylinder and observe, on running the Van de Graaff, that the spheres are supported between the two parallel plates. Why are they so supported? The spheres have somehow acquired charges and this leads us to questions on charging by contact and charging by electrostatic induction. C98

† If pupils have not seen the forces between electric charges, we must show them the forces that we associate with the field patterns. We should give them, for a class experiment to be done quickly, the electrostatics kit with materials to be charged by rubbing, and metallized balls for a qualitative look at forces. C99a

Pupils should try a gold leaf electroscope, but they should first see a demonstration of a giant open-air one (with leaf made of *very* thin but strong, metal-coated plastic). D99b

Then pupils try their own electroscope. However they should not spend long playing with it and they should not proceed to measurements. A quick look will teach them quite a lot and the matter can be resumed next Year. C99c

Electrostatic Induction

The teacher should show, and pupils should try, the process of electrostatic induction. They should see that this is a quick way of giving something a charge (of opposite sign) without losing some original charge. If they know how to carry out the experiment, they will be able to describe the stages. C99d

How far we extend that into a complete description will depend upon the interest of pupils and teacher and on the time available. One can give a simple story of charges and positions, or one can go further into motion of charges, effects of fields, patterns of lines of force of the fields, potentials – and by that time we have clearly gone too far.

Stories of Electrons. Pupils seem to find it much easier to under- *
stand or describe electrostatic phenomena if we, and they, tell *
romantic stories about electrons. All pupils have heard of electrons, *
and many have heard a good deal about the way electrons behave, *
running freely over metals, etc., and even hurtling round unrealis- *
tically sharp orbits in atoms. *

Some teachers wish to use their pupils' common knowledge and *
enthusiasm for electrons in explanations of electrostatics. Other *
teachers consider it bad science to embroider the experimental *
facts with stories about electrons of which the simple experiments *
give no hint whatever. *

The policy which we suggest in this programme is one of compro- *
mise: that we should accept children's familiar knowledge and *
speak of the behaviour of electrons in describing electrostatic *
phenomena, but the teacher should warn his pupils and should *
keep the same warning in his own thoughts that at this stage *
electrons are only an interesting concept. They make it easier for *
us to think about the things we see. Scientists have always enjoyed *
imagining material models. But so far as present experiments go, *
electric charge might be continuous like fluid, or it might come in *
small particles; and the electric charges that move freely in metals *
might be positive or negative or both. See the Note on 'Teaching *
Electrostatics with Electrons' in the General Introduction. (That *
note describes a case of electrostatic induction using a romantic *
story of mobile electrons.) *

If we do talk about electrostatic events in terms of mobile electrons, *
we are probably wise to give frequent warnings to our pupils that *
they are using a picture which is, at the moment, unsupported so *
far as they know. *

Electron Stream: Fine Beam Tube. Fortunately, we can immediately give one piece of 'support', though its connection with what we have been doing must seem tenuous. We bring out the Leybold fine beam tube. That has already been used to demonstrate an electron stream in low-pressure hydrogen, in Year II. Now we can apply a transverse electric field to that beam. We connect a battery or small power pack to the pair of plates just outside the muzzle of the electron gun. We can move the beam to and fro, and if we have some scheme for providing an adjustable voltage, we can swing it to and fro and point out how very quickly it obeys orders. D100

We ask what will happen if we connect that pair of plates to a small alternating voltage. We should leave pupils to guess about that; and unless they guess correctly at once, we should wait until next day to show it. Then they can see the electron beam wagging to and fro sideways so rapidly in obedience to the rapidly alternating electric field that the beam appears to be splayed out into a thickened pencil.

We can mention the fact that the electrons of the stream are accelerated from rest to muzzle velocity by an electric field in the electron gun. But we should not go into much detail of this.

Postpone Magnetic Field and Electron Stream. It is very *
tempting to show the effect of a magnetic field upon the stream of *
electrons. If we do that, we have one great reward: that pupils will *
see the same kind of effect that they saw when they applied a *
magnetic field to a wire carrying a current. But we shall meet one *
serious trouble: the problem of circular orbits for which we are not *
fully prepared. We urge teachers to postpone that to Year V. *

Chapter 8

A FRUITFUL THEORY

A simple Theory of Magnets, to teach the Use of a Theory

SIMPLE MAGNETIC THEORY

When pupils have looked at magnetic fields of bar magnets, we should offer them bar magnets that can be broken 'to see if you can get a magnet with a pole at one end and nothing at the other'. These may be steel knitting needles, that can be cut with strong pliers; or, better, hacksaw blades or pieces of clock spring hardened by heating cherry red and plunging in water; or, best of all, $\frac{1}{16}$ inch 'drill rod' – steel rod that can be hardened fully – heated cherry red and quenched in water or oil.‡ Each pupil is given a rod already magnetized. He tries it with iron filings (and a compass needle); then he breaks it with his fingers. He tries the pieces again with iron filings; and breaks one of them. Then we hold a class discussion. C101

(In a fast group the teacher may wish to show the magnetizing process. The pupil brings an unmagnetized rod to be magnetized in a solenoid. Then he uses the rod as described above.)

Pupils find out that apparently breaking a magnet always produces new, smaller magnets with pairs of poles. We can point out that this restriction does not hold in electrostatics when we charge by induction: we can separate the two induced charges and obtain a positive charge on one conductor and a negative charge on the other.) We say to pupils:

‡ A coil that is ready for use to magnetize bars and to demagnetize them is an essential piece of general equipment in any modern Physics laboratory. Commercial 'magnetizing and demagnetizing coils' are unnecessarily expensive. All that is needed is a coil such as one of those belonging to a demountable transformer, and arrangements for connecting it to a d.c. supply for magnetizing or an a.c. supply for demagnetizing.

(If the teacher decides to use a coil with many turns directly on the mains, he may wish to install a neon lamp which will show by its glow whether the supply of the moment is a.c. or d.c.)

To magnetize a bar place it in the coil and switch the d.c. supply on momentarily.

To demagnetize a bar place it in the coil (or hold it very near the coil), switch on the a.c. supply and slowly remove the bar from the coil. (If the bar is removed to a considerable distance in a short time such as 1/10th of a second it may not be demagnetized; but any smooth removal with a slow motion of the hand will lead to complete success.)

In the case of the magnets used here, we strongly recommend magnetizing by this method, because the simpler methods of stroking or touching with a strong magnet are apt to divert attention, and they are no longer used in professional practice.

'Suppose we start with this piece of experimental knowledge and try to make a picture, just an amusing "theory" of what a magnet is like inside. You can see that if you go on cutting up a magnet into smaller and smaller pieces and always find little magnets as a result, you might pretend those little magnets were there inside the big magnet originally.'

We draw a sketch of a bar magnet with well-arranged, aligned,
little magnets inside. We do not say that these 'basic magnets'
are molecular magnets, or atoms. (That was said in earlier magnetic
theories, but nowadays we know that real magnets are made of *
small regions, which we call domains, each of them with an *
enormous collection of atoms aligned (magnetized in the same *
direction). So the basic magnets, on the domain theory, are far *
bigger than molecules. They may be big enough to see, or they *
may be much smaller than that.) *

Then we suggest to pupils that we might imagine the basic T
magnets to be there inside a bar of magnetic material even when it is not magnetized. They would be disarranged, all pointing in different directions: or rather, they would be oriented in cyclic groups, pointing head to tail.

Since the laboratory has a large number of small compass needles, D102a
for use in the Westminster kit experiments, we can show a demonstration model. We arrange as many compass needles as possible in a rectangular crowd on the table. Then we 'magnetize' this model of a bar magnet by waving an ordinary magnet past it, or, better, by bringing near it a solenoid that is carrying a current. We can demagnetize it by waving a big magnet about arbitrarily near it, and taking the big magnet farther and farther away while we wave it.

In fact, we now know that domains *are* there in unmagnetized
magnetic materials. We can see their boundaries when we pour
very fine filings on the surface of a piece of iron that is being
magnetized. The iron dust collects at the boundaries where the
domains meet each other, because there are 'exposed poles' there.
In unmagnetized iron the domains are small, and are oriented in
various directions. When we apply a magnetizing field, we do not *
drag the magnetization of the domains round to the new direction, *
but rather we encourage 'favourable' domains (those whose *
natural direction of magnetization is near to the field) to grow at *
the expense of shrinking 'unfavourable' ones (domains magnetized *
'the wrong way'). We might imagine a country growing and *

spreading its political boundaries, at the expense of neighbouring countries. Thus the bar as a whole becomes more and more favourably magnetized along the general direction of the field. *

We do not go into that detail with pupils, and we certainly do not go into the further details of domain theory. *

The domains make their conquest of territory in a rather vacillating way, with little vibrations of growth and shrinkage, which can be picked up by a search coil and heard with the help of an amplifier. One then hears a hissing sound, made up of an enormous number of tiny clicks. These used to be believed to be signs of complete domains switching their direction of magnetization; but experiments now show that there are far too many clicks in the hiss, and that these show only minor oscillations of domain boundaries. *

There is a good film showing domain changes during magnetization. Most pupils are certainly not ready for that; but a very fast group might enjoy seeing it. F102b

We describe to pupils a crude picture of magnetic material with little magnets inside more or less completely aligned when the material is magnetized; and disarranged, in 'family groups', in the unmagnetized state. We explain: T

> 'Our theory is just a picture to help us think about magnetism and experiments with magnets. Having got the picture, we can ask our theory some questions.' T

> **Question 1:**
> 'Is there a limit to the strength of magnet that you can make out of a steel bar? There is probably no limit to the strength of electric current you could drive through a wire, provided you can cool it to prevent it melting. Given a steel bar, can you make as strong a magnet as you like out of it, supposing that you have a suitable magnetizing solenoid?' T

We can elicit the answer:

> 'There is a limit, when all the basic magnets have been lined up in the direction of the field.'

The teacher should say yes, and give the theory a pennyworth of praise for success. Since physicists already knew from simple experimenting that there is such a limit, they are unlikely to welcome this success as a triumph.

(If the laboratory has a demonstration experiment to show, not a hysteresis curve, but the first stage, from unmagnetized material to saturation, pupils should see it. It takes much time and trouble to rig up a demonstration with an old television tube using a horizontal pair of solenoids for the magnetizing coil and compensating coil the other side, and a vertical solenoid to make a horizontal deflection that measures the magnetizing current.) D103

Question 2:
'Does the theory tell us what will happen when we cut a magnet in half?' T

We sketch the answer to this, taking care not to let the line of our cut chop any of the 'basic magnets' in half, and then say:

'Yes, the theory tells us that we shall just find new poles. Isn't that wonderful?'

We ask for opinions on the last statement, and then say strongly:

'It isn't wonderful at all. It is no credit to our theory whatever. Our theory has merely given us back the story we put into it. We found that out by experiment ourselves and used it as a basis for building our theory!'

Question 3:
'Suppose we have a bar magnet with poles at the very ends, just on the end faces. What is likely to happen to those poles?' T

We can elicit the answer that the unpaired like poles at an end will elbow each other away, so that we should expect to find the pole regions of a bar magnet spreading from the ends round the corners to the last region of the length. This agrees well enough with what one sees. It suggests the usefulness of keepers.

We can ask about heating, hammering, twisting a magnet. If there is a good demonstration, we can show that. However, modern magnet materials are so good that we cannot say that magnets become demagnetized if one drops them or hammers them a little.

So far, our theory's answers to questions have been pleasant little examples, but hardly enough to justify the fabrication of this picture; and we say so to the pupils. We explain that we shall now come to a use of theory which goes far beyond that.

Question 4:

'I have here a ring of steel. I believe I have magnetized it – I have done special things to it which I think should have succeeded in magnetizing it. Yet I can find no poles: look, you see no clumps of iron filings hanging on this ring when I dip it in filings. I find no sign of a big magnetic field near it: when I put this compass needle nearby it is not affected. So I find no poles, no field, and yet I thought I had succeeded in magnetizing it. Here is my question for theory: is it possible that, in any reasonable sense of the word, this ring is magnetized?' T

Give pupils time to think about that. Leave it for a night, or a week, rather than spoil it by giving the official answer.

And do not give a demonstration; each pupil should have a ring to try for himself.

Coax and encourage by making it clear that there is some kind of sensible comment to be made and then leave it. When a pupil has thought of the answer he is pretty sure that he is right: that the basic magnets in the material may be arranged head to tail all the way round the circle.

As soon as a pupil brings us the answer we ask the next question:

'What could you do to test whether that idea is true of this ring?'

Again, the pupil who guesses right is pretty sure he is right. He should crack the ring in half.

Then we provide rings for the experiment, *one for each pupil.* The pupil tries his ring with iron filings and finds no poles – if the ring has been carefully magnetized. Then he snaps it in two with his fingers and again tries it with filings. C104

Then we discuss with pupils the help our simple theory has given us:

'Here is theory doing a wonderful job: it helps us to make sense in talking about magnets, in a way that we couldn't have done if we had no theory. If you had no theory and were asked if the ring could be a magnet without any poles or field, anyone would say "No poles, no magnet." But here with theory as your guide you have yourselves guessed at a very sensible possible meaning; and we have tried it.

'That is theory doing a wonderful job for you by providing extra language, by giving a new meaning for the word magnetized. Actually, that meaning is very important to electrical engineers, because they use rings of iron for the cores of transformers; and they are certainly interested in magnetization of this kind.'

This story loses most of its point, particularly with young pupils, if we just tell them about the ring and do not do the real experiment. We must at all costs let them do a real experiment. We need a ring of hardened steel that can be magnetized. The easy form is a small ring $\frac{3}{4}$ inch in diameter cut from a piece of very thin clock spring. We heat the spring in a flame and let it cool very slowly in stages so that it has lost its springy temper. Then we snip it to a circle and punch or drill a hole in the centre. For a much better ring, we put a pile of these crude rings on an arbor on a lathe and turn their outer edge to a good circle. Then we harden the ring, by heating it cherry red in a Bunsen flame and dropping it into cold water or oil. Such a ring will snap when held and bent with fingers.

These rings can be manufactured cheaply by stamping them from thin steel of the right quality. We find on experimenting that suitable dimensions for rings that will magnetize easily and allow young pupils to snap them fairly easily are: external diameter about $\frac{3}{4}$ inch and internal diameter about $\frac{3}{8}$ inch and thickness about 0·010 inch.

To magnetize a ring, take a short piece of thick copper wire, pass it through the ring, connect momentarily to an accumulator. A considerable number of rings can all be threaded on the wire and magnetized at the same time.

Even a small ring should have 100 amps. With a large ring we have to use a considerable length of wire, running it through the ring, far out and round and back through the ring again, several times, so that there are, say, ten wires through the centre of the ring. Then we connect this wire momentarily to a d.c. supply.

When the ring is first shown and tried and then broken and tried, pupils should not know what has been done to it to 'magnetize' it. But after that we should remember that the pupils in this course are in a position to understand, even to guess, the method of magnetizing the ring. We might well ask a question about this and reward the answer by magnetizing another ring. The pupil who asks how we could possibly know that the ring was not already magnetized before we did that will go far.

This work on magnetic theory should only take one period or at most two. It is here as a very unusual example of theory for young people rather than as a continuation of magnetic studies.

This is a good example for young pupils of combining imaginative thinking with experiment. There is plenty of thinking in the years to come.

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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Other Nuffield Physics publications

Teachers' guide I
Teachers' guide II
Teachers' guide IV
Teachers' guide V

Guide to experiments I
Guide to experiments II
Guide to experiments III
Guide to experiments IV
Guide to experiments V

Questions book I
Questions book II
Questions book III
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Questions book V