REVISED

NUFFIELD PHYSICS

General Introduction

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General Editors

Eric M. Rogers

E. J. Wenham

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Foreword

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

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

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

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

The new edition contains a preponderant part of the original material in edited versions. Their contribution in providing a firm basis for these further developments is gladly acknowledged here. It is a pleasure to praise the part played by the large number of teachers who have helped in discussion, feedback and persuasion but it is once more to Eric Rogers who, with an extraordinary vitality, has led and completed this work, that we especially record our thanks.

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

K. W. Keohane
Coordinator of the Nuffield Foundation Science Teaching Project

General Editors' Preface

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

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

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

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

Many teachers have followed some general suggestions:

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

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

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

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

We changed Dr Henry Boulind's excellent questions for thinking and understanding to

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

simpler wording, but retained their essential enquiry. In response to pleas from teachers, and to the needs of the new school structure, we added progress questions to provide a different and easier approach.

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

On behalf of teachers and pupils who will use these books, we owe thanks to many people: to our consultant teachers, without whose advice we could not have envisaged the needs of the project; to Professor R. A. Becher, who was our chief inspiration and guide in the original project, to whom we still turn for wise advice; to Professor K. W. Keohane as our coordinator with counsel concerning physics and teaching and people; to John Maddox, Director of the Foundation, for past interest and care, and now special encouragement.

Both teachers and pupils will owe much to the four teachers who constructed the 'progress questions'—forged and tempered them: Margaret Fawcett, Reinet Fremlin, Gwen Jones, and Hilda Misselbrook.

Where some apparatus has a pleasing successor thanks should go to Philip Baillie of Worcester, who tried out designs.

During revision we have kept closely in touch with the Examiners who frame the questions and organize the marking. We could not even recommend the programme as viable without the continuing loyal support of the Examining Board.

Publishing *Teachers' Guides* and now *Pupils' Texts* together has raised many problems of editing and printing. We owe a special debt to Hendrina Ellis for her long work of perceptive guidance and help. And to William Anderson, Publications Manager of the Nuffield Science Teaching Projects, for management, advice and, above all, wisdom of words.

Our work of producing these books has involved consulting, editing, sketching pictures, trying experiments, writing chapters: all these have depended on Elizabeth Aldwinckle, on her insight and full understanding of the project. She has transformed rough drafts to clear material, has collected, corrected, given wise criticism, and has seen the project through with constructive skill and care.

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

Eric M. Rogers
E. J. Wenham
General Editors

INTRODUCTION

SECTIONS 1–10

SECTION 1
THE ORIGINAL PROGRAMME

Development and Aims

The Nuffield O-Level Physics programme was originally designed as a five-year course for the range of ages $11\frac{1}{2}$ to $16\frac{1}{2}$, for all who did O-Level physics.

In constructing the course and writing detailed suggestions, we prepared it specifically for pupils likely to be average O-Level candidates. Within that group it offered physics to pupils of a considerable range of abilities and interests. That did not seem to present great difficulties since our emphasis is on experimenting and discussion aimed at understanding, because such teaching can be modified by the teacher who knows his pupils. Given time, understanding *does* develop, but it does take time—it can hardly be poured in by last minute coaching.

Before describing the present revised form, we invite readers to take a look at our thoughts and plans in constructing the first edition.

Physics for non-scientists Many of the pupils who take O-Level physics never go any further with physics. For this reason, the Nuffield course is designed as a programme of physics for any educated man or woman. The emphasis is on learning 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 to be in training future scientists, fail to give the educated non-scientist an understanding of science, or even that liking for science which might encourage him to preserve his knowledge.

Physics for future scientists In discussing plans, we came to believe that the future scientist, too, needs to learn 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 of today Young people hear a lot of scientific talk today, of satellites, of atoms and electrons, of radioactivity, and of use and misuse of energy, and we have a duty to meet their interest in our physics. We can accept their awareness of these things and build upon it.

Physics for all Therefore we think 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 or woman working in a bank, a lawyer, who must deal with scientists and even with science; a nurse; a shopkeeper; a history teacher in school or university; and the parents of young children who in their turn will approach science with an *attitude*—of delight or of boredom—that starts at home.

'Nuffield spirit' Teachers concerned with the first planning talked about the *spirit* of the programme. We did not say 'Nuffield spirit', which would have seemed boastful. Yet the term has come into use to mean something like this: 'learning for understanding in a course of practical exploration, leading to class discussion, leading to more experimenting and so on, with a constant interplay between class and teacher, maintained by a sense of purpose and curiosity.'*

Wonder and delight In consulting teachers about the revision, we asked (with diffident apologies for the sentimental flavour):

(i) 'How far do you agree with the following statement, as part of our guiding principles?'

> "Young people deserve to share some of the emotions of scientists. Without the reinforcement of wonder, delight and intellectual satisfaction, pupils who take their last science at O-Level may not have much lasting benefit."

(ii) 'How far have you found, in Nuffield physics, some of your pupils experiencing *wonder, delight, intellectual satisfaction*?'

The replies varied; but their sum total is heartening. Many saw wonder and delight in the

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* Margaret Fawcett.

early years and sensed pupils' intellectual satisfaction in later years—markedly more than in non-Nuffield teaching.

Analytical studies

Comparisons—a warning and reassurance Cognitive psychologists have made careful studies of stages in children's learning in science. And, in a less formal way, every Nuffield science teacher is making his own study—subconsciously. There are differing schools of thought concerning the psychologists' results.

The observers tried to find out what it is that children understand (e.g. abstract reasoning at a given age) *when they have been taught in conventional ways*. But there are new teaching experiments, including our own, which offer in essence to alter the data which formed the basis of the research.

We therefore believe that in making changes of method and attitude such as ours, we should not insist on strong positive or negative predictions, from those other studies, of what can be done at each age.

If, unconscious of the limitations of their sample group (however large), researchers offer us their findings as *universal*, we should not accept them as having cast-iron authority. The findings of Nuffield teachers in Nuffield science classes are just as real; and it would be inept to use the findings of one group as norms to judge the other. In our programme, wonder and delight, intellectual satisfaction—in general, *interest*—can surmount apparent barriers of growth.

Taxonomy of aims and outcomes It is fashionable in Europe now to carry out a meticulous analysis of separate objectives and outcomes of teaching and learning, so that they can be assessed in tests. This 'taxonomy of cognitive values' grew in the work of Bloom and others in the United States twenty years ago. As it developed it was a valuable revolt against careless, vague planning and testing. But it concentrates attention on aspects that are clearly measurable and it misses some of the most important factors in our hopes for lasting benefits from Nuffield science—the enjoyment, ambition, pride, that we look for in 'wonder and delight and intellectual satisfaction'. It asks 'can the pupil define specific heat capacity . . . has he mastered problem-solving techniques . . . can he frame hypotheses?'. But never 'did he enjoy experimenting, does he delight in new ideas . . . does he—in our loose wording—appreciate science?'.

Thus the enthusiastic analysis of cognitive values (which one American critic labelled 'the detestable testables') can lead teachers and examiners astray. Bloom himself added a second study, 'The Affective Domain', eight years later. Even then the difficulties of measurement almost prevent the essential values from shining through.

For Nuffield science to be fruitful, affective values must play a major part in our hopes.

SECTION II
PRINCIPAL AIMS NOW

In revising the programme we have the same general aims as before: we choose the content to give pupils opportunities for experimenting on their own, to provide for thorough discussion, to include some atomic physics; and to form a connected programme.

Physics should be shown as a fabric of knowledge, in which something learnt in one place proves useful somewhere else, and something discovered later throws light back on an earlier topic.

We want pupils to think things out for themselves, learning physics as they do so. We want them to find what 'being scientific' means.*

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 hitherto associated with physics courses can, we suggest, give place to less formal teaching of ideas as well as facts, with both teacher and pupils aiming at understanding. On that basis, it is more important to know the *meaning* of a formula and its *limitations* 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 to see that there may be more than one 'right answer'—more important than to follow a training in procedure without really understanding it.

'... All the laws and theories of physics have this deep and subtle character, in that they both define for us the needful concepts and make statements about these concepts. Contrariwise, the absence of some body of theory, law, and principle deprives us of a means properly to use or even to define concepts. How far out of date is that view of science which used to say, "Define your terms before you proceed."! The truly creative nature of any forward step in human knowledge is such that theory, concept, law, and method of measurement—forever inseparable—are born into the world in union.'

JOHN A. WHEELER

'The newer concepts of physics can only be mastered by long familiarity with their properties and uses.'

P. A. M. DIRAC

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* One aspect is described in the Nuffield Chemistry *Introduction and Guide:*

'... In all new situations one gropes and fumbles and is likely to make mistakes. This, however, is the exercise by which judgment develops. A pupil must have graded opportunities to be right or wrong, and he must be guided and encouraged to become better at finding out whether or not he is right. This is time-consuming at first but only time-wasting in the context of having to cover a traditional syllabus: properly organized, it brings considerable educational benefit later on. Our hardest task will be to extricate ourselves from "the straitjacket of chronic success" and be willing to reconsider our methods. For example we have to learn to judge when to keep silent, leaving the pupil to puzzle the problem out by himself, and when to give encouragement and advice.'

Heuristic approach? Discovery method? New projects in education easily collect a misleading rumour! Some reviewers have described our project as using the 'heuristic approach'; and some say we are devoted to the 'discovery method'.

Our programme is certainly *not* heuristic in the original educational sense of making pupils crawl through investigations with no help until they have found out for themselves. In the hands of a rare enthusiast like H. E. Armstrong, the pioneer of heuristic Chemistry, that can be a remarkable experience for some pupils. But we doubt whether the peculiar skill of running such a scheme is transmissible to other teachers: and we know that in practice it would be frustrating for many pupils.

We do want pupils to do their own experimenting, but not without reasonable guidance: *from the Pupils' Text,* sailing orders; *from the teacher*, suggestions and praise; and any amount of short-circuit help to those who would otherwise be delayed by discouragement.

We trust pupils will discover many things in their own experimenting, and many new ideas in discussions. But we make a very strong plea against calling this a 'discovery method' in which pupils are told their results are *new science.* That would be dishonest. However much enthusiasm it generated immediately, it would ultimately damage the reputation of science.

If pupils do an experiment to measure P and V for a sample of air and arrive at the conclusion that PV is constant, we should not tell them they have discovered a law that was unknown. Boyle discovered that three centuries ago. Some pupils already know that; and others will soon hear.

On the other hand, we should be unfair to Boyle himself if we said:

> 'Here is Boyle's Law: PV is constant. Make some measurements and *verify* it.'

Boyle enjoyed finding his Law and there is no reason why our pupils should not share his enjoyment. We can say:

> 'A long time ago, Robert Boyle did an experiment on compressing air with a piston of mercury. He discovered an interesting relation between pressure and volume. He said he was experimenting on the springiness of air. Did he discover the same thing as Hooke's Law for a spring? Try it and see what you can find.'

We try desperately hard to hand on the urge for discovery—and the delight of success—to our pupils, without deceiving them over history. We cannot always succeed; but each success builds understanding and confidence in science.

CHARACTERISTICS OF THE PROGRAMME—ORIGINALLY AND AGAIN NOW

We suggest three main components of teaching for understanding:

Experiments—pupils' own experimenting to give them experience of scientific work;

Questions—essential learning aids to encourage thinking;

Models and theory—a progressive discussion to give intellectual satisfaction.

Those components are just as clearly characteristic of our present revision. So we will discuss them here.

Class Experiments

A very strong influence in young people's understanding of science and scientific work is their own experimenting.

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 long formal records.

Our pupils can do the same, with both understanding and delight, if we give them the opportunity. Pupils need this personal experience of science.

For that, they need plenty of time and encouragement, but not too many detailed instructions; because they need to feel that it is *their own experiment* and to learn by their mistakes as well as their successes. (Of course we should provide guidance—something like 'sailing orders' for the captain of a ship, but not much more.)

Then pupils can acquire the feeling of *doing science*, of being a scientist. Some teachers even like to set the tone of work in the lab by saying: 'Be a scientist for the day.'

Many ways of learning A good critic warns us against programmes in which a pupil limits his knowledge to what he has obtained in his own experimenting. If that habit crystallized into a distrust (or a disregard) of reliable second-hand knowledge, science would be in a sorry plight among non-scientist adults.

Fortunately, there is no such danger in Nuffield Physics. In among the experiments done by pupils for personal experience, teachers—and now the five *Pupils' Texts*—provide a flow of further knowledge. In the progression from Year 1 to Year 5 the flow increases; from ideas of atoms in 1 and discussions of energy in 1 and 2; through more demonstrations, diagrams, descriptions and arguments in 3; to whole chapters in 4 and 5 on advanced kinetic theory, conservation of energy, radioactivity, history of astronomy, and atomic models—all for pupils' learning by reading.

We trust our programme to encourage a receptive critical attitude—sympathy with everyone's experiments—and not bitter scepticism.

Pupils feel the thrill of being a detective—not only finding the clues, but doing their own reasoning from them; and even assessing the reliability of the clues.

Questions*

Constructive problems or questions that ask for active thinking should often take priority over pupils' reading in texts. Direct contact with experiment is provided by work in the laboratory, and most of the reasoning is better done by class discussion or homework problems than by reading, especially since the ability to absorb varies very greatly from pupil to pupil.

No claim is made that the questions in the *Pupils' Texts* are the only possible sets of questions, and that nobody can invent better ones. Clearly the best person to set the questions is the teacher himself; he knows the abilities of his pupils and he can set the questions which are most suited to them and which are expressed in the form of language familiar to them. All the same, most teachers will not have sufficient time available to do this at first when they are following the Nuffield course. So our questions fill the gap and provide guidance; it is in this spirit that they are offered.

* This section is extracted and adapted from Henry Boulind's introduction to his Nuffield book *Tests and Examinations*. Dr Boulind not only composed the Nuffield physics questions and wrote the half-yearly tests for trial schools, but he was one of the two Chief Examiners for Nuffield O-Level Physics Examinations until his death in 1970. We give his commentary here as a tribute to his insight.

These questions are an integral part of the Nuffield Physics scheme; without them the scheme must fail. The principal aim of the scheme is *'teaching science for understanding'*. Understanding what? Not only understanding science, but also, and equally important, understanding what it is like to be a scientist. Training children to act reasonably and in accordance with common sense, to build knowledge on experiment, to recognize the importance of models and of theories: this is what we mean by 'being a scientist'. It can hardly be done entirely in the laboratory; it cannot be done at all by the types of textbook that provides the answers ready made.

The general objects of our questions may be stated: to encourage children to think and wonder about things; to lead them to the more difficult concepts by easy stages: and finally, to replace much of the tedium of note-taking and 'writing up'.

Theory

As reasoning and the beginning of informed philosophical thinking come naturally into play, there should be examples of theory taking its place in science. Theory should appear as an interesting fruitful structure of experimental facts combined with imaginative thinking and organized by reasoning.

In the early stages, we merely ask a gentle question from time to time:

'What can you *guess* about atoms in that crystal?'

'Do you think there really *are* atoms?'

'When you made that calculation, *did you take something for granted* (an assumption)? Did you say "*if* . . ."?'

'We can't see air molecules but what do you *imagine* happens to them when we make the air hotter?'

Atomic and molecular theory starts in the first year with simple, imaginative guessing about atoms in crystals and runs through the next four years as a connecting thread, ending with a discussion of atom models and our reasons for using them—and for changing them.

Our progressive discussion of energy necessarily involves an interweaving of theory with experiment.

We also offer two examples of building a theory from simple experimental beginnings: we develop a primitive theory of magnetism; and we ask older pupils to follow the development of planetary astronomy. In each of those examples, we extract predictions to show theory being fruitful.

As theory is treated, it is not a separate, abstruse occupation; it is helped by our questions and linked with our experiments. 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 its degree of reliability. In general, pupils should learn to question, and not to take for granted rashly, so much that claims to be 'scientific'.

Finally, pupils should ask themselves how they are *interpreting* their own evidence. They should see science building knowledge by 'models', with imaginative thinking playing an important part. We hope that many will consider models and theories to be sensible achievements of science, well within their grasp.

Models

Models play very important parts in our thinking about Nature—in our knowing and understanding. Their origin may be rooted in children's imaginative play, from which we may trace stages of development and use, up to the sophisticated models that express our science.

Toys We think a scale model of a diesel locomotive is just a toy, and so is a simple puppet. Yet, to a children's psychiatrist, play with puppets may offer diagnostic insight or provide valuable therapy.

And in every use, such toys encourage imaginative thinking—simple forms of lateral thinking and of abstraction, often at a visceral level, only sometimes with words or phrases to express the developing idea.

Learning models Simple models explain the structure or working of something. Examples: a Perspex model of a diesel engine, a plastic skeleton, a cardboard model of a cyclotron's dees and many a diagram or sketch in a children's science book. In a way, it may be our calling such devices 'models' that blinds us to the way we use models in our knowledge of Nature.

Teaching models attempt to clarify knowledge for beginners. They help thinking as well as knowing. When we use marbles in a tray to represent gas molecules, we are offering an analogy to help pupils visualize—perhaps in all too solid a form—air molecules in motion.

In teaching, we often give the feeling that such a representation has some element of *truth*. We may assert 'air molecules *do* rush about like that'. Is that wise? Is it dangerous?

Some teaching models are words, given without apparatus. We say, . . . 'there is an electron *cloud* . . .' or, 'an *avalanche* of electrons pours into the positive wire . . .'. Such verbal models usually contain imperceptible suggestive assertions. When we say, 'Light travels in straight lines' we are making an assertion in the word 'travels'. But pupils will not question it—'How do you know light *moves along*?'. They will just accept it and thus build it into their 'knowledge of nature': a useful short cut in our teaching, but dangerous. Dangerous because taking pictures or words for granted may support the belief that they represent the *true* structure of Nature; whereas most physicists believe their knowledge stops at a set of models.

Even a mathematical treatment is a 'verbal' model—in a special language.

Some models are more sophisticated; they are essential machinery in developing understanding and making further predictions. In our discussion with O-Level pupils we call those '*thinking models*'. And we call the grandest form of those a *theory*—or as some philosophers say, a 'grand conceptual scheme'. Then our grand model must fit the experimental observations—it must contain some of them—though its fabric is still woven with imagination: therefore it can change as we learn more.

In all modern theoretical physics we use models as essential structures of the framework of knowledge—but we take great care to remember that the words, phrases, and descriptions, are only parts of models. When we say we know about atoms, we mean we have found good models to serve as pictures of atoms.* 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 young pupils at this stage; and it would be unwise even to try; but we should think about our own picture of science and the part played in it by models when we use demonstration models as part of our teaching skill, and still more when we use 'thinking models' to build pupils' knowledge.

* In Year 5 we suggest to teachers in schools near London that they should show pupils the Underground's stylized map and the equivalent map of the bus routes (which has the curved paths of the Underground lines marked on it); then ask, 'Which is the *right* map?' Pupils who object, '*It all depends on what you want it for*' have the key to understanding our choices of models for atoms.

SECTION III
CHANGES IN THE REVISED EDITION

The New Books

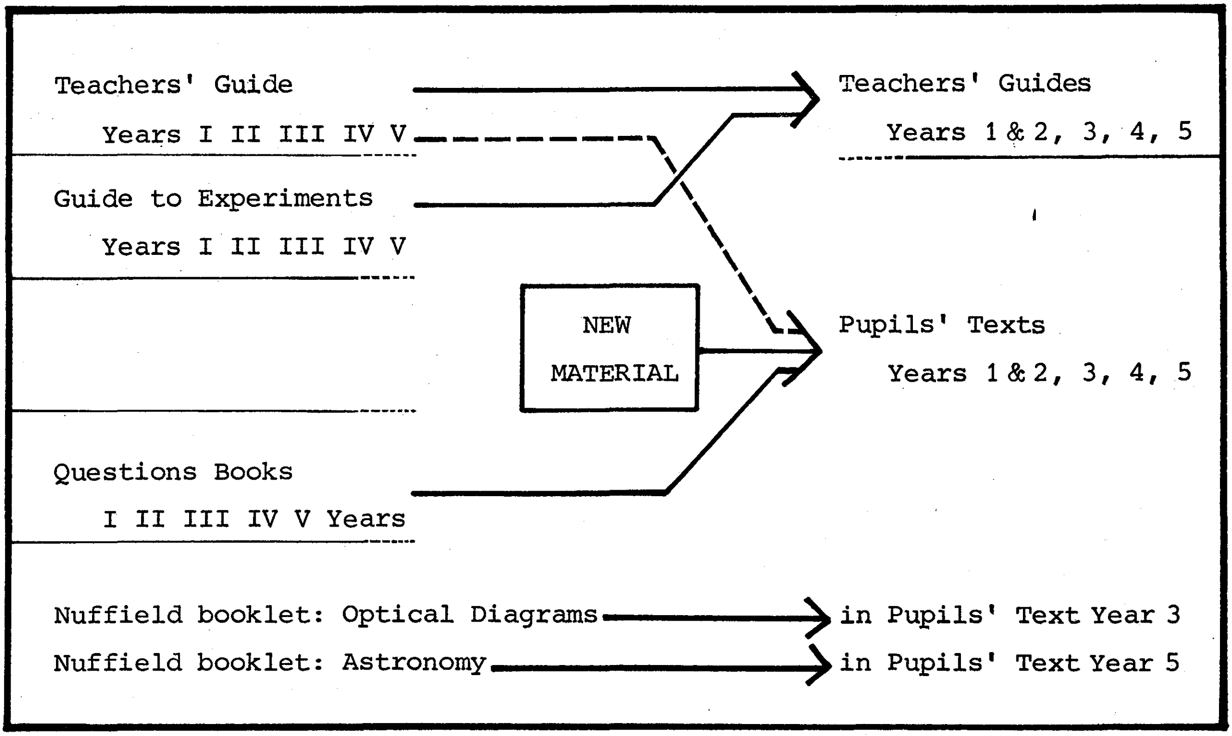
Teachers' Guides These have been completely revised and the instructions from the original *Guides to Experiments* have been incorporated in the new *Teachers' Guides*.

A few improved versions of experiments have been substituted. There have been changes of order—some topics moving to a different Year.

Books for pupils A set of four *Pupils' Texts* has been produced in response to many requests in feedback. The work for the first two years is included in one volume.

The questions of the original *Questions Books* have been largely rewritten and are printed in the new *Pupils' Texts*.

There are also sets of 'Progress Questions', easier and more factual, intended for the less academic pupils.



New Experiments and Apparatus

Effect on existing equipment In general, the suggested experiments and equipment have remained the same.

Some schools adopting this revised edition will already have Nuffield O-Level equipment. Therefore we have suggested few changes of equipment. They will find their present apparatus fits the revised programme well. Only in two or three cases may they be tempted to add a new alternative.

However, a school which has adopted Nuffield Advanced physics will have some extra equipment which will be useful for special experiments.

Effect on O-Level examinations O-Level examination questions will apply equally to the old apparatus or the new, where an alternative is suggested, with the exception of the three experiments marked †.

New apparatus and changes of design

Lever arm balance (all years)
replaced by kitchen spring scale, 0–1 kg.

Pound weights and foot rules
replaced by kilograms and slotted 100-gram loads, 30 cm rules and metre rules.

5 kg demonstration spring balance
to be graduated 0–50 newtons.

Perspex containers for class experiments (Year 1)
may remain 5 cm × 5 cm × 9 cm but inexpensive ones 10 cm × 10 cm × 10 cm are preferable and now available from Metric-Aids Ltd.

†*Volume change from water to steam (Years II and IV)* [previously done with large glass syringe]
Experiment now replaced by expansion of a drop of petrol to vapour.

†*Volume and temperature for air, Charles' Law (Year III)* [previously done with capillary tube]
replaced by large simple form (Experiment 77 in Year 3).

Monkey and Hunter (Year III)
changed to simpler horizontal gun, using lung power. No launching ramp needed.

Magnetic fields etc. with Westminster Kit (Years III, IV, V)
Instead of supporting the cards etc. with terminals of the power supply, a pair of wooden 'support blocks' are used.

Class oscilloscopes previously required in Years III, IV, V
Now optional in Year 3, essential in Years 4 and 5.

†*Colour filters previously red and green for Year V*
Now sets of six colours are required in Year 3 *or* Year 5.

Fine-Beam Tube
Teltron tube recommended, and put to extra uses, instead of Leybold tube—but the latter is satisfactory if the school already has it.

Current balance for magnetic field in e/m measurement
changed to much simpler form.

*Nuffield Science film 'Are there Electrons? (The Millikan Experiment)'** is necessary in Year 4.

Nuffield Science film 'The Rutherford Model of the Atom'‡ is strongly advised.

Some expensive equipment that was asked for in the first edition has been omitted. Where apparatus was marked 'optional', its appearance in original *Guides* suggested—often mistakenly—that it was advisable or really needed. And some apparatus catalogues accidentally emphasized the latter impression. We have omitted several such items.

Apparatus now omitted

Demonstration trolleys and attachments

Graph plotting board

Polaroid camera

Xenon flasher

Perrin tube, demonstration triode, demountable discharge tube, deflection tube, Maltese Cross tube

CO_2 rocket

Transistor oscillator

PSSC films for pupils**

Apparatus remaining optional but strongly desirable

Some modern electronic items were suggested as optional additions in the original list. The following are still optional. They may be available in some schools—and will be needed for Nuffield Advanced Physics—in which case they will be useful for some good demonstrations. They are:

General purpose amplifier

Signal generator

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* Colour, sound, 2 reels, 13 minutes. Reference No. 21.772 Rank Film Library, Rank Audio Visual Ltd., PO Box 20, Great West Road, Brentford, Middlesex TW8 9HR.

‡Colour, sound, 2 reels, 16 minutes. Reference No. 21.7852 Rank Film Library, Rank Audio Visual Ltd., PO Box 20, Great West Road, Brentford, Middlesex TW8 9HR.

** We no longer list the PSSC films as needed in Year 5. We think the explanations and pictures in the *Pupils' Texts* are adequate substitutes.

Loudspeakers
and, possibly, 3 cm radio wave equipment.

There is one item previously listed as optional which we shall urge schools to buy if it becomes available. That is an electron diffraction tube arranged to show a pattern of spots—*one that only shows rings is quite unsuitable* for an O-Level demonstration.

Numbering

Experiment numbers Each experiment is given a number. These numbers run serially through a Year.

Although most of the experiments are the same as in the original edition, the numbers are *not* the same—additions and changes of order have necessitated new numbering.

A conversion list between old numbers and new numbers is given at the beginning of each *Guide*.

Apparatus item numbers These are the same as in the original edition. They refer to descriptions in the *Guide to Apparatus*, and in Suppliers' catalogues.

The *Guide to Apparatus*

This is still available in the original edition. It lists and describes, with some specifications, all the Nuffield O-Level Physics apparatus and gives the quantities needed. It is intended for the guidance of teachers ordering equipment and of firms supplying it.

Most items remain the same, so we do not expect to issue a revised edition. However teachers will find some supplementary specifications, with occasional warnings, in the revised *Teachers' Guides*.

A correction sheet to bring the *Guide to Apparatus* up to date can be obtained from:

The Association for Science Education, College Lane, Hatfield, Herts.

Ask for the 'Correction Sheet for the Nuffield Physics Apparatus Guide'.

Units

Although the original programme made strong moves towards the MKS system of units we also used British units, such as inches and pounds—and even rogue units such as foot · pounds and pounds per square inch—to make the teaching more comfortable and familiar in the early years.

Now that all measurements are 'going metric' in Great Britain, we have changed the *Teachers' Guide* measurements to metric ones and we have written the *Pupils' Texts* with metric units.

Teachers and textbook writers have been urged to use only SI metric units. That has necessitated the publishing of a new edition of many a textbook. In our case general revision offers us a comfortable opportunity to make the changes.

The Système International of units offers a magnificent move to uniformity in scientific journals in all countries which adopt it. All research results will be published in the same set of units: an excellent scientific simplification. However in constructing teaching material for young pupils we considered we must use some common sense and link our teaching with common knowledge—and our Foundation advisers agreed. (We did not propose to adopt the cubic metre as the unit for milk—that would weigh a tonne. We shall sometimes use a litre, which will come into use more and more for milk as well as wines. We shall not describe the width of this page in metres for our younger pupils, but in centimetres. We shall sometimes use millimetres, grams, hours, days, when those seem the clearest descriptions for pupils.)

In the later years, beginning with Chapter 5 in Year 4, we shall express *all* forms of energy in joules. Before that we shall deviate from the recommendations of SI units in order to keep our teaching clear—see the special note on page 30.

In a few cases such as speeds and performance of cars, we think some children may find the new units unfamiliar,* so we have sometimes offered old units as well in apologetic parentheses (such as *miles/hour* and *miles per gallon*). And in some cases

* Vehicle testing records such as '0–60 mph in 15 seconds' will be familiar for some time to come.

of mechanical specifications we have also kept the old familiar units, such as an electric motor's speed in r.p.m. instead of radians per second or Hertz, and wire sizes in SWG.

We trust that teachers who are disappointed because we have not enforced rigid adoption of SI units will accept our policy with forgiveness, joining our belief that choice of units, though important, is a far smaller matter than choice of good teaching and learning for understanding.

FILMS

Films to Aid Teachers with Experiments

A series of films for science teachers has been sponsored by Esso Petroleum Company in consultation with the Nuffield Foundation Science Teaching Project. These films are intended to help teachers in preparing or running experiments which pupils will do. They are not suitable for showing to pupils because that would sabotage pupils' initiative, enjoyment, and ultimate gain.

The films are avilable on free loan from Esso Petroleum Company, Public Affairs Department, Victoria Street, London, SW1E 5JW, or direct from Esso's distributors, Travelling Films Limited, 78 Victoria Road, Surbiton, Surrey (01–399–1022).

The following films are relevant to the teaching in Year 2:

'Worcester circuit board'
'Elementary experiments in heat radiation'
'An approach to kinetic theory'

The following films are relevant to the teaching in Year 3:

'The electromagnetic kit'
'Worcester circuit board'
'Experiments in ray optics'
'Waves and the ripple tank'
'An approach to kinetic theory'
'Experiments in force and motion'
'Oscilloscopes and slow a.c.'

The following films are relevant to the teaching in Years 4 and 5:

'Experiments in force and motion'
'Momentum and collision processes'
'Oscilloscopes and slow a.c.'
'Kinetic energy: introductory experiments'
'An approach to kinetic theory'
'Waves and the ripple tank'

PSSC Film for Pupils

We originally hoped to illuminate the teaching of atomic physics in Year V with the excellent teaching films made by the Physical Science Study Committee in the USA. The films 'Photons', 'Interference of Photons', 'Matter Waves', and 'Photoelectric Effect' offer experimental descriptions which we considered essential when we had no *Pupils' Text*; but to our regret they are too expensive.*

Copies of those films can be hired from:
Guild Sound and Vision Ltd (formerly Sound Services Ltd), Kingston Road, Merton Park, London, SW19.

But if we listed these films as essential and suggested hiring, schools might have difficulties in planning borrowing dates, as well as in meeting the expense. Therefore in this revised edition we refer to those films as optional luxury aids; and O-Level Examiners will not expect pupils to have seen them. Instead we give pictures, descriptions, and discussions in *Pupils' Text 5* to cover the same advance through atomic models.

Nuffield Films for Pupils

'The Rutherford model of the atom' reproduces the original experiment on alpha-particle scattering by Geiger and Marsden. The Nuffield Advanced Physics Project collaborated with Rank and Mullard to produce this film for the A-Level programme. It is highly desirable to illustrate the description in our Year 5 with this 16-minute film. It is available in 16 mm colour with sound, Reference No. 21.7852, from the Rank Film Library, Rank Audio Visual Ltd., P.O. Box 20, Great West Road, Brentford, Middlesex TW8 9HR.

Millikan electron Electrons are common objects in modern physics, and even young pupils

* Although the huge costs of production of those films were borne by Government grants their price, in most countries, has to match that of films made by other enterprises.

talk glibly of them. Yet *none* of the experiments with cathode rays or thermionic effects provide convincing evidence that electric charge comes in atomic particles. Measurements of e/m, which come in Year 5, merely show a constant proportion of CHARGE/MASS for all cathode ray streams. And thermionic experiments merely show that hot filaments emit negative electricity which can travel across a vacuum. Even the photo-electric effect fails to show individual electrons *in the usual demonstrations*.

The only experiment that genuinely shows pupils 'atoms of electricity' is Millikan's experiment. Since the idea of universal electron charge is essential to any picture of atomic structure that we build, we regard that experiment as a very important part of our teaching.

We would like pupils to see the real experiment —and even try it themselves. But the watching is not easy—even with the successive improvements of teaching apparatus claimed year after year—and in any case the time needed for all the pupils in a class to observe profitably is very great.

Therefore we suggest this experiment should be shown by the Nuffield film; and we list the film as *essential* in Year 4. Its treatment fits the discussion* of the experiment in *Pupils' Text 4*. It is:

'Are there electrons? (The Millikan experiment)',† (16 mm, colour, sound, Reference No. 21.7772) obtainable from Rank Film Library, Rank Audio Visual Ltd, P.O. Box 20, Great West Road, Brentford, Middlesex TW8 9HR.

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* There is an excellent PSSC film but its method (measuring terminal speeds) differs from ours (droplets held poised by a measured electric field).

† There is also a short 8 mm film loop 'Are there electrons? (The Millikan experiment)' Rank Film Library, Reference No. 290316. This simply yields data. Teachers would need to explain in detail and show the real apparatus.

SECTION IV
THE FIVE YEARS—IN BOTH OLD AND NEW EDITIONS

The Early Years

In Years 1, 2, and 3, children make acquaintance with materials and their behaviour in the physical world; a stage of *seeing* and *doing*, without formal note-taking and without expressing the results in formal statements.*

Many schools are following Nuffield Combined Science instead of Years 1 and 2 in separate sciences. That will give them much the same experience in physics—except for the lack of our stimulating questions, which we feel are very important for able pupils, even at these early stages.

We suggest the general aim should be to give young people the experience of working on their own in the lab, and building a simple vocabulary and using a little reasoning with some imaginative thinking.

Logical order? Children are not logical in their learning. They will not thank us for strict logic in building a teaching-order and in providing experimental checks before each new step. That is what we should perhaps do in the sixth form and probably 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. Of course we must build sound science as far as we can; but we should accept the limitations of our pupils' viewpoint and skills and make the best of them.

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

For example we treat *atoms* as a familiar name from the beginning and encourage children to learn more about them in the early years; but we should maintain a warning flag by asking from time to time:

> '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 as well?'

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

Later Years

The spiral approach Continuing from Year to Year, we follow the 'spiral approach' advocated in an A.S.E. document.* As with 'atoms', we introduce a topic or concept lightly in an early year and come round to it again and again in several later years, expanding it and enriching its use as we treat it with greater sophistication.

Pupils experiment very simply with forces in Years 1 and 2; then they treat force and motion a little more formally with experiments in Year 3. In Year 4, they explore Newton's Laws; and in Year 5 they put them to uses that range from electrons' e/m to gravitational theory of the solar system.

A progression of electrical experiments with circuit boards in Year 2—for learning by constructive play—leads into more complicated experiments with the electromagnetic kit in Year 3; and those continue into Year 4.

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* We should be very sorry, on behalf of pupils taking the later part of the programme, if these early years changed to a notebook outline of Nuffield topics without sufficient thinking or doing. Such diluted forms may appear at first a welcome simplification: but then the teaching will lose the spirit.

† The fashion of requiring formal definitions before beginning a study has suffered some attacks.

At university level definitions may be intertwined with an operational approach—though Professor Wheeler, quoted earlier, warns us against that. At school level, gaining familiarity by use is nearer to the way young people learn.

To insist on stating and learning definitions at early school stages will make bright pupils bored and some slow ones ashamed.

*The Association for Science Education (1963) *An Expansion and Teachers' Guide to Physics for Grammar Schools.* John Murray.

The minimum span for O-Level In the future, if the Nuffield Physics programme is still to achieve its aims of teaching physics as a modern science and giving pupils a lasting sense of understanding physics as a structure of knowledge, the three Years, 3, 4, and 5, form the *minimum* for its teaching.

Year 3 In Year 3, as well as continuing with electromagnetism and developing knowledge of forces and behaviour of gases, pupils also embark on class experiments in two new fields: waves and optics. And if they continue to Year 5 they find those topics meeting and joining there. There is also an optional extension in Year 3 into theories of light, for those who wish to meet them earlier.

Year 3 is thus a rich intermediate stage with plenty of doing in class experiments, and some stronger demands of thinking—but still not very formal.

To enable teachers to adjust the programme to their pupils' needs, the later parts of some topics are labelled '*OPTIONAL NOW*' to suggest that they may be postponed to Years 4 and 5.

Then we hope teachers will be able to keep Year 3 free from shadows of external examinations and make it an interesting, happy year of physics for all—for those who will leave science after that, as well as for those who continue.

Years 4 and 5 In Years 4 and 5 there is more organized investigation and learning; and the questions will be harder but still intriguing and aimed at provoking thinking. So there will be stronger intellectual demands on pupils heading for O-Level examinations; but there will still be lighter choices for other pupils in the class.

In Year 5 the part played by theory in making a grand scheme of knowledge is explored overtly and shown to be an essential characteristic of scientific work. The chief example chosen for this, the development of astronomy, is now arranged for pupils to learn by reading in *Pupils' Text 5*.

Thus, in the later stages of our programme, 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.

A LONG GUIDE, NOT A SYLLABUS

In planning the revision, the Foundation felt that the programme should still be presented in the form of extensive *Teachers' Guides* 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 suggested treatment—altogether, a volume of commentary instead of a syllabus.

{**Digressions**} Sometimes there is a discussion—of physics or of teaching philosophy—which is not directly relevant to the current teaching. Such digressions in the main text are often placed in brackets {like this} as a signal, in case readers wish to postpone or omit them.

Teachers who find the general commentary covers familiar ground can always omit it. The topics are marked by subtitles. And in the main part of the *Guide* each suggested experiment is described in a box.

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.

This general introduction to the revised programme will, we hope, serve to set the stage for teachers before they turn to the *Teachers' Guide* for each Year.

Many teachers, both 'old hands' and new ones, will wish for a compact syllabus as well. Yet, although we sympathize 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. More serious still, examiners might adopt only its *content* and write questions for rote memory. So we would prefer to give our full *Guides* to a critic and to examiners. Moreover, teachers who have already embarked on our programme 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 wished to have in their own private summary. So, instead, we hope each teacher will extract his own summary from the *Teachers' Guides*. The *Guides* are therefore provided not as a track to be followed rigidly in detail but as a description of our suggested programme.

Nevertheless teachers will feel the need for some kind of outline of the course outside the Year they are teaching, so we give here outlines of the five Years for that purpose. They are only skeleton *outlines* and should *not* be taken as a syllabus.

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

Key to brackets in this list

( ) means *optional.*

{ } means this was *listed in an earlier Year*. Omit now unless it was missed before.

[ ] means *optional now*. This is listed again in a later Year; it may be postponed till then.

OUTLINE YEAR 1

Materials and Measurements. Instruments

Exhibit of materials. Testing a vacuum.
Discussion of crystals; idea of atoms.
Using magnifying glass and microscope in class experiments.
Weighing and measuring samples of solids, liquids, gases.
General comparisons of 'heaviness' encouraged but no formal definitions of density or calculations of density until Year 4, or even later.
Problem: estimate number of atoms in a block of metal.
Class experiment to make a microbalance.
Measuring sheet of paper, penny, paper thickness, aluminium leaf.
Rough guesses of lengths, masses, times.
Timing.
Simple introduction to statistics.

Open Class Experiments

Empirical investigation of simple seesaw, to look for a rule.
Empirical investigation of springs:
copper wire springs; steel springs—open experimenting,
stretching copper wire (demonstration and class)
[discussion of laws and their limitations].

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 uniform atmosphere.

Molecules

Model of a gas.
Brownian motion—seen with smoke in class experiment.
[Diffusion of gases.]
Simple surface tension experiments; spreading of oil.
Estimate of oil-molecule length: class experiment with measured drop of oil.

Energy

Note that discussion of energy and work is resumed in Year 2. 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, this year's final experiments on forms of energy, with cloud chamber and spark counter, should not be postponed.

Introduction of energy as something provided by fuel and needed for 'useful jobs'.
Informal naming 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.
Idea of work to measure transfer of energy introduced.
Energy and machines: perpetual motion?
'Nuclear' energy: cloud chamber as demonstration and as class experiment; spark counter.

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OUTLINE YEAR 2

Forces

{Short review of forces}: turning effect of a force.
Forces between magnets, electric charges.
Weight, as 'pull of the Earth'.

Electric Circuits

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

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 1 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 as
MASS OF WATER × TEMPERATURE-RISE.
(?Estimate of specific heat capacity by electrical heating, without meters.)
Idea of heat as a mode of motion: model of a gas.
Temperature, treated very briefly.
Effects of heating, *qualitative* study: expansion of solids, liquids, gases; {pressure-changes of gas;} melting, boiling.
Atomic and molecular pictures of solids, liquids, gases.
Heat transfer: class experiments on convection, conduction, radiation; spectrum demonstration.

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

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OUTLINE YEAR 3

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 of idea of 'rays' as guide-lines for the motion of wavefronts, and idea of an image for waves reflected from a wall.

Use of simple hand stroboscope to observe continuous ripples.

Optics: Behaviour of Rays; Images and Instruments

Simple pinhole camera as class experiment; and conversion to lens camera.
Demonstration of image formation with smoke box.
Class experiment to make a telescope.
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.
Experiments with eyes.
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 experiment: second experiment with telescopes.
Class experiments: magnifying glass, (compound microscope).

Light and Colour: Experiments and Theories

Reflection and refraction; *qualitative* behaviour of rays.
[Spectrum and colour.]
[First look at theories of light: particle and wave models.]
[Diffraction and interference. Young's Fringes—qualitative—in demonstration and class experiments. Comparison with ripple tank.]

Motion and Force, Informal Introduction

Class experiments: timing running pupil, accelerating trolley, by tape and vibrator.
Inclined plane and pendulum demonstrations.
Frictionless motion: Newton's Ist Law—Inertia.
'Frictionless' demonstration with solid CO_2.
[Illustrations of inertia.]
Simple investigation of FORCE and ACCELERATION, with tape and vibrator; informal approach to part of Newton's IInd Law.
Free fall; rough measurement: investigation with tape and vibrator.
Projectiles: demonstrations and class experiments; guinea and feather; pulsed water jet; monkey and hunter.
Independence of motions.
[Idea of gravitational field strength.]

Energy

{Special chapter for pupils who missed the discussions in Years 1 and 2, or in Combined Science.} [This also contains a short commentary on power.]

Qualitative Kinetic Theory

Models of molecular picture of gases.
Brownian motion (repeated from Year 1).
Diffusion of bromine in air and ? in vacuum.
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;
magnets and their fields; electromagnets;
applications of electromagnets;
'catapult force' on wire carrying current across magnetic field;
models of moving coil meter, motor;
commercial meters and motors;
qualitative investigation of electromagnetic induction.
Experiments with bicycle dynamo, a.c., oscilloscope.
[Voltmeter as a cell counter; use of voltmeter.]
Model power line, d.c.: class experiment and demonstration, for discussion without measurements.

Electrostatics

Fine-beam tube: electron stream in electric fields.
Charges and forces; [electroscope;] electric field patterns.

A Simple Theory and its Use

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

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OUTLINE YEAR 4

Newton's Laws of Motion

Multiflash demonstration: free fall.
{Introductory revision of tape and vibrator: free fall; trolley on hill.}
Relations for uniformly accelerated motion ($s = ut+\frac{1}{2}at^2$ etc.)
Measurements: {force and acceleration;} force and mass; Newton's IInd Law.
Motion with no force: CO_2 pucks; terminal velocity in fluids.
Quick measurement of g.
Comparison of inertia.
(Illustrations of inertia.)
Comparison 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.

Kinetic Energy

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.}
Kinetic theory: prediction of expression for PV (choice of several methods).
Boyle's Law: demonstration: theoretical discussion.
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.}

Evidence for Conservation of Energy: description and critical study of the great variety of 'Joule' experiments—a chapter for pupils' reading.

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 and Power

{Revision demonstrations: water analogy; electrolysis.}

{Series and branching circuits; lamps in parallel.}

Experiments with capacitors, charging and discharging.

Use of voltmeter.

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.

Relationships between current and voltage: Ohm's Law; temperature effects; other materials; transistors.

Measurements of resistance.

Power measurements and calculations.

[Experiments with transformers, bicycle dynamo, and C.R.O.]

[Model power line extended to a.c.]

Electrostatics

{Forces,} electroscope.

{Comparison: charging by friction and by E.H.T.} (Electrostatic induction.)

Ions: candle flame; ions in air.

{Electric field patterns.}

Pattern of field between parallel plates.

Calculation of field between parallel plates, from voltage and separation.

Electron Streams, etc.

Rectification by diode, shown by meter and by C.R.O.

{Deflection of fine beam by electric field.}

Diode as electron gun.

Uses of C.R.O.: demonstrations and class experiments.

Millikan Experiment

Full discussion, with Nuffield film for pupils.

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OUTLINE YEAR 5

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 $a = v^2/R$ with choice of methods; class tests; class experiment: application to satellite.

Electron Streams: Measurement of e/m

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 ions; mass spectograph; e/M.
Simple atom model: electrons and positive body.
Mass spectrograph—Nier type. Isotypes.

Planetary Astronomy—to Teach Development of Successful Theory *(Pupils' Text 3)*

Facts and early history; Greek theories—uses and meaning of a theory. Copernicus; Tycho Brahe; Kepler and Galileo.
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 and more details. Idea of a *model*.

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.)

Alternating Currents

Transformers.
{C.R.O. to show wave-form of mains, bicycle dynamo.}
C.R.O. to show wave form of scaler, voice, musical instruments.
Model power line with a.c.
a.c. meters: peak value; R.M.S. value; 'Ohm's Law'.
Study of a.c. at very low frequency with R, C, (L).

Waves

{Revision of properties of waves.}
$v = n\lambda$
Stationary waves.
Diffraction and interference; measurement of Young's fringes.
Grating: simple experiments.
Spectra: simple observations.
Electromagnetic spectrum.
Theories of light.

Pupils' Demonstrations for Revision

Small groups of pupils set up, and demonstrate to others apparatus and experiments such as:
- oil-molecule measurement;
- catapult magnetic field;
- model a.c. dynamo;
- electric bell model;
- winding a transformer turn by turn;
- ripple tank 'to answer questions';
- ray-streak models of telescope, etc.;
- model eye;
- trolley collisions;
- slow a.c.; . . .

Radioactivity

Simple experimental study of alpha-, beta-, gamma-rays;
illustrations with cloud chamber and counter.
Radioactive changes, treated briefly, with demonstration.
Alpha-particle scattering, illustrated by cloud-chamber photos, as evidence of atomic structure.
Rutherford atom model.

Modern Atomic Physics

Brief descriptions of the following, mostly by assertion and illustration by photos and diagrams in Pupils' Text 5.
Photoelectric effect:
'coarse' effect demonstrated; 'medium' effect and 'fine' effect described.
X-rays; diffraction by crystals.
Quantum behaviour; photons.
Matter waves; electron diffraction; wave-particle behaviour.
Suggestions for atom models.

SECTION V SETTING AND MARKING EXAMINATIONS

It would be useless if we taught for understanding and then gave examinations that ask for formal calculations, and definitions learnt by heart. Both pupils and teachers would encounter disaster.

For example, the following questions would show pupils that our intentions had not changed after all.

1. *a.* State an expression for the distance, s, travelled from rest in time t by an object moving with constant acceleration a.
b. A man leans out of a high window and drops an electric light bulb. How far will it fall in 3 seconds, from rest?
c. How far will it fall in 10 seconds from rest?

Whatever the teacher has told him, a well-trained pupil revises formulae the night before the examination. He produces a formula for part *(a)* and uses it in *(b)*. Faced with *(c)* he knows his duty; he ploughs ahead with the formula, not stopping to think about air-resistance. And he little cares that his answer requires a deep hole in the ground.

Instead of that we can move a little closer to asking for understanding by setting the question in this form:

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.
[. . . 3 lines for answer . . .]

b. If you used that 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.
[. . . 3 lines for answer . . .]

c. What kind of motion would you expect for the bulb after 10 or 20 seconds of fall? Why?
[. . . 2 lines for answer . . .]

Those questions ask 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 discussion of some of the problems of giving tests in a programme of this kind, are to be found in Appendix II.

External Examinations

We are fully aware of the importance of external examinations at the end of Year 5. They play a very serious 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 could be imagined would be largely spoiled within a few years if it had to be tied to external examinations that did not fit its methods or spirit.

The Nuffield Physics programme has been extremely fortunate in the skilful sympathetic examining carried out by the Oxford and Cambridge Schools Examination Board on behalf of all Boards. The Board accepted the *Teachers' Guides* in lieu of a syllabus, understanding that the aims and style of learning discussed in those books are just as necessary guidance for Nuffield examiners as the content of topics.

And the Board has further been remarkably successful in guiding examiners towards flexible marking that looks for understanding in candidates' answers.

Some specimens from the Board's Nuffield O-Level examination papers are reproduced, with permission, in *Pupils' Text 5* and some others in *Teachers' Guide 5*.

Nuffield O-Level examinations in the future We hope that the external examinations will continue to do justice to our programme, both to its syllabus-selection and to 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 for the examinations.

A school which tries our programme along the lines suggested and carries its pupils in the spirit of these *Guides*, through Years 1, 2, 3, 4, 5, or at least* through 3, 4, 5, should consider its candidates have as good a chance as they would have had in a traditional examination after a traditional physics course.

Marking 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 questions that are more informal, but more penetrating.

Some of the marking of answers in such examinations needs to be done in a rather different way. For example, if examiners were to construct a model answer beforehand they would probably find it necessary to broaden it. If a certain formal statement is required for some portion of marks, pupils who have worked hard in a Nuffield 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 they have 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.

* *Saving time.* However, schools sometimes find they need to shorten their programme or to let pupils enter a programme like ours for a shorter time; and in such cases we must give a strong warning that the pupils may be at a serious disadvantage when they sit external examinations based on the full Nuffield course. We do not boast that pupils *cannot* be coached with some success for 'Nuffield' examinations; but we are sure that the value of coaching is far smaller for such examinations than for traditional examinations—particularly on account of the kind of answers that are expected, and the marking that is used.

A good score in a Nuffield test?

Mankind aspires to many higher virtues, but mortal man should be content to be endowed with *some* of them. Our tests consist of questions which look for 'educational higher virtues' in the form of aspects of understanding. We should be content if only *some* of those questions elicit successful answers.

In Nuffield questions for homework or tests we aim at more than just *testing* understanding. We aim at *encouraging learning* for understanding; and we would like our questions to give pupils intellectual satisfaction. Then there will often be a haphazard element in different pupils' reactions to a question when they meet it in an examination. There, a particular question may stimulate some pupils to think scientifically and show their understanding; but it may fail to catch the fancy of other pupils, who will need a different question for their opportunity of success. Pupils who *do* understand the science very well may yet seem *variable* in the sense of scoring well on only some questions. The result, found by teachers in class and professional examiners alike, is: *lower scores for a group of questions asking for understanding than for a similar group asking for facts.*

Teachers need to remember this and be reassured—40% on an 'understanding' test is like 80% on a 'fact' test.*

* In American schools, where *percentage* marks are considered to be given on fixed (absolute?) standards, both teachers and pupils were dismayed when the PSSC test questions—which looked for a measure of understanding—yielded low percentage marks. The project organizers had to issue just such reassurances.

SECTION VI
THE TEACHING OF ENERGY IN THIS PROGRAMME

(We give great importance to the teaching of energy as a binding thread throughout our programme. So this is a long section, some of it explaining our programme of teaching energy and its conservation and some of it discussing general philosophy.)

Early Introduction

We mention Energy at an early stage and build increasingly sophisticated knowledge of its nature and uses as we return to it year after year in pupils' 'spiral' of learning.

From the beginning, we want to avoid *ENERGY* being used as a magical, little understood, catchword to '*explain*' almost everything in Nature. Therefore it is particularly important to provide a factual or operational description at the beginning when varied uses of the concept have not yet built understanding.

Fuel as an energy store Whenever in the first three Years pupils embark on Nuffield physics, we first describe energy as something very important which we 'get from fuel', something which 'does useful jobs' for us in raising loads, etc.; also something which can warm things up.

In an age when fuel, including food, seems to determine the well-being of nations—running machinery, feeding us all, providing money for some, threatening others with war—we may expect even young pupils to consider fuel supplies as of paramount importance.

Energy from fuel When we raise a brick vertically *it gains* gravitational potential energy (or the gravitational field gains that) but *we lose* some chemical energy. That chemical energy was provided (earlier) by our food. If we go on hauling up loads we need extra food.

If we raise a load by using a petrol engine or a steam engine, or an electric supply from a dynamo driven by a steam engine, fuel is being converted somewhere into less useful materials. 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 a car 100 kilometres the chemical energy of petrol ends up as low-temperature heat which is of no value to motorists.

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

We say we get energy from fuel for 'useful jobs'.

'Useful jobs' But what *are* the jobs that require fuel? Some obviously need fuel, such as hauling a load up to the top of a building, speeding up a car, heating bath water. Each of those needs fuel, whether food for men, petrol for an engine, or coal for a power station. But what general criterion can we give?

Holding a heavy load in our hands *does* take some chemical energy from us. (See a note about that.) 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 minute Brownian motion, which is reversible). The shelf does not produce heat; it does not need any fuel to do its job. That suggests a good criterion for fuel-using jobs: *can we replace the man or horse or electric motor by some inanimate prop which needs no fuel?*

Forms of energy Some of the energy we get from fuel goes to mechanical forms: the energy stored in a stretched spring or the 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.

At this stage we are naming energy and energy forms and using the names in experiments so that children build a practical sense of their meaning. This is somewhat like the way in which a very young child learns language, by increasingly clear use instead of waiting for definitions.

In Years 1 and 2 we describe P.E. as *'up-hill energy'* and as *'springs energy'*; and we go on to name other forms, with practical illustrations: *chemical energy* (stored in food, oil, fireworks . . .), *electrical energy* (supplied by a battery); and, provisionally, *heat* as a very common important component in interchanges.

The energy circus We illustrate forms of energy and *interchanges between various forms* by a collection of devices:

a steam engine raises a load or drives a dynamo which lights a lamp;

a spring is wound up; and as it unwinds it raises a load, or drives a dynamo, or accelerates a small wagon;

a battery lights lamps or drives a motor to raise loads, etc.

When we first tried out that energy-conversion kit we found that even the steam engine soon loses its glamour when the teacher runs the experiments as a long compound demonstration. But when they are distributed among pupils for different groups to run and explain, this 'energy circus' runs well and becomes a very important stage in teaching about energy.

Quantitative Discussions

Although in the early Years pupils become familiar with qualitative descriptions and discuss interchanges, they cannot make extensive calculations until Year 4 when we derive $\frac{1}{2}mv^2$ for kinetic energy.

True, we introduce the concept of WORK in Years 1 and 2 but that only measures energy-transfers in cases where a measurable force moves through a measurable distance. We can measure some jobs in WORK units (newton · metres). We can calculate and compare input WORK and output WORK for (ideal) machines. But we cannot go deeper in our study of energy without measurements of kinetic energy and some way of measuring heat.

By Year 4 we can discuss interchanges between K.E. and P.E. and we approach the general problem of Conservation.

Approaching Conservation of Energy

In early discussions we tacitly take conservation of energy for granted without pupils (or even ourselves) 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 understanding of nature.

In the teaching of other sciences, energy conservation *will probably be assumed throughout* and that places a stronger moral burden on physics teachers to talk about the experimental basis. Until then, we should be careful to keep a warning flag flying from the very beginning.

In a separate note that follows this section we offer a philosophical discussion of the importance of conservation laws in developing science and in teaching science. Here, we assume we have a duty to give O-Level pupils a clear understanding of energy conservation; so we discuss the experimental support for the Principle.

Experimental evidence for conservation 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.).

That 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 output of mechanical energy is always somewhat 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, such that interchanges among kinetic, potential, electrical energy etc. and interchanges of them with heat keep a constant total in a closed system.

How far does each of those lines of attack give the assurance that we owe to our pupils—that we owe to the next generation of the general public?

Comments on the evidence Let us examine each line in turn.

a. Machines. We should certainly deal with simple machines; and, for our introduction of conservation, we might well treat them in ideal form, or nearly so. We show, by arguing about forces and distances, that a lever does not multiply energy; nor does a pulley system.

b. Conservation of [P.E. + K.E.] This 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.

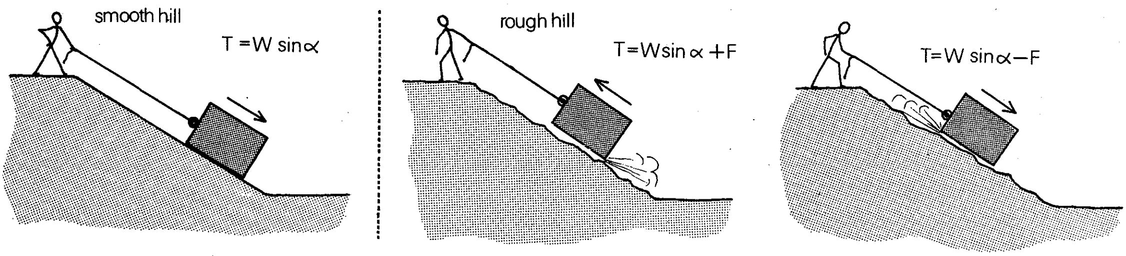
The expression $\frac{1}{2}mv^2$, which we must use in calculating out any test, is itself derived from FORCE × DISTANCE in a way that necessarily makes it the complement of potential energy in any conservative system.

Without a definition of 'conservative system', the last remark may be meaningless. It is 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 smooth cylinder and pushes against a frictionless piston which is used to compress the spring. The spring pushes with the same (outward) force, when it is 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 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 being hauled up a *frictionless* hill as a conservative system; but on a *rough* hill it is not. (See the sketch.) Again, an easy overall test is to see whether heat is developed.

Neither experiments on real machines nor the constancy of [P.E. + K.E.] can provide adequate evidence of conservation. In every practical case heat appears or disappears. When heat or electrical energy or chemical energy is involved, *(a)* and *(b)* are of no avail. So we turn to *(c)* for proper support of energy conservation.

c. Many forms of Energy. We appeal to 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—whether there was much friction or little.

Although the result of each measurement was reduced to a numerical value of 'J' these experiments did not just show that *heat* and *mechanical energy* are interchangeable: they compelled a belief in conservation in a much wider variety of interchanges.

The Experimental Testimony. 'The Court will sit'

In Chapter 9 of *Pupils' Text 4* we invite pupils to survey that evidence, not as an arbitrarily chosen topic in the history of science, but to show the building of a very important part of science. To support the great generalization, the many and varied experiments need some description; and then the converging values of 'J' form an exhibit of evidence.

If pupils know beforehand that these are pieces of testimony from difficult experiments, pointing to a crucial verdict—a universal constant for 'J' as a symbol for conservation—they will not find this great story confusing.

If we adopt that policy in teaching, then *until the case is proved* we must have a different unit for the thermal measurements (most of them done with water) from that used for the mechanical measurements.

The trouble may be illustrated by a story: 'A murder has been committed. The police believe they have found the culprit. In the trial, the police may not call the defendent "the murderer" before the case is proved.'

Otherwise the testimony in favour of conservation would be given in a series of numbers in the strange units 'joules/joule'; or, worse still, there would be statements like this: 10 000 joules of mechanical energy went in; 8000 joules of thermal energy appeared; and 2000 must have been lost somewhere, probably as escaping heat.

That would make the story confusing as well as lame.

Therefore our plan is to keep some thermal units until we have discussed the evidence for general Conservation of Energy.

In early years there are thermal measurements with thermometers and water,* and we express the results in *temporary* units. Those experiments suffice to give a feeling for 'heat', and they prepare for our later discussion of Conservation of Energy.

Temporary Thermal Units

Our temporary unit based on metric measurements is the energy (heat) required to warm up 1 kilogram of water 1 degree on the Celsius scale. Until recently, we have all used the name 'kilo-calorie' (Calorie) for that.

Now scientific societies in many countries have agreed to use a standard set of units (SI) in physics journals and other reports.

Physics teachers and textbook writers have been recommended to extend that agreement on SI units to teaching and books in schools. Strict insistence on a single set of units is very valuable in learned journals throughout the world. But some relaxation from it proves helpful for young pupils.

For example, while a journal might report the measurement of a small length as 1.2×10^{-2} metres to maintain uniformity, a beginner may find it easier to see the width of his or her finger as 1.2 cm, or perhaps 12 mm. In that way, an extension to decimal multiples of the standard SI unit promises to be helpful and harmless in teaching.

Through the best of intentions one recommendation for uniformity has taken quite a different turn. In learned journals the SI system quite rightly asks that energy be given always in *joules* (newton · metres). That applies to thermal energy (heat) as well as all other forms. Therefore the Calorie is no more needed for use in learned journals etc. than the inch and the gallon and the mile/hour.

However, in the extension of the recommendations to school teaching a new aspect has been attached—accidentally we trust—to one of those changes. The Calorie is regarded not just as unnecessary—soon to be phased out of professional use—but as *improper*. Some teachers,

* In modern chemistry teaching, calorimetry to measure reaction energies is important; and it can easily follow our simple measurements with water.

We take the idea of specific heat capacities for granted and do not labour it. Once one has left out the usual emphasis on specific heat capacity in physics teaching one is surprised to find how little one misses it. Specific heat capacities have long been routine measurements in elementary physics; but, taken at room temperature, they are not very useful or interesting. Only when we meet their *variation with temperature* for solid elements and for gases do such measurements become vitally interesting to a modern physicist, by pointing to quantum effects—but unfortunately that seems too difficult for young pupils.

Moreover, the traditional method of transferring a block from boiling water to cold liquid is out of date. It has hardly been used in professional physics since the beginning of this century. A modern method would use electrical heating—as in our Years 2 and 4—and usually electrical thermometers.

and some educational authorities, have given the Calorie such a strong feeling of impropriety that they consider that even in discussing the historical support for the Conservation of Energy we should not mention Calories in the necessary thermal measurements. Yet they say we may quite properly use a kilogram-of-water · °C as a temporary unit.

As a diplomatic compromise, we have tried to use this latter clumsy but explanatory unit for early stages in our present books—sometimes calling it a 'thermal unit'—although we expect many teachers, and pupils too, will call it, for short, a Calorie (or kilocalorie).

In Year 4, Chapter 9 of *Pupils' Text 4* is the chapter for pupils' own reading which discusses the history of the work of Joule and others that led to the belief in the Conservation of Energy. That work still provides the experimental support for the great principle.

In that chapter we adopt a special temporary name for the thermal unit kilogram-of-water · °C. We call it a '*caloric unit*' while we are carrying pupils through the conflict between a caloric theory of heat as a conserved fluid and the view which we hold that heat is a form of energy.

At the end of that discussion, when we hope pupils will agree that heat should rank as a proper form of energy, we ask that heat should be measured in joules from then onward.

The suggestion that we should not mention the Calorie did not come solely from enthusiastic support of the SI system. It also arose, earlier in the history of science teaching, from a strong plea by engineers and by scientists in other fields that we should take heat for granted as a form of energy—and no longer get into an unwelcome historical discussion.

Each of us concerned with teaching must sympathize with that view when we consider the damage to young people's enthusiasm and understanding that would be wrought by teaching out-of-date history at many points in a programme. We have only to think of our own reaction to an interlude of history in some unfamiliar branch of science which we ourselves are trying to learn. Once pupils—or students at a later age—complain that they are 'being dragged through a study of other people's mistakes', the science which we ourselves love can lose its power and charm.

However, in constructing the programme of this project we decided that the Conservation of Energy should be offered as a great generalization emerging from a convincing variety of experimental tests—and we note that some similar teaching projects emphasize historical discussions more often than we do, rather than less.

That is why we offer a chapter in Year 4 which describes experimental evidence for pupils themselves to judge.

The 'Court Sessions'

O-Level pupils Pupils who aim at O-Level should read the Year 4 chapter. Teachers who do not wish to spend time on this discussion in a busy year should note that it is offered as a chapter for pupils' own reading; and therefore any O-Level examination question* on it would be given as a test of that reading.

Other pupils Some less academic pupils prefer clear-cut statements to discussions of alternative views; and they may learn more science if we do not press such discussions. So with a wider range of abilities in physics classes we think teachers may find with their less academic pupils that only some will enjoy the 'joule' discussion in Year 4. Therefore we hope teachers will offer it to them with the flavour of 'Read this only if you like it; but there is a reward there, of understanding science.'

A Philosophical Discussion with Teachers: The Importance of Conservation Laws

Both scientists and young children look for cases of conservation: scientists in order to formu-

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* This programme of O-Level Physics differs in many places from a traditional programme in choice of topics and in treatment. Consider our inclusion of cloud chambers in Years 1, 4, and 5; our use of the fine-beam tube to measure e/m; our omission of hydrostatics and some of statics; and our use of astronomy to show the growth of theory in Year 5.

The Examiners of the O-Level Examination have respected those differences. They also respect our special attitudes, such as our development of optics by images, rather than in formal laws; and our view of atomic structure as a series of 'thinking-models'. We consider an understanding of scientists' belief in energy-conservation ranks among such attitudes. That is too important, in these days, to be replaced by assertions. We trust teachers will not be deterred by a convention of units from doing it justice.

late 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 Constants.) 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—they contain implicit assumptions and definitions. Yet they are tied to the natural world and do contain experimental knowledge though their *form* is the result of our choice.

Therefore we ought to feel uncomfortable about letting our pupils take all conservation laws as axioms; or as 'obviously true' premises for deduction, because they would lose some understanding of the quantity that is conserved and even of the nature of science—they might lose sight of the experimental basis of our knowledge.

Yet we should not crawl through several long series of experimental explorations or tests. Experiments to demonstrate conservation of mass usually look like bungling attempts to verify the obvious. Experiments to show conservation of charge, which scientists still believe in without modification, lose much of their point when we have to apologise for 'errors' due to 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, will lose 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 capable physicists for a century after Newton. If we now say it is obvious to every schoolboy, we only mean 'obvious' as a catchword or 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 phrase which *states* conservation! It is really only a catch-phrase description applied to energy after we are convinced of conservation—therefore that remark is much better avoided in our teaching. The phrase is *not* true of other things: you can get any amount of force or 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 we calculate the quantity m^4v^2 we find that its total increases in some inelastic collisions, decreases in others.

General Importance of Energy-Conservation: Modern View

Second, the Conservation of Energy has grown to be so powerful and useful that we now support it at any cost. Our belief is so firm that 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 an agricultural subsidy to maintain an essential product). *Yet as good scientists 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 that was imagined in order 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, the neutrino fitted consistently into an otherwise incomplete picture. 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.

In discussions of environmental problems, Conservation of Energy is used—and misused—again and again. It now seems more important than ever for the general public to understand the First Law of Thermodynamics—and, the Second Law also, if we can convey it with confidence and clarity.

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 to take the consequences in the picture of the world that it then enables us to draw.

Of course this philosophical comment is not something that any of us should teach in dealing with young pupils. But it gives the background for our concern over the teaching of energy.

NOTE ON THE USE OF 'WORK' TO MEAN ENERGY-TRANSFER

In this programme, we have returned to an old-fashioned use of the name 'work' in physics. We take WORK calculated by multiplying FORCE by DISTANCE as a statement of the *amount of energy transferred* from one form or place to another.

We do not use 'work' as a name for a type of energy itself. In particular, we do *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 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 that *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 outward. 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 of view. 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. That is one reason why we suggest using work for energy-transfer.

For example: we lift 3 kg to a shelf 2 metres higher. We are lifting 3 kilograms, each pulled by the Earth with a force of 10 newtons. We raise that load 2 metres, so we say the WORK is 60 newton·metres. That is true; but then we say, 'That means there is a gain of potential energy of 60 newtons·metres.' That also is true, but it is only half the story. We ought to add: 'And there is a loss of chemical energy in our muscles.'

Pupils are apt to 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 say unintentionally that energy is being manufactured. To avoid that trouble, we suggest a treatment that applies generally and easily and is more fully proof against mistakes. If we say,

'WORK *is* 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, 'WORK is our way of stating HOW MUCH ENERGY HAS BEEN SHIFTED *FROM* one form *TO* another'.

For example, a 3-kilogram lump of lead, pulled by the Earth with a force of 30 newtons, falls freely 2 metres downward. The work FORCE × DISTANCE involved in this is 60 newton·metres or 60 joules. That is the transfer of energy *FROM* gravitational potential energy *TO* kinetic energy. With beginners, we need not use such formal wording; but we should use *FROM* and *TO* in this way.

If this emphasis on *transfer* or conversion 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.

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:* the change is *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 would 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. Then we can calculate how fast or how far, for the ball.

(Quite apart from a 10% 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 might 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. Here too, we say clearly which way the energy goes, without bothering about *work done by* or *work done on.**

The Change to a New View

To pupils who say they have already learnt that work *is* energy and complain about the strange new view, we say:

> 'Think of a cheque (or a postal order) that is used to pay a bill. The cheque is not itself 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 measurable *transfer* of money. In the same way WORK shows a measureable 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 have spring balances marked in newtons so that we can proceed empirically to joules.

Even in our earliest teaching we shall measure work in newton·metres.†

NOTE ON 'PERPETUAL MOTION' (YEARS 1, 2, 4)

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.

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* To make the essential idea clear, we have carelessly linked the descriptions above to coulombs without stating the other units. If we use SI units, the p.d. (measured in volts) is the energy-transfer (measured in joules) for each unit charge (one coulomb).

† A foot·pound—meaning a foot·pound-weight—has been used extensively in engineering. It may survive for a time as an old-fashioned unit; but we suggest it should not be used in teaching.

And use of a kg·metre—meaning kilogram-wt·metre—would only store up trouble for the future.

Physics teachers should discuss perpetual motion with their pupils at various stages, perhaps beginning as early as Year 1, perhaps much later. We hope these can be enjoyable and very profitable discussions.

It is not wise to say harshly, 'Perpetual motion is nonsense. You must remember that it cannot happen'—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 what the 'catch' is.

We should discuss general 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 others 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—agreed summaries such as the 'Lever Law'—to every design of machine that has been offered; and we have been able to show that, unless our general 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 (e.g. that the Sun rises in the east day after day) and if some scheme for a great invention is clearly impossible unless it can be an exception to our most *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 firm belief. Here is a strong reason for the discussion of evidence supporting that belief which we advocate in Year 4.

We *cannot* prove that the principle is universally true throughout our world; and we should not try to do so by verbal tricks such as, '*You cannot get something for nothing.*'

Even when we have done our best to expand and support our belief in Conservation of Energy, pupils will bring suggestions for perpetual motion machines and we should be sympathetic and comment on them gently.

'Perpetual Motion' *versus* 'Perpetual Movement'

Pupils' suggestions Some of the arguments or plans that pupils 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.*

Perpetual motion In physical science, a 'perpetual motion machine' 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 back to the input to provide the input-energy for the machine itself—and the rest available for our use—a surplus of energy delivered to drive a car or run a power station or do 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 gas under it to provide an almost frictionless bearing).

It is such examples that pupils quote, asking anxiously if perpetual motion is not, perhaps, almost possible after all. 'It only needs better oil!'

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 confusion.

To claim that *perpetual movement* would be the same as *perpetual motion* but for the practical effects of friction would be to miss the essential distinction entirely.

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 the machine—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 to young people; and they offer that as a perpetual motion. It is almost 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 together against each other on a test bench like that by manufacturers, with only a small extra supply from an auxiliary generator to make up for the heating losses that would prevent perpetual movement.

NOTE ON GETTING TIRED WHEN HOLDING A STATIONARY LOAD

When we think of food providing energy for a useful job, we all 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 more 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 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 not any FORCE × DISTANCE?'

In answer, there are two separate things to be explained: 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 make muscles contract to exert a force, they squeeze the neighbouring 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 nearby 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* arises from the mechanism of muscular action. A muscle is a bundle of many fibres. Each fibre can develop tension as it contracts and swells. It can do that very quickly, taking some chemical energy to make the mechanical change.

But an individual fibre cannot maintain tension for long. It soon relaxes and releases the energy it took. It cannot repay that energy which it took as chemical energy: it releases it as heat.

When nerve impulses arrive instructing a large muscle to contract, fibre after fibre is fired into tension and each fibre soon relaxes and later renews the tension in turn, again drawing on chemical energy.

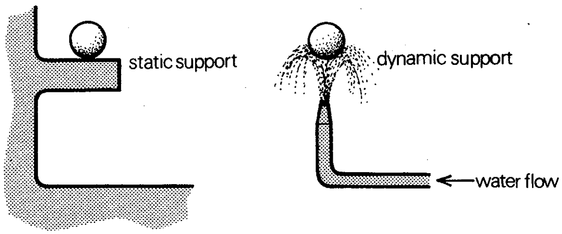
So the steady pull of the muscle is really the sum of many brief tugs. We might call this a *dynamic* force, like the force made by air molecules bombarding the wall of their container,* in contrast with a *static* force such as the pull of a stretched steel spring—though even the latter might appear to be the 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 vertical jet of water supporting a ball with a dynamic force.

* The pounding molecules of gas never experience fatigue because at each impact they bring in energy of molecular motion (which we may call heat) and carry it away again.

As with the jet, there is a continual conversion of energy into heat; but, as with the jet and the ball, the muscle can respond amazingly quickly to commands.

Thus, there is a continual output of heat from a tensed muscle. This waste output increases surprisingly little when the muscle is made to do external jobs as well. (Of course for those jobs an extra amount of *chemical* energy is taken.)



The pull of a muscle, the sum total of the fibres' pulses of force, 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.

SECTION VII
CHANGES IN SCHOOL STRUCTURE AND THE PHYSICS PROGRAMME

The Original Programme and its Use

The programme was formed and published in the '60s as an O-Level physics programme for Grammar Schools. It was joined by similar programmes in Chemistry and Biology.

Those were followed by suggested A-Level programmes which we hoped would benefit from a pupil's start in O-Level Nuffield sciences, and would continue the 'Nuffield spirit' of teaching for understanding. Those advanced programmes were designed to draw upon some Nuffield O-Level equipment and knowledge.

Early trials Trials of the O-Level Physics programme brought a rich stream of commentary and suggestions from teachers in feedback, which was welcomed and used in preparing the first commercially published edition of the *Guides*.

Most of these trials were in Grammar Schools with pupils who had reasonable prospects of success in an O-Level examination.

Some of the trials were in Secondary Modern Schools usually with medium or fast streams. In those schools teachers soon found they needed to make modifications; and the yearly tests provided for trial schools seemed to receive unacceptable answers—until we learned to read those answers with the pupils' less mature vocabulary.

In view of the change to a Comprehensive pattern, the experience of those trials in Secondary Modern Schools is of importance now.

The original programme in Secondary Modern Schools In Years I and II, most of the activities were simple experimenting for acquaintance; and teachers could easily make adjustments of scope, even of aims and of teaching method.

Year III—where we intentionally asked for more careful experimenting and some reasoning—was harder and less interesting for many Secondary Modern pupils.

Year IV with much stronger demands in thinking—demands of abstracting, reasoning and imagining, also some elementary algebra—proved altogether too discouraging for most Secondary Modern pupils.

In describing that near failure of our programme's later years in Secondary Modern classes, we *do not* say it was due to less ability—who can tell, by a brief attempt at teaching a sophisticated science, which boy or girl will prove in the long run bright and which will not? We *do* say there are differences of *interest*. Science can be thrilling and offer success in learning to a great variety of pupils. But some will have great interest in the thinking as well as doing—in reasoning and imaginative discussion—while others will enjoy the doing and the acquiring of information.

Teachers, anxious to continue with 'Nuffield Physics', made modifications that they found necessary. Looking back on those early modifications in Secondary Modern Schools, we see that in many cases the teachers rescued Nuffield Physics from disappointment and failure by making drastic changes of treatment, while keeping most of the apparatus and experiments. In those schools, 'going Nuffield' often meant adopting the apparatus, getting rid of the questions, providing detailed instructions, and loosening the intellectual demands very largely. There was sensible use of fill-in sheets to cope with the arithmetic that seemed to be required.

Those were noble rescues, at a time when Nuffield Secondary Science had not emerged; but they did not prepare for the Nuffield O-Level examinations and they missed major aspects of the 'Nuffield spirit'.

We were glad when some Nuffield physics was put to those new uses; but sorry when the new uses were also claimed to be a full replacement of Nuffield physics for able pupils.

And we were very sorry when some C.S.E. examinations followed the Nuffield O-Level questions closely but accepted fragmentary answers—we knew that a different programme with a relevant examination would be much more humane and would contribute so much more to the pupils' lasting knowledge.

In a matter of labels, it seemed misleading that such modified programmes should be called 'Nuffield O-Level Physics'. Yet nowadays in the Comprehensive pattern some such changes provide the hope of continuing our programme.

Nuffield Secondary Science Recognizing the different needs arising from different interests, the Foundation sponsored an entirely different programme, *Nuffield Secondary Science* (Longman, 1970) to be offered to Secondary Modern Schools as they then were. That course is simpler, more factual, more careful in its vocabulary; and it is a magnificently constructed *integrated* programme.

The New School Pattern

Comprehensive Schools The Comprehensive pattern has grown, with obvious advantages, but also with serious difficulties for the original Nuffield single-science programmes in their later years.

Years 1 and 2 can go well in a group of pupils with a wide range of ability—except for the demanding questions. Nuffield Combined Science which includes much of the physics of our Years 1 and 2, can go very well too—though it lacks both the stimulus and the discouragement of our main questions.

If it were not for our new provisions, Year 3 would lead a class of mixed abilities to more disappointment than success.

Years 4 and 5 present a different picture. They are likely to be taken in the future, as in the past, mostly by pupils ready for an 'O-Level treatment'. Yet there will still be many with uncertain plans; so some modifications will still be needed.

Revising the O-Level Programme

What should be our policy for classes in Comprehensive Schools? In commissioning revision, the Foundation decided that the general standard and aims, the attitude of the O-Level programme, should be kept. Such a programme may now seem ill-fitting or little needed; but the Foundation considered that there may well be needs for it in the future. And the present flow-rate of 20 000 pupils a year through the Nuffield O-Level physics examination suggests that a need may remain in the near future.

Yet we have kept the Comprehensive pattern strongly in mind in our revision. We have made some modifications and we trust teachers will make further choices and changes.

Teaching Nuffield physics today We hope teachers will find the *experiments* of Nuffield programmes as useful as ever; and we hope they will let the 'Nuffield spirit' influence their teaching as far as that seems suitable.

As we are maintaining the general standard of study and enquiry in the Revised O-Level Programme, the honest suggestion for a class of pupils *not* aiming at O-Level is *'Try Nuffield Secondary Science.'*

With a class of mixed abilities, the same advice may well be the best. But various forces are pressing some schools to continue Nuffield O-Level physics—hopes of parents and pupils, plans and preferences of teachers, and even a recently grown tradition of 'Nuffield spirit'.

So, in revising the O-Level programme, we must also provide for those pupils in a mixed band who have less academic skill or interests. *We suggest they should do the same experiments.* They will enjoy the doing of them—if given longer time when they need it—provided there are far fewer demands of concomitant reasoning. Those demands can be lightened by omitting our 'Nuffield' questions.

The Nuffield questions The questions of the original Nuffield *Questions Books*, with some additions and some omissions, are now printed in the *Pupils' Texts* in boxes, each headed 'Questions'.

Those are the questions for O-Level pupils. Most of them were written originally by Dr Henry Boulind, who was one of the two chief examiners for Nuffield O-Level Physics. They were designed to promote reasoning and imaginative thinking. In revision we have simplified their wording but have kept their academic demands.

They are the questions we still recommend as preparation for O-Level examinations. And if O-Level examinations were to disappear, we should still recommend these questions as *essential learning aids* for pupils following the full form of the programme.

In view of our aims for those questions, the *Pupils' Texts* do not contain answers to questions, any more than they give full statements of the results of experiments—aids which would save pupils from doing and thinking.

(If pupils need those aids, there are well-made books commercially available which will lead pupils through the 'syllabus' of Nuffield physics without worry—but also, we fear, without the pride of understanding, the stimulation, the wonder and delight, the intellectual satisfaction which we hope the Nuffield spirit entails.)

Easier questions needed In feedback advice for revision, teachers of O-Level classes supported the keeping of the questions but almost all asked for some easier questions as well: simple straightforward ones to give each topic an encouraging start.

Progress questions Coupling that request with the less academic pupils' need for questions of quite a different flavour—more factual, more direct, leading faster to success—we decided to provide an *alternative* set of questions. Four experienced teachers, familiar with teaching physics to Secondary Modern classes, constructed a large bank of such questions, and then sorted out the best collection. We call them 'Progress Questions'.

The Progress Questions are printed in the *Pupils' Texts* in boxes headed 'Progress Questions'.

The questions and pupils' plans In the *Pupils' Texts* we give no statement of the difference between the two kinds of questions; but teachers should bear the difference in mind. They may need to explain it to parents and possibly in some gentle way to pupils.

The progress questions are *not* suitable preparation for O-Level examination questions—their standard and nature may even be misleading in that respect. A pupil who finds the progress questions easy and the main questions puzzling and unpalatable may need some warning if he or she is intent on trying O-Level.

ADVICE FOR USING OUR REVISED PROGRAMME

If, instead of being a programme for pupils in 20% to 30% of the school population's 'ability range', our programme is to be used by 50% to 70%, there *must* be general modifications.

We trust each teacher will make his own changes to fit local circumstances; so we suggest only some extremes of treatment—assuming that teachers will construct many intermediate forms.

PROGRAMME FOR ACADEMIC PUPILS AIMING AT O-LEVEL

The experiments: carried out by pupils without cookery-book instructions;
The reasoning that we have suggested (some of it now in the *Pupils' Texts*);
The main questions: essential for learning.
And, occasionally a few progress questions.

THE CHIEF AIM *should be clearly told to pupils: doing and thinking, to learn for understanding, with a sense of success.*

PROGRAMME FOR PUPILS WHO HAVE OTHER INTERESTS AND DO NOT (OR SHOULD NOT) AIM AT O-LEVEL

The experiments, taken more slowly if that helps; with simple instructions offered;
Reasoning not insisted on;
Any arithmetic either omitted or done by the teacher;
And the progress questions.

THE MAIN AIM: *for pupils to enjoy doing science and collecting scientific information, with a sense of success.*

WORK CARDS . . . PUPIL TEXTS . . . PROGRESS ACTIVITIES

Work cards? We have discussed with many teachers the practical problems of teaching a mixed ability group. We are sure there is no single solution, such as work cards. Work cards are regarded as a strong help and palliative; but can they be fruitful if they are uniform, the same for all members of the class?

Suppose that in our science teaching, instead of trying to make all pupils *learn alike*, we aim at helping all pupils to *be alike in learning contentedly and gaining a sense of success*. That would unquestionably mean different work cards for different pupils—an impossible task if each teacher or school is to make them. What can be provided from outside, without spoiling the teaching? How would such materials be used?

In theory—to those of us who are not using them—work cards give short clear words of help to keep slower pupils going. In practice, they give condensed, often profuse, instructions to enable fast pupils to go ahead with their work while the teacher helps slower pupils individually. On that view we are providing a substitute for work cards in the form of our *Pupils' Texts*. The way in which work cards are often used is not due to misguided discrimination by teachers: it results from the actual abilities and speeds of reading. For slow readers, the work cards usually suggested are only frustrating, with their profusion of words.

And for other pupils short sentences of short words tend to make suggestions look like instructions and make instructions look like commands.*

* 'We found instructions on every worksheet that we looked at: What to do—What to write—Write—Explain—Give a name—Look—Copy—Collect / fetch—Stick—Read—Label—Put—See what happens—Think about—Make a list—Draw—Add—Go and talk to another group . . .' Many of the worksheets were strongly coloured by this regulative tone. At its best, a dialogue seemed to be set up between the writer and the reader as if the teacher were talking directly to the pupil. . . . At its worst, the total effect was a kind of relentless sergeant-major battery of instructions: 'Collect . . . Observe . . . Write . . .'

From the booklet *Writing in Science. Papers from a seminar with science teachers,* Schools Council/London Institute of Education, January 1975. Obtainable from the Project Secretary, Writing across the Curriculum, Institute of Education, 36 Bedford Way, London, WC1H ODB.

We hope teachers will consult this human, helpful report of educational experimenting.

Pupils' Texts instead of Work Cards

For fast pupils heading for O-Level, our *Pupils' Text* books *are* our work cards: bound together in an organized mixture of instructions, suggestions, discussions, and questions.

Any significant reduction of those books to work cards would deprive abler pupils of learning for understanding by *doing and thinking*; and for those pupils the 'Nuffield spirit' would have died out of our teaching.

For slower pupils, we hope teachers will make extracts from our instructions.

For pupils with poor reading speed or ability, there is a need for experiments that require no written instructions: experiments that can *start* with a teacher showing a specimen, or just offering a picture, and then continue as interesting activities. Such *progress activities* are not in the main line of our programme; they are not examinable; they should not be interrupted, or followed, by questions.

We suggest small collections of apparatus to be worked with. Each collection should provide opportunities for interesting experimenting which can extend from simple beginnings.

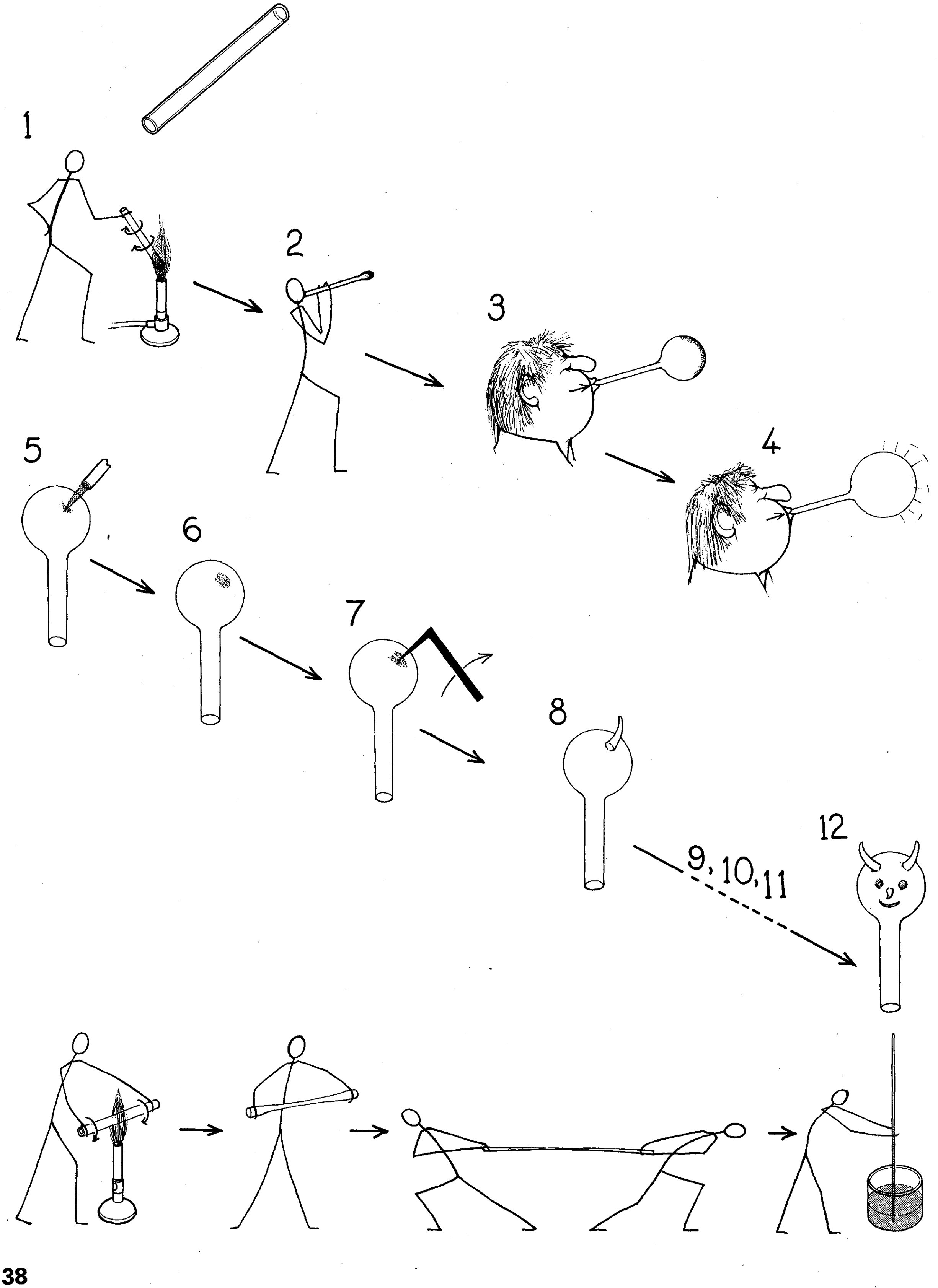
(Teachers may need to warn O-Level candidates that these are happy diversions which would not contribute to the main course in proportion to the time they take.)

Progress Activities

We offer a few suggestions below, with the hope that teachers will find others suited to their pupils' tastes and the lab's resources.

GLASS BLOWING. Needs: bunsen burners, soft *soda* glass tubing, bits of iron wire, asbestos table mats. The only warning necessary is: 'Avoid blowing a bubble of over-heated glass out into thin paper-glass like this. The thin bits float in the air and may be bad for lungs.'

(We should not expect much success, except in making and trying capillary tubes; but even unsuccessful work with glass is satisfying; and it exerts a simple impersonal discipline—it's no good being angry with glass.)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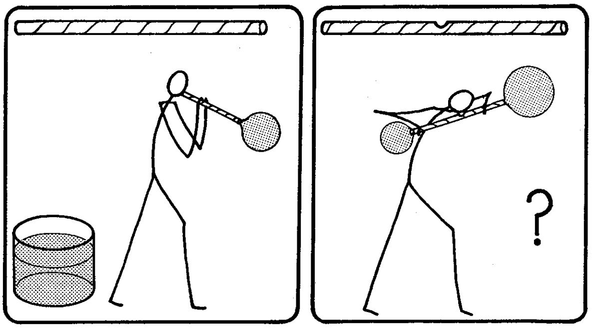
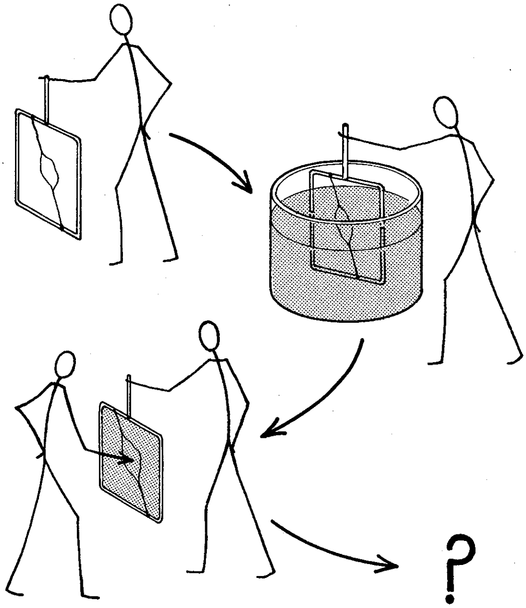
Soap films. Needs: soap solution, wire to make frames, drinking straws, beakers to cover lasting bubbles. Show specimen wire frames. Offer threads to tie across frames. Show how to bend and pierce a straw so that a bubble can be blown on each end.



Magnetic fields. Needs: many shapes of magnet, paper, iron filings, nails, scrap paper.

Monochord. Needs: a taut wire, with wood blocks to act as bridges. A hand stroboscope will help.

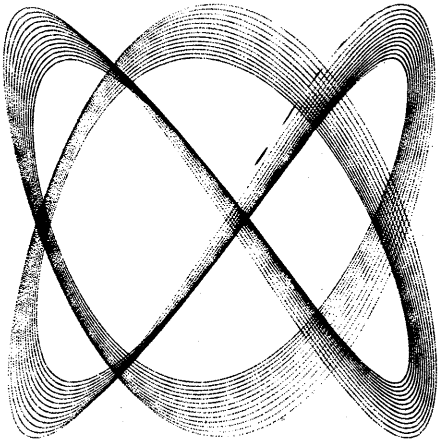
Class oscilloscope with microphone. 'Bring your own musical instrument or try your voice.' Pupils who are learning a foreign language will be amused to try different vowel sounds, and can profit greatly.

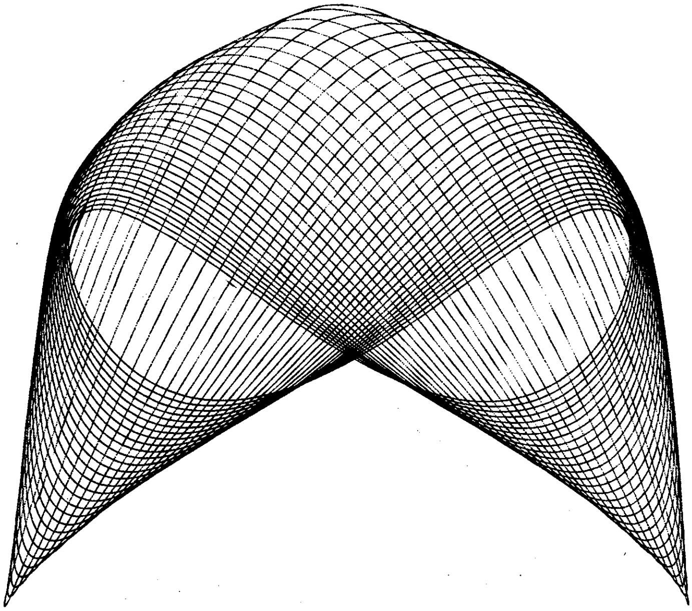


Lissajous figures. Needs: two heavy pendulums, one with a table on its upper end, the other with an arm to carry a ball-point pen. The pen falls by its own weight onto paper on the board. The pendulums must be set up beforehand; but making the designs has an unending attraction.

(If an oscillator is available, the figures can be made on an oscilloscope. Apply oscillator's output to Y plates; a sample of mains a.c. to X plates.)

(A thin rod of *rectangular* section firmly clamped in a vise at one end will make Lissajous figures with its free end.)





SECTION VIII
PRACTICAL ASPECTS OF TEACHING THE PROGRAMME

Following the Programme

Teachers ask whether the programme given in the *Guides* is intended to 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 certainly do not boast that our programme is ideal or unique. But we do remind teachers that it is the outcome of considerable work in building a connected scheme whose structure and aims become more fully apparent as one teaches one's way through it.

Both from earlier trials and from recent consultations, it is clear that teachers view the nature of a year of this programme quite differently in retrospect, at the end of the year, from their plans at the beginning. Many insist that in a second round they wish to follow the programme again in much the same form, using their experience to modify the amounts of emphasis and proportions of time.

After that, if not earlier, they should construct their own teaching programme.

Thus we hope that teachers who know our programme well and like it—its suggested aims and methods even more than its contents and equipment—will make changes to their hearts' content. Yet we do plead with newcomers to examine the structure and aims of the programme carefully first.

We believe that our programme is an organism rather than a collection of separate items. As one commentator says: 'If you chop out pieces, it bleeds.'

Thus, for the general good of education in science, we offer our suggestions of changes in aims and methods as much more important than changes of content or apparatus.

Extensions

So far as our programme aims at O-Level, it does not branch out into options or alternative channels. Branching might lead to difficulties both in administration and in examination arrangements; but we do wish to encourage special interests. We hope that every teacher will develop his own teaching scheme and sometimes follow some particular branch which interests him or his pupils, even though it diverges from the main tree. Such excursions along small branches often stimulate the best teaching and learning. From time to time in our books there will be suggestions of possible extensions.

The main tree—the general framework of the course—is suggested for all who are ready for a full O-Level programme. It was designed to build connected knowledge; and it will do so for pupils who follow its five years.

The Label 'Optional'

Optional experiments in these *Guides* In our revision we have labelled clearly the few experiments and topics which—for one reason or another—fall outside the normal scope of our programme. We have labelled them *OPTIONAL* in the *Teachers' Guides*. It would not be fair to have questions directly on those items in Nuffield O-Level examinations.

Nevertheless we recommend some of those optional items as useful extensions for fast pupils; and others as attractive excursions where the school has some special apparatus or the teacher and pupils have a special interest.

'Optional but contributory' Many an optional item could be regarded as *optional but contributory* meaning that, although it would not be examined directly, a candidate might perhaps use his knowledge of it to illuminate his answer to some general question;* and in Nuffield O-Level marking he or she could certainly receive bonus marks for a relevant addition.

'Optional now' The label *optional now* has a different meaning. It does not mean the item is optional in the sense described above. It means the item *may be postponed*, say from Year 3 to

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* As an example from another subject, suppose the 'set book' for an English paper is *Macbeth*. There should not be a question on *Hamlet*. Yet a pupil who wrote a good answer about Macbeth's fighting and then added a relevant comparison with Hamlet might well receive a bonus mark—in the type of marking used for Nuffield examinations. A pupil who also quoted Winston Churchill's war history in a relevant comparison might obtain a further bonus.

Year 5. We use this label quite often to help teachers to make choices in the earlier Year, in terms of pupils' interests and speeds.

This discussion of the examinations which our pupils may find ahead is intended to offer both the necessary assurance which teachers need if they are to take on this different kind of teaching and a warning that it may be very unwise, from the point of view of an O-Level examination, to take on only a fractional version of the programme.

Coping with Experiments in Class

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 some pupil who has paused to think. Most teachers are used to getting pupils through the experiment by the end of the period. Yet in this course, one experiment done by a pupil on his own is worth more—in understanding science—than five done quickly under efficient guidance.

Our main hope is that teachers will encourage pupils 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 trust 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 full directions?'

Two difficulties will arise:

(i) Faster pupils may run far ahead of slower ones. Teachers should have good questions ready or suggestions that will lead on to further experiments—usually new ones rather than a more accurate repetition of the one the pupils have done. Such 'buffer experiments' can 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?*' There, we are appealing to self-respect.

(ii) Lazy pupils will get little done. This is a difficulty more feared by critics beforehand than by teachers in a real lab. Perhaps that is because an open lab 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. For fruitful experience, a pupil needs some drive from within—which an open lab can encourage. A teacher's skilful drive from without may carry the lazy pupil through an experiment, but it may contribute little to his understanding of science.

Sharing a class experiment: how many in a group? Sharing apparatus may promote co-operation, but it may cheat pupils of the personal involvement they deserve.

Consider other kinds of sharing. Think of four beginners having to share one piano all at the same time, or two children sharing a bowl of soup with a single spoon between them, or a young poet hurrying through his writing because there is a queue for the only 'poetry desk'. Good sense objects; and common sense suggests the cures.

How much sharing is good in a physics lab?*

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* If the reader finds this questioning absurd, he is lucky to have missed the 'economy lists' which have been suggested (and published), where eight children share a Nuffield class experiment. Where funds or skills are lacking, or traditions prevent, quite a different programme would be fairer: a few simple demonstrations by the teacher and a few *very* simple class experiments with 'string and sealing wax' can start to build the good name of science.

Young pupils in a group of mixed abilities, learn in various ways at differing rates. A circus of different experiments with a few pupils at each may do well occasionally, but it makes great demands on the teacher, who must also be concerned with guidance and safety. That is why we suggest that there should be enough equipment for all the class to do an experiment at the same time—though with individual differences of treatment.

Best of all, some experiments form a long series through which pupils progress at their own rates.

Slower pupils may make different use of an experiment or complete fewer parts of a series; but by having the same equipment for all we provide a needed sense of 'equal opportunity'. (Then it *can* be equal opportunity for *satisfaction* rather than opportunity for equal *coverage*.)

Unless the teacher is especially lucky—e.g. having a small class—a general 'circus programme' is inept at this level. At the other extreme, a uniform scheme with every pupil working *alone* at the same experiment would be unsuitably expensive too.

Two pupils can work together with considerable benefits. In a group of three or four, pride of possession is harder to come by; and even such a small group may detach an unconcerned spectator.

Therefore we recommend pairs for nearly all class experiments. We suggest groups of four only where *space* restricts the number of sets.

Kits For a class of 32, we therefore suggest a 'kit' of 16 sets of apparatus for a class experiment. It is the factor 16 that makes Nuffield apparatus expensive—£6 for a single set would seem moderate, but £100 for a kit makes a big bill. Yet we believe the kit is not only worth while but essential for pupils to learn with a Nuffield spirit. We want to get the apparatus into the hands of pupils to let them get the feel of science, to experience finding out for themselves.*

Other Aids

Demonstrations Sometimes we suggest a demonstration, to save money and to save time. (If pupils did every experiment themselves we should never get through the course.)

Films Only where a demonstration is not possible should we resort to a film. Films are farther from personal experience and should not be allowed to become a substitute for live demonstrations or a cheap way to avoid buying apparatus.

Insurance for Apparatus borrowed to take Home

To encourage home experiments by pupils as an important educational activity, a small private fund is available to underwrite the possible loss or damage of apparatus while on loan. *This is a serious offer to Nuffield classes.*

A valuable link We hope teachers will sometimes allow equipment to go home for an evening or a weekend. An experiment taken home can establish a very important link with parents. To parents our programme may seem strange and new. Many a parent has doubts or questions which are best answered by seeing at first hand what we are doing. A home demonstration is the best ambassador.

Where apparatus is used by several class groups, it may be impossible to let it go out during the week; but we hope teachers will let it out for a weekend. (Those who provided the Fund have reports of good ventures; but they are saddened by uniformly negative reports from boarding schools.)

During Year 3 we hope that the *simple telescopes* will be taken home by pupils who wish to show them. Also the full equipment for *ray streaks*. The latter would have to include the transformer and lamp; but, though heavy, those are not likely to suffer much damage. The lenses need care so obviously that they are likely to be treated very well on loan.

The 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.

The insurance fund is intended to make it easy to enable schools to allow such loans.

Reimbursement Where a school lends items of apparatus to a pupil to take home for

* Manufacturers have offered 'economy kits' of $\frac{1}{4}$ size; but, in most cases, if pupils therefore work in large groups so much of genuine learning will be lost that '*no kit*' is a better Nuffield recommendation than '*quarter kit*'! Missing an experiment will not deprive pupils of Nuffield spirit, but crowded spectator groups will hamper participation and may do damage.

experiments and finds that they are not returned or that they come back damaged or broken, teachers should apply to:

The J. Willmer Home Experiments Endowment, c/o The General Secretary, Association for Science Education, College Lane, Hatfield, Herts. The General Secretary, administering this fund, will only ask: whether the apparatus went on loan with permission, whether the class is following a complete year of Nuffield O-Level physics, 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.

Written Work

Records of experiments A pupil's own notes, written informally like the notebooks of most research physicists, 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 uncouth to a child as it does to a research scientist. Nor does he gain much of lasting value 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 should be one to be kept and treasured.

In the early years, some experiments are best 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 'we enjoyed it'; and in some experiments a formal conclusion would be equally out of place.

How questions help Questions leading towards an experiment can save teaching time by preparing for it. Questions after an experiment can reinforce its outcome and extend pupils' thinking.

Other types and uses of questions 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 for regurgitation 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, part of the pupils' learning.

The Nuffield teaching questions A large collection of questions is provided in the new *Pupils' Texts*. Many of those questions are taken from the first edition *Questions Books*. These questions are intended to stimulate thinking and help to build knowledge. Since they call for understanding, answering them should be good preparation for O-Level examinations.

(The *progress questions*, described on page 36, do *not* offer that preparation.)

Pupils' answers In marking answers to the main questions, one should remember their objectives: to encourage thinking and to test general understanding. One needs to be very flexible in accepting unusual answers. One should be ready with praise for sensible thinking and use of imagination even if the result is not technically correct.

General descriptive enquiries Although we ask for some of the precise calculation characteristic of good physics, we should also encourage pupils to write general accounts of some experiments, and make critical comments on experiments. And some questions should be 'open ended'.

Open questions invite pupils to think *round* the matter rather than in a straight line from question to answer! They give pupils a chance to realize that speculation is an important aspect of scientific thought.

Asking for rough estimates And sometimes pupils should make rough estimates, even using imaginative 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 rough guesses, we quote a note by Professor Philip Morrison, now of Massachusetts Institute of Technology, concerning 'Fermi Questions'.

'. . . It is by no means possible to specify the training and readiness of a prospective [post] 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 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. . . .'

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.'

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

Professor Morrison gave examples of Fermi's own questions and some similar ones. Most of those would be too hard for the young pupils in this programme. But the same game of combining a little practical knowledge with imagination can be played by young people if we choose problems that fall within their experience.

Pupils will need encouragement and some discussion in class at first, because they will hesitate to make rash guesses in what they consider is a precise science. However we should assure them that such guessing plays an important part in research in physical science, and particularly in astronomy. It is something for which pupils should develop a taste and some skill.

Here are some simple questions—these and others will be found in the *Pupils' Texts* preceded by a 'worked example', to illustrate the kind of guessing + reasoning that such a question asks for.

How many teaspoonfuls are there in a cup of tea?

How long would 100 heartbeats take (when you are not frightened).

How many dogs are there in your town?

How many pencils are there in a kilogram of pencils?

What is the speed of a sparrow in flight?

What is the heaviest basket (airline bag, etc.) of books you can comfortably carry to school every day?

What is the average lifetime of a bird?

How many teachers are there in the schools in your town?

What is the volume of water (in cubic metres) in a swimming pool?

What is the WEIGHT (in newtons) of a small car?

Quantitative Work: Patterns . . . Abstract Concepts . . . Proportions?

Looking for patterns Finding a law is far more important, and nearer to professional science, than learning to state it. Sometimes, even using a law without understanding its origin seems weak science.

But in the early years, we should be making a relentless uninteresting demand on abstract reasoning if we asked children to extract a law of levers from see-saw experiments or to see Hooke's Law in a graph of stretching a spring.

Coaxing a summary from them may be much easier and more satisfying. ('Can you find a *story* . . . the magic secret of all balanced see-saws?' 'Why was Robert Hooke so pleased?') We have to make the puzzle attractive.

Many discoveries of laws—or rules, or stories of the way things behave—begin as glimpses of simple proportional or linear behaviour. Is such a glimpse immediately attractive to the young investigator? Is he thrilled with it? Hooke was thrilled, and jealous of his priority; Boyle said he found his law 'not without delight and satisfaction'; but they were ready to appreciate the simplicity of mathematical form. If our pupils are to experience those pleasures, they must already know and understand the essence of such form: proportionality.

A Feeling for Proportionality

Much of our knowledge of physics is expressed in the form of proportionalities. (See also the note below 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.

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, with only moderate success—the stumbling blocks often remain.

Some critics suggest that we have in physics good examples with which to make a fresh start and teach proportionality successfully; and that we should not assume previous knowledge or skill. Instead, we should start by explaining very carefully what proportionality is and how to use it, before we involve it in codifying our knowledge of physics. For teachers who wish to experiment with such a preparation before using it for Hooke's Law, Newton's Law II etc., we offer the following comments.

Simple examples Start with simple examples of proportionality as a relationship, in which some quantity A doubles, triples, etc., when another quantity B does. For example:

COST OF A BASKET OF EGGS *versus* NUMBER OF EGGS

MASS OF POTATOES eaten per week *versus* NUMBER OF MEN in an army camp

MASS of copper wire *versus* LENGTH of wire

AREA of a square *versus* $(\text{SIDE})^2$

MASS of copper wire *versus* $(\text{DIAMETER})^2$

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.*

Graph With the help of the graph, point out another view, that if A varies directly as B the ratio A/B keeps a constant value—it is the slope of the graph line.

Constant ratio In many uses in science it is the *constancy* of A/B rather than the particular *value* of that constant ratio 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 applies to many different wires but the *value of the resistance* applies to a particular wire.

A stumbling block Since we are aiming at using proportionality 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 unitary 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 kilometre long, one metre deep and one centimetre wide: that result then to be built up by mystical multiplication and division into the required answer for the time needed by many men to dig some huge ditch.

That method, which often failed as a rival to clear-headed skill, carries pupils far away from a simple feeling for proportion. Instead, 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 a 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.

Another stumbling block In our first discussions we have not emphasized the value of the proportionality constant, the actual 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 foster a clear understanding—so we should avoid it as far as possible.

Use common-sense feeling 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 km instead of 50 km multiplies the time by 200/50, therefore *4 times as long*. The TIME needed *goes inversely as* the NUMBER OF MEN. It goes as 1/[NUMBER OF MEN]; so 4 men instead of 12 men makes a factor of 12/4. They will take *3 times as long*.'

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 mankind in an attempt to find simple relationships first. Therefore, there is 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 examples to the contrary, even some flippant ones.

a. A spiral spring of steel wire is hung up and loaded.
Its length with no load is 10 cm.
With a 1-kilogram load its length is 12 cm.
With 2-kg load, 14 cm; with 10-kg load, 30 cm.
Is LENGTH directly proportional to LOAD? What has happened?

b. A camp needs each week:
220 kg of potatoes when it houses 100 guests
420 kg of potatoes for 200 guests
620 kg of potatoes for 300 guests.

Why is the potato supply *not* directly proportional to the number of guests? (The answer is not spoilage—which is likely to be a constant fraction—but the silly story, 'We have forgotten the permanent kitchen staff, who need 20 kg 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 cm high with no load.
With 1 kilogram on the piston, the spring is 15 cm high.
With 2 kg, the spring is 10 cm high.

As pupils have 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 we pretend it remains frictionless and has negligible weight). The air enclosed in the tall jar is now the 'spring' to be experimented on.

With no load, the piston is 20 cm above the bottom.

With load 1 kilogram, 15 cm above. With load 2 kg, 12 cm above.

We ask the same question.

(This is of course a Boyle's Law story for a tube of cross-section about 3 cm^2 so that atmospheric pressure provides the equivalent of 3 kg *extra* load all through. This should not be used to divert a treatment of proportionality into a discussion of 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 a very fast group for the height with load 3 kilograms, 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. In a recipe which makes approximately 20 biscuits the cooking time is 20 minutes at 375 °F. If I halve the recipe and make about ten biscuits, how long should I cook them?

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

g. A fence consists of light wire netting with a thick wooden post every 2 metres. The fence runs along one side of a field. It has 10 posts. How many posts would a fence twice as long have?

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

i. A current of 5 amps driven through a certain resistor immersed in 1 kg of water warms it up 3 °C in 1 minute. How much would a current of 10 amps through the same resistor warm up the same water in the same time?

The Remarkable Role of the Word 'Constant' in Science

Young pupils think science consists 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 appears strange and difficult to young pupils if we put it to them too early or in too formal a way 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. The theory may yield predictions, or increase our sense of understanding.)

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 when they name abstract qualities, and are involved in 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 '$p \cdot V$ is always constant'; or 'constant $p \cdot V$'; but they state Boyle's Law in a much fuller form. 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 scientific 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, that always give 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 the quantity MOMENTUM or ENERGY—in fact it is chiefly because we find constancy that we take the trouble to give a name to 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, and for increasing our understanding of nature. No wonder the conservation laws are very important; and, when we extend 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.)

In teaching young pupils we should not surround the conservation laws with heavy mysterious insistence, but we should praise the general idea, saying: 'The total stays the same through thick and thin; and that will help you to keep track of things in experiments, in engineering, in making predictions, 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 those things in his environment that stay the same or repeat in the same way.

Starting to Teach this Programme

Nuffield teaching takes extra time: preparing apparatus beforehand, teaching classes, then reading the descriptions that pupils write. This is the burden of a programme of teaching for understanding. It is a heavier burden still on teachers carrying out a first trial in a school.

We hope the initial 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 suggested teaching approach.

During the original development of the Project, there were in-service courses of this kind for teachers in the trial schools, conducted in association with the Department of Education and Science. Such courses for this programme continue to be offered by colleges and science teaching centres; and we hope that teachers who wish to embark on the programme will be able to attend one, both for work with Nuffield apparatus and for discussions with colleagues.

SECTION IX LABORATORY

Preparation of Experiments by Teachers

Physics is an art as well as a science: an art of understanding nature; and so is physics teaching: an art of 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 acting freely yet 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. The reason 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 first-hand 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 like ones already 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 his own comfort, we urge every teacher to try out the new 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 1)*. 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 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 make sure the tray is cleaned or suggestions of what to say if a child finds leakage round his boom can ensure a successful class experiment with proud pupils, as will a previous trial.

EXAMPLE B: ELECTRIC CIRCUIT BOARD KIT AND ELECTROMAGNETIC KIT *(Years 2, 3, 4, 5)*. 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 2, 3, 4, 5)*. 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 discipline the electron stream and give a very valuable demonstration. Pupils should share the teacher's delight in this wonderful experiment, rather than sense the anxious feeling that any of us have when demonstrating an unfamiliar piece of apparatus in a half-dark room.

EXAMPLE D: RAYS AND IMAGES *(Year 3)*. Where the apparatus carries with it a new approach, trying it out beforehand is even more important.

It might seem safe enough to ask the pupils to get out lamps, shields, slits, and cylindrical lenses, and then 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 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 group of experiments does need extensive trial beforehand. A first quick look at a pinhole camera or at cylindrical lenses and rays will give an impression that the whole series of experiments is easy but rather vague and unproductive. Only if one works through the whole set can one discover their potentialities as well as their minor difficulties.

(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 in 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.)

(ii) Fan of Ray Streaks. Again, if one has tried the first experiment of a fan of rays hitting a *strong* cylindrical lens, one is ready to guide a pupil into treating the aberration of the outer rays as a minor interesting trouble—and perhaps to ask, 'Is it the same if you turn the (plano-convex) lens the other way round?'

(iii) Telescope Ray Model. And again, a teacher who has set up a ray-streak model with two lamps as remote objects for a simple telescope knows how to get pupils to try it fairly quickly. And when the model shows the obvious 'eye-ring' he is ready to say: 'Now go back to your real telescope and see it 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. This is often best done by placing that apparatus ready on a side bench. Pupils can help themselves to items, use them and then return them.

This method is of great help in, e.g., work with the Worcester circuit boards (Year 2), ripple tanks (Year 3), the ray streaks (Year 3).

Safety screens Whenever a teacher gives a demonstration with something 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 about 1 metre high by 60 cm wide. That is not so wide that he cannot reach his arms round from behind and manipulate the apparatus; and it is high enough to shield his face. The sheet between the apparatus and the class should be about 75 cm square. These sheets (of 1.5 mm Perspex) should on no account be framed for that would spoil the feeling of full transparency. They could well be supported by pairs of slotted bases.

Ordering Apparatus

The Nuffield Physics *Guide to Apparatus* gives descriptions and suggested quantities of all the equipment involved in the programme. The original edition of that book is still available; and since we have not made many changes of equipment we have not produced a revised edition of it. Instead we are issuing a correction sheet, listing all the changes. That can be obtained from: The Association for Science Education, College Lane, Hatfield, Herts.

Teachers will find two other sources of guidance:

(i) Teachers' Guides. In some cases where we recommend an unfamiliar form of apparatus we give notes on equipment in a special box at the appropriate place in the *Teachers' Guide*.

(ii) Suppliers' Catalogues. Now that the project has been running for over a decade,

several suppliers list equipment with our Nuffield item numbers; and both the pictures and the descriptions are often helpful.

We advise teachers equipping a new lab to indulge in some 'comparison shopping' to start with—designs differ as well as prices. Where there is a choice, the *simplest* design may be best; and *crude but strong* is often better than *ingeniously foolproof*. Designing to produce components that can only be assembled in the 'right' way may increase pupils' speed but may well spoil the atmosphere of genuine experimenting.

Also, in consulting catalogues for kits, one needs to note the *size* of kit being offered. The Nuffield *Guide to Apparatus* states clearly how many of each item are needed for a full kit—usually 16. But sometimes, due to an obvious humane wish, a catalogue tempts teachers with '$\frac{1}{4}$ kit' or even '$\frac{1}{16}$ kit', under the name 'economy kit'. That would be false economy—better none than too few and slum crowding.

'Kitchen equipment' The *Guide to Apparatus* has a section listing basic items (The 500 Series). Although we hope that a school embarking on our programme will already have much of this 'kitchen equipment', we must emphasize strongly its great importance. A Nuffield lab, like every good lab, needs it in robust form and *in full quantity*—clamps, stands, large metal beakers, . . . are even more important for flexibility and enjoyable experimenting than many more romantic 'set pieces'.

D.I.Y. In addition to encouraging the commercial production of apparatus (including kits) for our teaching, we have also produced pamphlets of instructions and drawing to enable schools to make some apparatus in their own lab or workshop. These can be obtained from: The Association for Science Education, College Lane, Hatfield, Herts.

(At present these are available for items 29, 63, 103, 105/1, 115, 116, 117, and for kits 11, 91, 92, 94, 96 and 97.)

SECTION X NOTES ON SPECIAL TOPICS

NOTE ON VECTORS

In Year 4, pupils should see illustrations and uses of vectors. If they are studying vectors in their mathematics, 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 3 and 4 no longer make 7: the sum may be anywhere between 1 and 7—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 adding *vectors*, but say 'a problem 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 geometrical way: trips or distances travelled; velocities (because these are distances travelled in one second or 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 'forces *must* be vectors because they have magnitude and direction'—there are certainly things that have magnitude and direction but do not add by vector addition.)

If we take vectors as things to be added by the geometrical (parallelogram) construction they seem clear, simple, useful things to older students. The school pupil who first meets vectors at too early a stage in physics may find them queer and difficult; and nearly 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 so quickly that they can be handled without thought—perhaps without understanding. That is no reason why we should insist on introducing vectors when it is too early to catch a pupil's fancy.

There will be no need to touch on vectors in Years 1, 2, and 3. Even the simple discussions of projectiles which we offer can be treated without overt teaching of vector constructions.

In Year 4 we should offer a demonstration of a collision in two dimensions, to be analysed by means of multiflash photographs. That brings in vectors, at the right moment.

In Year 5 a knowledge of vectors and an understanding of their *subtraction* becomes essential for O-Level candidates 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 ON TEACHING ELECTROSTATICS WITH ELECTRONS

Here is an account of an experiment that demonstrates 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 some of 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 at the near end. Those positive charges are always there embedded in atoms which are part of the crystal structure of this metal. But their effect was neutralized by the effect of the loose negative 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 on 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. I can hold those quite separate. They have 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.

They run away as far as they can, to the great Earth in a proportion which leaves practically no extra electrons on the sausage although they have to move a little in the wrong direction first to get to my finger in the middle and then down through my body and away.

Yet there are still positive charges, unaccompanied by neutralizing electrons, at the end of the sausage 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 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 do, 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 illustrated those ellipses on the covers of many text-books? We now know that there is no way of locating an electron in a sharp orbit like that. We know that those early descriptions contained embellishments that were actually misleading.

Newton said 'hypotheses non fingo'—'I will not feign [unnecessary] hypotheses'—and Bohr and Einstein have followed the same general precept.

In the case of electrons in metals, we are well assured that some 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, many 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 probably tell our pupils that we are being old-fashioned.

We should not be intimidated by that, but we should not be too stern; 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 unsupported so far as they know at the moment.

NOTE ON INTERACTION

We assume that masses are additive—that one mass does not interact with a neighbouring mass in any way that changes the response of either to a field of force.

We also assume that energies are additive, that there are no interaction terms.

And we superpose velocities or accelerations or forces by vector addition (until Relativity suggests modifications).

These assumptions—of additive behaviour—seem obvious to us *because we so often select* cases where that behaviour 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. Another example: intense excitation of a crystal by red laser light *can* produce blue light.

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 increases in proportion to the intensity, $I_w = k_w N_w$ where k_w is the 'irritation-constant' for whispering. And we might possibly find that $I_t = k_t N_t$ where k_t is a different constant applying to trombone noise.

Even if we could take measurements and discover such simple relationships, we should not be wise to assume that the total irritation, I, is given by the sum of the two components; that

$$I = I_w + I_t = k_w N_w + k_t N_t,$$

because one kind of noise is quite likely to affect 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 ks are not constant or be lucky enough to express I by an extra interaction-term such as $kN_w N_t$. In that case, with

$$I = k_w N_w + k_t N_t + k N_w N_t$$

we see that the irritations are no longer additive.

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

In general, masses *are* additive, and changes of energy *are* additive.

NOTE ON LOGIC AND VOLTMETERS

Perhaps this is the moment to confer privately with teachers about the general logic of using moving-coil voltmeters in an experiment to 'discover' or to 'test' Ohm's Law.

The question of logic about using them is not so important here as in many teaching programmes, because we do not stress Ohm's Law very strongly. Pupils will meet the Law in Year 4; but they will also meet materials and devices which have non-linear behaviour.

To make a practical moving-coil voltmeter we install in a box a high resistance which obeys Ohm's Law and a milliammeter to measure the current through that resistance. Then we label the meter's dial in volts.

We realize that there is a threat of serious illogic if we then use 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 he has comforted himself by expounding the logical difficulty to both pupils and colleagues.

In fact, however, that is unnecessary: it is carrying our logical worries much farther with voltmeters than we carry them in other cases. We never worry about using a stop-watch—whose balance wheel controls the time by executing simple harmonic motion—to time a pendulum or even to time a loaded spring. We use the watch and make perfectly good discoveries concerning S.H.M.

A full and careful logical examination of the statement that 'light travels in straight lines' or of the meaning of FORCE in Newton's First Law of Motion can reduce a competent physicist to tears.

In practical teaching, where our aim is some sense of understanding, rather than a structure of rigorous logic which we shall never achieve, we all of us have to leave out some of the argument and indulge in occasional loosening of logic—even our colleagues in mathematics do that, whether they are compelled to do so or not.

Here, we want to build up ability to use a voltmeter, knowledge of *what* it does—not minding too much *why* or *how* it does it—and some practical sense about volts, and amps, and then in turn about watts and kilowatt · hours.

Avoiding Illogic

Moreover, we do not have to take an immoral line in using a voltmeter. We can present it as a ready-made, closed instrument and assure ourselves of its behaviour by tests from outside—just as we can do for a stop-watch.

We do not open the instrument, we do not enquire into its interior, we do not reveal how it is constructed, we do not mention that it contains an Ohm's Law resistor; and none of these things matter because we can satisfy ourselves by experimental tests that this 'black box' does in practice measure the energy-transfer, between electrical form and other forms, in joules for every coulomb.

We do that first by making a crude overall test, connecting the voltmeter across 1 cell, then 2 cells, then 3, in series, acting on the basis of our trust in the Conservation of Energy. If we are not sure of that basis, we shall probably meet troubles* in discussing *any* form of voltmeter.

Then our voltmeter can be tested at one or more points on its scale by a calorimetric method. Except in very skilful hands, with a lot of time given to careful corrections for heat losses, that method is so rough that one cannot call its results proper calibrations. However, this can serve as an 'experiment of principle' to show that one *could* substantiate the behaviour of a voltmeter without opening it, and therefore without illogic.

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

Then we must be careful not to use voltmeter, ammeter, stop-watch, and calorimeter to measure 'J' in a class or demonstration experiment, if we are already using a calorimetric experiment—in practice or in imagination—to give validity to our voltmeter's scale!

Thus, there are several levels of knowledge at which we can put a moving coil voltmeter to use:

a. The unexplained and untested black box. 'Here is a voltmeter. You connect it up like this; and you take the reading and multiply it by . . .' This produces at most the practical facility of some amateur radio enthusiasts, but no sense of understanding. As part of physics teaching, it is 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 3.

c. The black box turned grey by systematic external tests. This is the treatment in which we give the overall test with several cells and 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 the picture 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 combination of a current balance that weighs the forces between measured coils against known gravity-pulls, with a Lorenz disk which measures a standard ohm in terms of dimensions of some coils and the speed of rotation.

This is satisfying to much more advanced students but to describe it to young pupils is

* Of course such troubles are not inevitable, since there are ways of making mechanical measurements to assure ourselves that energy-conservation includes electrical forms of energy.

The basic experiment uses a Lorenz disk which can produce a voltage that we can predict from *mechanical* measurements together with an absolute measurement of current—though in practice that disk is used to produce a standard *ohm*, by making the current measurements cancel out.

There are other methods that use electrostatic devices, but these involve awkward transformations of units.

probably to produce a sense of insecurity, an impression that physicists let two of the passengers in the back seat hold the steering wheel.

e. Complete revelation. We open up the voltmeter, 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.

Such a theoretical throwing away is a good move for an advanced physicist, though it should not be accompanied by unjustified celebration, or condemnation of levels *(b)* etc. The business of making voltmeters is an interesting experiment and important practical engineering.

This discussion is not intended to suggest any discussion of these matters with pupils in O-Level Years.

APPENDIX I

The Aims of Science Teaching: Teaching Science for Understanding

This is an account, with some modifications, of a paper read by Professor E. M. Rogers at several conferences on science teaching and of a lecture at the annual meeting of the Association for Science Education when the original Nuffield Project was being launched.

This is not a formal statement of the aims of the Nuffield Science Teaching Project but is offered here as an informal guide to some of the opinions and thoughts which have played a part in the Project.

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. The world needs skilled scientists, and technologists who can draw upon a full knowledge of science, and 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.

Other pupils 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 conducting 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 them as educated citizens. Many of our young people, though not preparing to be 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. And now in the '70s all are faced with paramount problems of use and misuse of energy, of treatment and mistreatment of our environment—matters which all ask for help and guidance from science. With such needs in mind what should we teach them and how should we teach?... That is my question for this discussion.

I am thinking of our young pupils when they are grown up, not when they are learning science at school or taking exams soon after, but a dozen years later when they are out in the world: a young man in a bank, a manager in business or industry; a civil servant; a shop steward; a nurse; 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 they learn. If they understand, they may retain some sympathetic knowledge all their lives. So attitude in learning may be more valuable than content.

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 characteristic ways of thinking and planning and working—which we call scientific attitudes or scientific methods or science itself—that offer intellectual resources and guidance to all.

Do we send our pupils out delighted with their 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 vital problems? 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 pupils' needs and hopes?

Young children are thrilled with the idea of scientific experiments and knowledge. Many a young child is eager to learn physics and chemistry and biology. 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—if you do not believe me, read the newspapers.

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 our science as we now build it: 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 a single word for 'know', but I will offer some English nouns to describe these different levels.

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

I hope we can move our teaching *downward* in this list, 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 we may 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 will help. 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 we may expect even young pupils to be able to 'teach' something they understand to others. We ask them, in homework or tests, to describe an experiment or explain an argument *in their own words* to, say, another pupil who has been away ill. This old device is a powerful teaching aid and of great use in setting the tone in examinations.*

* There is a deep difference between giving an informal explanation in one's own vocabulary and repeating a carefully learned account in the full splendour of a textbook's words. The latter may look grand but the memory is short-lived. The former is a talisman for understanding.

To encourage pupils to learn by teaching, we suggested in the early years of the Project a 'hypothetical uncle' who was sympathetic, intelligent, educated, but had missed all physics. We asked pupils to explain things to that uncle and to answer his objections. Unfortunately, he proved unpopular. Teachers found that pupils thought him undignified, unreal or comic. And perhaps his insistence on full, clear answers struck pupils as an *inescapable* demand. In any system of teaching that relies on intensive revision and learning by heart for 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 thorough logical 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. Adults seldom report success.)

2. Acquaintance with the main facts of a science is itself 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. Thorough study, including learning material that is boring or difficult, is valuable discipline 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 trains pupils in scientific method—that is, it makes them more scientific, a virtue to be transferred to other studies and other activities in general life. (This would give a cogent reason for any studies which did 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, in the past, the results were disappointing. Young scientists arrived at the university well crammed with older material but far behind in modern physics; and their lack of deeper understanding made progress slow. They considered kinetic theory 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 heat capacities. Radioactivity came as a list of names and properties and early studies of stopping powers rather than as powerful evidence that helps us to build speculative models.

And our non-scientists went out into life without any clear feeling for science itself. Even today, 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 have been 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

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that uncle would certainly be unpopular with pupils and their teachers.

Instead, in our Revision we now ask pupils to give a clear explanation to 'another pupil who has missed the experiment' or 'a pupil at another school where they do not have that experiment'.

That is consonant with the practice, in teaching today, of asking one pupil to teach another. We hear of a remarkable modification in small country schools in Hungary: a Year 3 class and a Year 5 class share a room, instead of 3 and 4. That lessens wasteful confusion but affords fine opportunities for the older pupils to give help.

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 teaching 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 hope; and still so often claim!

If transfer 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:

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 lab, it is almost certain that this training will transfer to another physics lab, and he will weigh the more accurately there. It is moderately certain that he will carry his good training to a chemistry lab; 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; it is unlikely to help the pupil to think critically about arguments in newspaper advertisements, and very unlikely to make him a better economist.

That is what the earliest experiments showed. That is what threatened to make a 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 such people range as widely about the same 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

* In the course of the last three-quarters of a century opinions on the extent 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 by heart. Then he switched to learning English verse and practised techniques for several weeks, making considerable progress in speed. Then back to French verse. No improvement, no gain from the English practice.

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 emotional 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. Above all, a pupil who is proud of his own knowledge and skill and who enjoys feeling he understands some science may keep that understanding as a resource in his later life. He may enjoy reading more science and when he meets scientists he may work and talk intelligently and successfully with them.

With pupils doing scientific work that they like and understand, there is some good hope. Pride can help. 'This is *my* experiment, *my* knowledge'—proud possessions that may last a lifetime.

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

With those warnings 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 classes 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 so that the syllabus is not too crowded, so that there is time to teach for understanding.

What topics should we omit? Each of us should make his own examples. My own 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 nearly all be omitted. Hydrostatics is not undesirable; it is respectable but unnecessary. Studies of the Principle 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 heat capacities 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 heat capacities without much understanding. They follow cookery book instructions for a method that has not been used in research in this century. They boil a lump of metal and throw it into water. (The size of the lump may even be 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 and probably electrical thermometry.

I do not suggest that either of these topics *must* be omitted. I merely mention them as examples of

* To most practising scientists there is no unique 'scientific method' such as the idealized scheme set forth three centuries ago 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.

material which seems 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 illustrations. And they should, I believe, put them to the use for which Newton himself formulated them: making a great gravitational theory of the Solar System. But, if we examine our usual teaching, we find that the principal 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 several uses. I do not mean practical applications, so much as 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 teaching our chosen topics we should 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 pupils to behave as a rubber stamp, to reprint on every examination paper the standard things that we have taught them. Our examinations must be different.

And so must our practical work. Pupils will need to do many 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 content, 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—just sailing orders—and leave them to work on their own. They need some encouragement from the teacher, and some questions about their experiments—and a teacher can provide this environment.

Above all 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, pupils will do far fewer experiments in the time available; and to make up for that the teacher should do some 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. They will all hang loads on it and measure stretches and perhaps plot a graph. Finding the simple Hooke's-Law relationship gives lasting delight to many young experimenters. We should not falsify the story by telling pupils 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 may tell them that Hooke was delighted and proud of it too.) But then we encourage them to try other spring experiments of their own devising. Some will continue to stretch their spring far beyond the elastic limit. Some will notice torsional motions and will investigate them. Others may try the effect of heating and cooling. And still others will make springs of copper wire for further experiments. With the teacher using plenty of patience and giving some encouragement (but without prompting by suggestion of particular problems) this becomes an open experiment that continues for several periods.

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 classes 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 varied series of experiments with more and more skill.

And to teachers who foresee discipline troubles I point out the world of difference between pupils doing experiments because they (most of them) want to and pupils 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 keen 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 then 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 by the questions 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 require understanding—even questions that pupils themselves see in that light.

And 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 a vital part of our teaching.

[There followed some examples of questions that can be used for homework or tests 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 a pupil's answers to them show clearly 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?

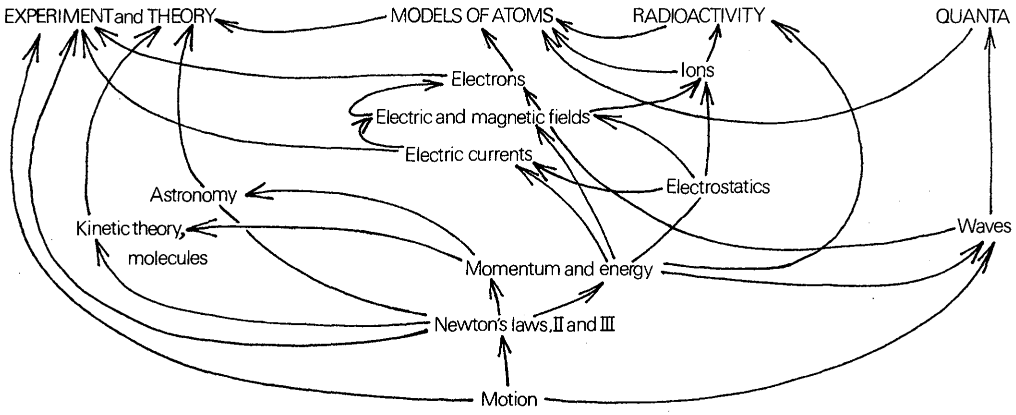
Rather than teach fast to cover the whole field of a bare-bone syllabus, we should reduce our syllabus with a clear conscience, yet make a connected scheme. As an example, I will construct one such syllabus. Note that I construct it *backwards*, beginning with the end-points, ultimate aims for my pupils;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

Suppose we decide, in a physics course, to include some 'atomic physics' and choose to teach: radioactivity; knowledge of electrons alone and moving in streams; and something of atomic models. All that will come near the end of the programme; 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 general electricity and magnetism, some kinetic theory of gases, and some Newtonian dynamics. And the latter needs a beginning in studies of motion. (This is shown in the sketch.)

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 general 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 astronomy from empirical beginnings to Newton's overall gravitational explanation, all as an example of the growth of theory.



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.) Every teacher will find it interesting, and a very valuable discipline, to make his own version.

In my discussion so far, I have concentrated on the teaching of science to future *non-scientists*. But now I hope that you will consider that this development of teaching science for understanding is needed equally 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 when needed at more advanced stages.

Consider technology Two groups of people are needed: the technical person who mends an amplifier or runs a telephone exchange and the advanced technologist who designs new things, who puts a full knowledge of science to practical uses.

Many skilful technical people are needed in every country but some of their special training for their work is best done after schooldays, when they are starting 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 technique with understanding.

Technologists are needed, at the top level of designers and organizers, in every country: clever, creative people equipped with scientific knowledge right up to the frontiers of research. The technologist 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, most institutions plan to give them more technical training, less pure science. I suggest that is a mistake. Science provides an intellectual nursery for the next generation of scientists and technologists. The technologist must have a tremendous knowledge and understanding of science as well as his own special knowledge and skill and interest, which differ from those of the researcher in science.

Therefore, all through, for non-scientists, scientists, technicians, and technologists, I consider 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 training 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 interesting doing and clever thinking; science makes sense.'

APPENDIX II

Examinations

(This is an account, with minor modifications, of papers read by the Revision Organizer, Eric M. Rogers, at conferences on science teaching, combined with extracts from his UNESCO report.* This is not a formal statement of policy or practice of the Nuffield Physics 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 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.

The original paper related to examinations for students with interests and abilities like those for whom the Nuffield programme was originally suggested. For commentary on testing in classes of mixed abilities, see Note 3 at the end of the paper.)

* 'Improving Physics Education through the Construction and Discussion of Various Types of Tests.' Report of workshop at Montevideo, SC/WS/506, Paris, 22nd August 1972.

Purposes and uses

Examinations have many uses which have been argued about, praised, regretted, blamed, used and misused—and they are still with us:

- 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 act as a test of general intelligence in applicants for jobs.
- to award scholarships, determine university entrance, etc.

These have been analysed and discussed by many, and I shall not discuss them directly here, except for one warning: disastrous confusion may ensue if we try to put the same examinations to several uses at once—the dangers are obvious but often neglected.

Two powerful effects There are two more effects of examinations, important here:

(i) For teachers and training. External examinations influence the manner of teaching for good or ill. If a teaching programme leads to public, external examinations, teachers keep that testing in mind and cannot help being influenced by it. Examinations that do not fit a scheme of teaching that is being tried threaten to cramp and distort the teaching. But examinations that do fit the teaching, in spirit as well as content, can encourage teachers and keep them free.

(ii) For students. All examinations exhibit a set of teaching aims to students. The questions tell the students the real aims of the teaching—at least so the students believe. If in our teaching we stress understanding and aim at a growing knowledge of real physics, traditional examinations may completely sabotage our efforts. Students will judge by the questions—and so will next year's students who hear about them.

These are overall functions—well known but seldom mentioned—that pervade all other uses. These are my present concern, because I see that examinations—whatever else they do—control the success of any teaching plans.

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

- 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.

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. Therefore, after discussing aims and their relationship to examinations, I shall offer comments on some types of examinations.

Teaching and testing for learning-by-heart 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.

Teaching and testing for understanding 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 soon 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 for benefits which are likely to last and may transfer to life in general. With such hopes, some of us are trying to aim our teaching at giving understanding* rather than filling pupils with information (which will fade or become muddled) or training them in formal knowledge (which seems unlikely to transfer to later uses).

We shall teach fewer topics, but teach more carefully; we shall encourage pupils to do more creative thinking and less memorizing of formal statements or results; and we shall ask them to do experimental work themselves, so that the work is their own experimenting rather than a matter of dutiful carrying out of detailed instructions.

If we are to succeed at that, we must change our examinations to fit our new aims and treatment. And the examinations themselves must show our aims.

The success of a teaching programme is affected vitally by the flavour of *every* test and examination.

Examinations for different aims: aids or hindrances? 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 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 to apply 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 a grammar test 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.

* 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 who would 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 demands 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 might 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.

Examinations and physics 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 experiments 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 small 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!)

'Formula questions' A single 'formula question' like that does little damage; and it gives comfort to those pupils who learned in some other 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 novice 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.

Relevant questions We should give much thought to making sure that all the questions are as relevant to our real aims and teaching as possible.

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 arguments. 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 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 taught in the course. And in framing them we look for the knowledge that enables the pupil to teach other people what we (and his own experimenting and thinking) have taught him. In a way, we ask the pupil to 'teach' the examiner.

If we are teaching for understanding, 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 ultimate success. The best we can do is to make them encourage success rather than prevent it.

The Work of Testing and Examining for Understanding

Examiners Examining for understanding is neither very mysterious nor very difficult; but it does require hard work and a strong guiding attitude. Teachers become involved, too, in framing questions for homework and tests. Then constructing questions is 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.

Making examinations is itself a valuable process of heuristic gymnastics for teachers when they meet as examiners to invent questions and then criticize each other's questions with the ruthless clear vision of scientists.*

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 bright new 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; but, in conference with them, 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 glad to use the questions that they then devise. The important moral is this: if question-making seems too difficult at first, persevere. Every physics teacher *can* make good questions—and there is always a need for new authors.

General Construction

Easy beginning An examination or test should encourage pupils to show what they *do* know rather than inhibit them with fears about what they *don't* know. Many of our questions will ask for some form of recall; some of them for recall of information. Only one or two should make an easy beginning by asking for what I name 'cheap recall'—recall of a small item that can be learned by rote.

Examples of Cheap Recall

1. Ice melts at 0 °C. What is that temperature on the old Fahrenheit scale?

2. A force of 6 newtons acts on a 2-kilogram lump of metal on a frictionless table. Calculate the acceleration of the lump.

Cheap Recall in Objective Test Form

3. The heat to change 1 kilogram of solid to liquid at the same temperature is called

(A) Heat of formation
(B) Specific heat capacity
(C) Thermal capacity
(D) Heat of fusion
(E) Latent heat of vaporization

Cheap Recall: 'Formula Question'

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

Improving a 'formula question' Many 'formula questions' in traditional physics examinations are close to cheap recall. In a test where formulae *are given to candidates*, a formula question would be very cheap recall unless specially constructed—e.g. inverted.

However a question that gives the formula and then asks questions about it would be good 'simple recall' or even 'expensive recall'. To assure pupils that we do not want them to memorize formulae for substitution, I myself issue a public guarantee at the beginning of the term that *formulae will be provided free at any of my examinations*. Then, we print many formulae (without explanation) on the front of the examination paper.* Nevertheless, many a doubting beginner still memorizes formulae just before the first test. Then he finds the test begins thus:

5. In the relation $s = ut + \frac{1}{2}at^2$,
(i) What does u stand for?
(ii) What does ut tell us?
(iii) Explain where the $\frac{1}{2}$ comes from.

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

Each of those questions (*i, ii, iii*) asks for an understanding of the formula's meaning and use—simple recall.

Improving a rote-memory question With a similar technique, a question that says 'State Newton's three Laws of Motion' (expecting them in textbook wording) may be replaced by a question in which the Laws are printed on the examination paper in textbook wording and the pupil is asked to explain what each means, in his own words.†

* For a description of such a gathering—known as a 'shredder'—see the Montevideo UNESCO report mentioned.

* This is done in Nuffield O-Level Physics Examinations.

† Teachers who have tried the two forms with parallel groups of pupils, all well drilled in the textbook version, have been surprised at the difference between the results—for example 80% of successes in giving the formal wording, 40% of successful explanations. Moral . . . ?

Digging deeper 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.

Many qualitative questions 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 the 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 'slack, careless, examining' I reply, 'Please try some. If you make them, you will find that they need not be loose or too easy. And they do reveal what pupils are learning and thinking.'

Such qualitative questions cannot be marked with the same objective precision as definite 'cheap recall' questions or numerical problems. 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 scheme 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 part of our personal interview with someone we are considering for a teaching or administrative post—one of our most important types of examining—we are humane but quite vague, and yet consider that we can discover 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.

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. Most of these are 'vague' general questions relating to the material of the course. They offer pupils over a wide range of ability enormous scope to show what they know. Those 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 those pupils feel they may write freely and do themselves justice. Other weak pupils dislike the looseness of the question: they must depend on the short questions.

But—as 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 I will describe later.

There is good correlation between the rough marks for these 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' picture of physics, now and in the future.

Marking The process of *reading and marking* examinations sympathetically is just as important as the inventing of suitable questions. In marking, we should adopt the attitude of one scientist (the examiner) conversing with another (the candidate) 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 should reward every piece of intelligent thinking, as we would in conversation with a neighbouring scientist; but we should punish stupid answers, or lazy 'anti-scientific' ones.

To train examiners for marking we must not just tell them which answers are to be rewarded in some specimen questions offered for training; nor must we just preach sermons about broadmindedness; 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 which 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 teaching. A question may be a very good one for a particular class because it draws consecutively on several things that have been taught. And yet it may be a very poor one for another class which missed one of the necessary components. In the latter case the question hangs on guesswork 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 and their marking to fit our teaching—there is my heartfelt plea for Mode 3.*

The Forms and Enquiries of Questions

Format The value of a question lies in the answer(s) it can elicit and not in its particular format. Yet some styles 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 consider the objective test types risky, often rather harmful. They bring pupils back to memorized facts and clever tricks and they reduce communication between examiner and candidate.

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. It gives science the image of a crossword puzzle game.*

So I myself prefer to use the following two types of question, but I make no claim that they are essential or best:

a. Short-answer questions that show clearly what is wanted. The question may be followed by a space in which the pupil writes his 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 treatment.

Among these, the ideal questions are those that make every pupil—slow, average, or 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.†

Giving space for answers 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.* Yet the format allows creative writing; the answer will be in the pupil's own words. This not only gives some humane freedom for creative expression but also allows pupils of differing abilities or knowledge to do themselves justice by giving their own best answers.

This format is also preferable because it ties the question and answer together for the pupil's review if 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

* In 'Mode 3' for schools in Britain, the teacher (or a group of teachers) chooses the syllabus, constructs the examination to fit the teaching, and does the marking; but the initial syllabus and the ultimate scripts written by candidates are subject to external assessment by Examining Boards.

* See Note 2 at the end of this paper, for further discussion of objective tests.

† One of the rare examples is: 'What is meant by a scale of temperature?'

seriously; that often reduces 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.

Levels of enquiry Questions for cheap recall neither test for understanding nor encourage learning for understanding. They will not encourage able pupils with intellectual interests.

Simple recall 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 should 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.

Examples of Simple Recall

6. A flask full of smoky air has been pumped out by a vacuum pump. The flask looks clear, but some air may be left in it. How could you find out how much air remains in it?

7. *(i)* A circuit consists of a battery of e.m.f. 15 volts, an ammeter, and a resistor. The ammeter reads (correctly) 1.5 A. Calculate the resistance of the resistor.
(ii) Suppose you wish to set up that circuit and the only resistors you have are two fixed ones each of 20 ohms. What would you do?

Experiment–recall questions are a form of simple-recall questions that ask about an experiment. They need careful construction to encourage pupils to draw on their practical experience and avoid regurgitation of textbook instructions.

Such questions may extend to expensive recall, e.g. by asking for improvements of apparatus or technique.

Example of Experiment-Recall

(For pupils who have set up their own telescopes in lab.)

8. Suppose you want to make a telescope. You are given lenses of powers about +3 and +20, and a means of mounting them and sliding them along a metal rod. You also have a piece of tissue paper. In order to make a telescope:
a. Which lens would you take first, and whereabouts on the rod would you mount it?
b. What would you do with the tissue paper?
c. Where would you put the second lens?
d. At what position would you expect to have your eye when looking through the telescope—up against the lens? 25 cm from the lens? or where?

If we ask the 'omnibus' question, 'How did you make a simple telescope?', then the pupil, starting as it were from scratch, has to sort out and write about the whole of a long piece of work, and this is probably beyond the capabilities of most thirteen-year-olds. Instead, leading questions are asked about four separate stages. Answering these questions involves an element of thought and is not the same as note-copying.

Expensive recall 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. I call this *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 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.)

Examples of Expensive Recall

9. *(This is a question for students who have seen the 'jumping ring' demonstration: an aluminium ring jumps up from an electromagnet carrying a.c.)*

A lecturer who showed the 'jumping ring' demonstration held the ring to stop it jumping.
(i) Why did he soon let go?
(ii) When he let go, the ring jumped *but not so high as usual.* Why?
(iii) What preparation could he give the ring to make it jump *higher than ever*?

10. If you hold the axle of an electric motor with a gloved hand while the motor is turning, the axle and glove will get hot. But if you grip the axle so hard that the motor stops, the whole motor gets hot. Why does the motor get so hot when it is at rest?

Intelligent guessing 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 might then ask the candidate to criticize his own guesses, and say which he prefers and why.

Teaching-recall Scientists often say, of some piece 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. (For an examination common to many schools this does require the experiment to be done in all those schools.)

Open questions 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 *open* questions that are vague and general so that each candidate feels free to fashion his own answer. 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'.

(There are three examples among the specimens below.)

Marking 'open' questions The marking of answers to such questions looks hopeless at first. In practice, a loose but otherwise relevant marking is easy after one round of training. We ask the marking examiners to class every answer **A**, **B** or **C**.

Every pupil whose answer shows that he *does reasonably understand* the matter gets **B**. (Score 7 out of 10 for the whole question.)

An outstandingly good answer gets **A** (score 10 out of 10), not to be awarded unless the reader meets an answer which he feels positively deserves it. A poor, bad, or irrelevant answer gets **C**. (Score 3 out of 10 or even 0.)

When a new examiner asks, doubtfully, 'How will I know it is a poor enough answer for **C**?', I ask, 'How do you know when you've been stung by a wasp?'. In other words, my advice is that he should give **B** unless an answer *drives* him to give **C** or **A**.

We warn examiners that there may not be a single 'right answer' to an open question. 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 marking open questions, different examiners agree sufficiently after a little training. They usually work more by general feel than by a strict marking scheme of item-credits. A marking scheme is apt to make an examiner lose sight of the 'wood' of understanding and concentrate on the 'trees'. Furthermore, a marking scheme may fail to take note of a contradiction between separate parts of a pupil's answer. But 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 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 mark of **B** to a wide range of answers. We should merely be saying that many have achieved reasonable success in general understanding.

Virtues of Technique—and a Danger

While we are making tests for understanding and using them in our teaching and examining, professional testmakers offer criticism and help. They suggest that each test question should be judged for 'reliability' and for 'validity'.

'Reliability' is a technical term in testing; it is a measure of the repeatability of marking, from one examiner to another—a value for a question which indicates how well different examiners agree in marking answers to it.

The *'validity'* of a test is a measure of its success in testing whatever we plan to test—a value for a question's relevance to our aims.

In some parts of the world the professional testmakers' enthusiasm for high *reliability* has run away with them, taking attention away from *validity*.

Tests of factual knowledge can themselves be tested easily for reliability and validity—very easily if they are in objective-test form.

Testing for understanding is often more subjective, but the defect of less reliable marking is offset by the higher validity of making the examination deal with physics instead of being a game of puzzle-solving or a test of mechanical memorizing.

Specimen Questions

11. A 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 off or damage. One of the blocks has a lump of metal concealed inside it, that someone hammered into it before it was painted.

(i) How could you find which block has the metal in it? Give a reason for the experiment you suggest.

(ii) If you can think of other tests, mention them here.

(iii) 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. (i) is simple recall, from a class experiment in the lab.

Part (ii) 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 a magnet with a comment that it will distinguish iron, he gets a bonus mark.

Part (iii) asks for intelligent guessing.)

12. A TEST 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 meet a friend of your age who is intelligent and interested in science but has 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 an open question to be marked **A, B, C.** *The question itself must be worded so that it gives confidence and interesting excitement.)*

13. A QUESTION FOR 13-YEAR-OLDS WHO HAVE BEEN DOING SIMPLE CLASS EXPERIMENTS IN THE LAB, WITH BATTERIES, LAMPS, SWITCHES, ETC.

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

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

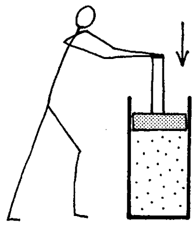
(ii) One of the arrangements of *(i)* makes the two lamps light more brightly than the other arrangement. *Put a ring round your drawing of the brighter arrangement.*
(iii) Neither of the arrangements of *(i)* makes the lamps light quite so brightly as the single lamp did. Suggest a reason for each case.
(iv) With the same two lamps and two cells you can make both lamps light brightly. *Draw the best arrangement.*
(v) Freddie Jones follows your instructions for *(iv)* 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.
(vi) Tell Freddie how he can test your suggestion(s) of his mistakes.

(NOTES: This ranges from simple recall to intelligent guessing. Part (i) carries little or no marks. It is only there to set the stage 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 students. In an examination there would be a few cheap recall questions to encourage candidates with an easy start; then questions like the specimens below. Some would ask for calculations, chosen to avoid cheap recall, and usually ending with a request for an explanation of the method used. Some are longer 'essay' questions. The format shown below, with a few lines for each answer to be written on the question paper, is to be preferred to 'objective test' types, because the form here gives pupils better opportunity for independent thinking. Since the answers of many candidates are quite similar, marking is quick.)

14. 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.



(i) Describe, in terms of molecular behaviour, the mechanism or process by which the gas grows hotter.

....

....

(ii) Where or what is the heat that is gained?

....

....

(iii) Where does the heat that is gained come from? What provides it? *Note:* The piston grows no cooler.

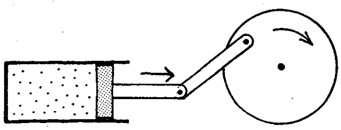
[. . . 2 lines for answer . . .]

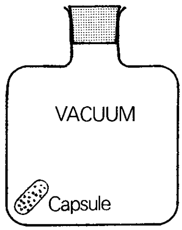
b.(i) A compressed gas in a cylinder with a movable piston is allowed to expand by pushing the piston out. Explain briefly why the gas cools.

[. . . 3 lines for answer . . .]

(ii) If the piston is connected to a frictionless fly-wheel, what happens to the heat lost by the gas?

[. . . 1 line for answer . . .]





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.

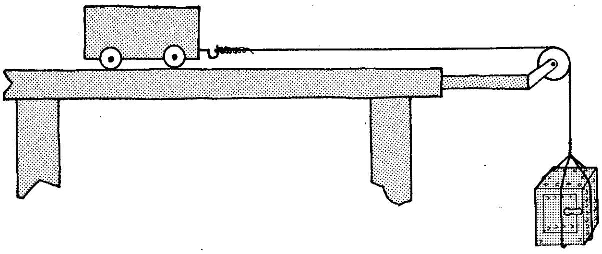
[. . . 4 lines for answer . . .]

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.)

[. . . 3 lines for answer . . .]

(NOTES)
a. (i, ii, iii) are simple recall from class teaching.
b. (i) 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).

15. An experimenter makes a toy 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 truck, 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.

[. . . 5 lines for answer . . .]

(NOTE: Expensive recall.)

16. 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.

[. . . 1 line for answer . . .]

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

[. . . 2 lines for answer . . .]

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.

[. . . 1 line for answer . . .]

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

[. . . 2 lines for answer . . .]

(NOTE: This follows much use and discussion of graphs in the lab.)

17. 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.)

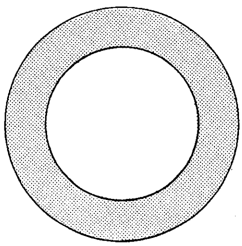
[... a whole page offered for answer...]

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

18. 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: Open 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.)*

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

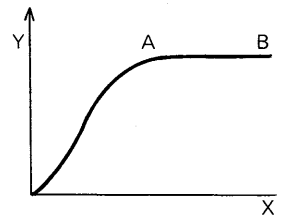


a. A man thinks he has magnetized a steel ring, but finds no poles. Is it possible that in any reasonable sense of the word it is magnetized? Explain.

[. . . 1 line for answer . . .]

b. How could you test your explanation?

[. . . 1 line for answer . . .]



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

(i) Interpret the stage shown by the nearly horizontal part of the curve, AB.

[. . . 1 line for answer . . .]

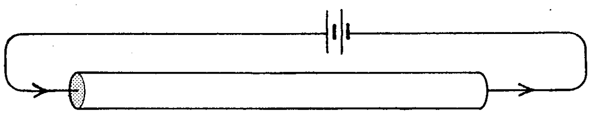
(ii) What is (probably) being plotted upward on this graph, that is, on the y axis?

[. . . 1 line for answer . . .]

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

[. . . 1 line for answer . . .]

d. (*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?

[. . . 1 line for answer . . .]

(NOTES: (a) and (b) are simple recall. (c) is expensive recall. (d) 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.)

20. A research organization, 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.

(i) 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........................

(ii) Experimenters B and C go to planet P_2 and make very careful measurements, arriving at answers $g = 18.6$ and 18.8 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 17.7 metres/sec^2. They calculate his error and report it as 5.32 per cent. Criticize their report.

[. . . 3 lines for answer . . .]

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 lines for answer . . .]

(iii) 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.

[. . . 3 lines for answer . . .]

(iv) 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 $g = 4\pi^2 L/T^2$, 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..............

(v) 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 M is an ordinary mercury barometer with its scale marked in cm.

In barometer S 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 S is marked in 'cm-of-mercury'.

In the laboratory on Earth both barometers read 76 cm before starting. On arrival at the other planet, barometer M reads 40 and barometer S reads 80. 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.)

NOTE 1
COMMENTS ON THE PATHOLOGY AND HYGIENE OF TEST QUESTIONS

Unhealthy Questions

Mind reading We need some such name for the defect of a question that 'asks the student to guess the examiner's mind'. We may want to give questions that ask the student to make his own choice, or to do imaginative thinking, or even to make intelligent guesses with his knowledge of physics as basis. But it is bad examining if the question seems to say—by some careless accident—'We, the examiners, are thinking of a definite, interesting matter in physics; here are some hints about it; now be clever and guess what we are thinking of.'

For example:

In a certain method of measuring low pressures, the standard instrument necessarily omits a part of the total quantity to be measured. What is that method and how is the defect allowed for?

The examiner when reproved, says, 'Obviously I am asking about the M'Leod gauge for measuring very low gas pressures. Since it uses a mercury piston it fails to measure the pressure of any mercury vapour present.'

The question does not lose its legitimate demand if we state it more clearly.

A M'Leod gauge, used to measure the pressure of residual gas in a vacuum system, fails to measure one part of that pressure. What part is left unmeasured, and why? How would you allow for that part?

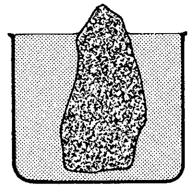
To be quite sure that we are not taunting the student with uncertainty, we might tell him more and still have good assessment.

A M'Leod gauge measures the pressure of residual gas in a vacuum system by taking a sample, compressing it by a mercury piston to a known fraction of its original volume, and measuring the pressure of that compressed sample (in mm of mercury). The original pressure is calculated by applying Boyle's Law. The device fails to measure one part of the pressure . . . etc.

'Iceberg questions' An old problem, well known to many physicists and some students, runs like this:

1. A block of ice is floating in a beaker brim full of water.

What happens to the water level when the ice melts?



If we use this question in a test on hydrostatics, those students who have met it before will answer it in a few seconds. Those students to whom it is quite new may spend many minutes puzzling out the answer. Therefore, such a question is an undesirable trick question which will distinguish strongly between those two categories of students—not just between those who do understand the physics and those who do not, but between those who happen to know the answer already and those who must think it out.

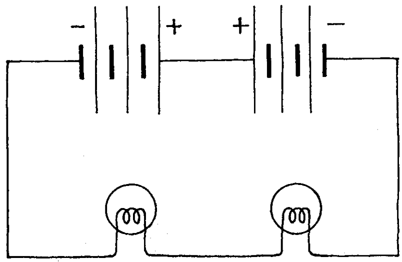
Two more examples:

2. In the circuit sketched, each battery is a 6-volt one and each lamp is a 6-volt lamp.

When the switch is turned on, the lamps do not light.

a. Explain why.

b. If you are given *one* extra piece of wire, how would you connect it to make both lamps light?



Part *(a)* is a good question, ranging from simple recall to expensive recall or even imaginative guessing, according to the stage the students have reached. But part *(b)* looks like an iceberg question, because it asks for a trick which, once seen, is not likely to be forgotten.

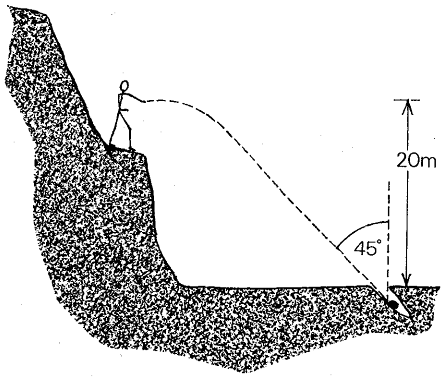
We should avoid iceberg questions, except when they are first invented. (At that time, such a question is not an iceberg question—but by the following year we may regard it as one.)

That does not rule out all questions which ask for imaginative guessing. We may ask a question like the following without being accused of setting an iceberg question:

> Astronauts in a space ship have the following instructions for their breakfast:
>
> 'Weigh out 100 grams of chocolate . . .' Describe one or more pieces of apparatus that they might use to follow these instructions when their spaceship is moving freely without rockets.

Tuesday questions This is a name* for a question that is unfair because its wording misleads the student strongly. Here is an example:

> A man standing on the side of a mountain throws a rock out horizontally. The rock travels a long way outward and downward (as in the sketch) and lands in snow, making a tunnel at 45° with the vertical. That place where it lands is about 20 metres vertically below the man's hand.
>
> *a.* What was the horizontal velocity that the man gave the rock?



* The name is derived from a teasing joke with children.
Adult: 'How do you spell true?' *Child* 'T-R-U-E'
A. 'How do you spell the colour of clear sky?' *C.* 'B-L-U-E'
A. 'How do you spell the second day of the week?' *C.* 'T-U-E . . .'
A. 'No, it is Monday.'
The criterion for a 'Tuesday question' is whether it leads to anger and that may depend on the level of ability of the students.

Part *(a)* is a good question, calling for simple—or possibly expensive—recall. Its only bad quality is that it lulls the student into thoughtless confidence for part *(b)*.

> *b.* What is the acceleration of the rock when it is *EXACTLY half way* down?

The emphasis on 'half way' produces some surprising answers, even from capable students—and leads to anger afterwards. I consider such questions bad examining.

Troublesome errors Where a question asks for several answers to be calculated, one after the other, those may be *consequent* answers or only *subsequent* answers. For a consequent answer the student must use his answer to one part to calculate the answer to a later part. This may worry a candidate. And it will give a faithful examiner a lot of trouble, because, if a candidate's earlier answer is wrong, the examiner should, to be fair, *carry the error forward* through the later part and reward success.

Composite questions requiring *consequent* answers should be avoided, except where the early part is extremely easy, placed there to give the candidate a start (known as 'garden-path encouragement').

In questions that ask for *subsequent* answers later parts merely *follow* the earlier parts and do not depend on their answers. These save time and trouble by using the same introduction (stem) and may contain a valuable series of increasingly penetrating enquiries.

Punitive questions This is not a particular type of question: it describes a particular reason for including a question, when we aim at punishing a student who has not read a certain chapter, or done a certain experiment carefully, or attended a certain lecture. The question may be justified because it enquires about important matters; but if our reason for including it is primarily to enforce or reward obedient study, the remark, 'This is a punitive question' may be a useful comment in discussion among examiners or educational planners. It is an ugly comment—best used as a gentle doubt, by asking whether it is wise to include the question.

Discipline questions These are similar to punitive questions, but the flavour of reproach is not so strong. A discipline question asks for something that we wish to tell the student he must know, probably for some future use. It does not necessarily require a full understanding, but is rather more a check on knowledge.

The term is sometimes useful in reply to an objection that a question is punitive.

Useful Devices

Demanding a reason We might ask this question:

> A 2-kilogram ball of clay, moving horizontally 3 metres per second, hits a 4-kilogram ball of clay at rest. They cling together. *Find the speed of the combined lump.*

But we may be wise to split the question thus:

> *a.* Calculate the speed of the combined lump.
> *b.* Explain how you arrived at your answer to *(a)*.
> *c.* If, in *(a)* and *(b)*, you used any general principle, say whether it holds universally or is limited to certain circumstances.

Then we not only make sure that we receive enough to judge the student but we also tell the student that we expect a full story.

Adding a tail with a sting We may add further parts, to ask for creative thinking. In the example just above, we may add:

> *d.* How much kinetic energy disappears in the collision described above?
> *e.* If it is a head-on collision, what happens to the kinetic energy that disappears?
> *f.* If the collision is not head-on, but the balls still stick together, what happens to the kinetic energy that disappears?
> *g.* Suppose large magnets are concealed in the balls, and arranged so that the balls attract each other strongly as the moving ball approaches the stationary one. Describe the way in which the magnets affect the final speed of the combined lump and how they affect the fate of various forms of energy.

Some teachers dislike questions which have many parts which are all based on the same description of an event (the same 'stem'); but this is often an economical way of offering the student several questions of increasing difficulty.

Inverting a problem Interchanging the *material given* and the *answer asked for* often makes a problem seem more unusual, 'less like the example in the book'. For example, early in the study of Newton's laws of motion we asked:

> A force of 6 newtons acts on a 2-kilogram lump of metal. Calculate the acceleration of the lump.

That is cheap recall. But to most students it seems a little more enquiring if we ask:

> A force of 6 newtons gives a lump of metal an acceleration of 3 metres/sec^2.
>
> What is the mass of the lump?

Sometimes inversion makes the problem really harder. A problem that asks students to use conservation of momentum in solving a collision problem is printed below, in two forms. The description of the event is the same for both forms, but the righthand form does seem harder. (The numerical details differ, because they are chosen in each case for easy calculation.) See opposite.

Humane Examiners

The examiner is flexible: bonus marks Sometimes, after reading many students' answers, an examiner suddenly finds a student giving a new, acceptable, answer for which he has made no provision in his scheme of marks.

Rather than revise that scheme and start all over again, the examiner would be wise to give such a student a special bonus for his particular answer.

Where students see their papers again after the marking, that also has great value as a piece of praise, which is likely to act as good teaching for that student. (It is also good *preaching* to the student: that the examiner is flexible.)

Problem on collisions

A 2000-kilogram car, moving due North on a slippery road, is hit by a 10 000-kilogram truck, moving due West. The two lock together and the combined wreck proceeds in a slanting direction. (Neglect friction of road and air.)

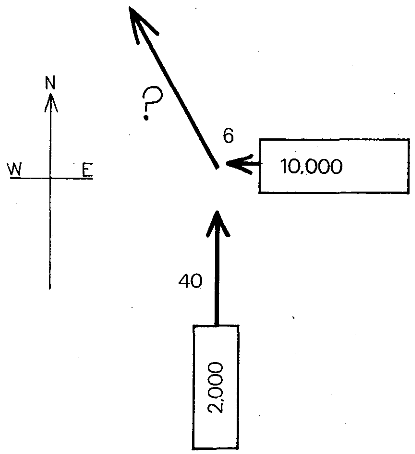
USUAL VERSION

The 2000-kg car was moving 40 km/hr due North.

The 10 000-kg truck was moving 6 km/hr due West.

a. Calculate the speed of the combined lump of wreckage.

b. Describe the direction of the motion of the wreck.



INVERTED VERSION

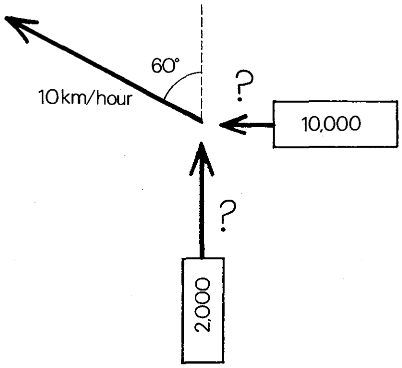
The lump of wreckage moves in a direction that makes 60° with the due North direction.

The motion of the wreck was measured by the police. It slid at 10 km/hr.

The police say the car was exceeding the 35 km/hr speed limit at that place.

The driver says he was not.

Find out.



The examiner as a private consultant: mirror tests What do examination marks do to the pupils who receive them? When they are not attended by anxiety, marks can give much-needed judgment, a guiding standard. Most well-balanced pupils want some tests, to enable them to look at their own progress. I like to call examinations used for that purpose, 'mirror-tests'. (A mirror in a corridor tempts each of us to take a passing glance: and here I suggest an intellectual mirror for pupils to glance at.)

A mirror test is an ordinary test or examination, constructed, given and marked with the usual formality and care, and then returned to the pupil *without the mark ever being recorded.* So, although we ask pupils to treat such a test seriously, it ends up as a purely private matter.

And in countries where a traditional examination prevents changes in teaching, new testing can be started at once in the form of mirror tests.

'The examiner insists on sound knowledge' —the 'dead-mouse principle' We point out to students that a personal interview for a job is a form of examination that most of us meet from time to time in life, an examination whose underlying marking-system is severe.

Suppose the job involves several essential skills: then the interviewer tries to find out whether the applicant possesses *each* of those skills to a reasonable degree. He tests for each skill; and if the applicant fails any one test, he does not get the job.

Thus, if we imagine the interviewer giving marks for each needed skill, he does not finally *add* the separate marks together: he virtually multiplies them; so that if any one mark is zero—failure in one test—the product is zero and the applicant does not get the job.

Students know that; but they may not realize that this can happen in many examinations where the examiner insists on genuine success. As students grow more mature and their knowledge increases in extent and depth, we may tell them that in physics examinations a zero for one part of a question may be very damaging—as if the component marks were *multiplied* instead of being added.

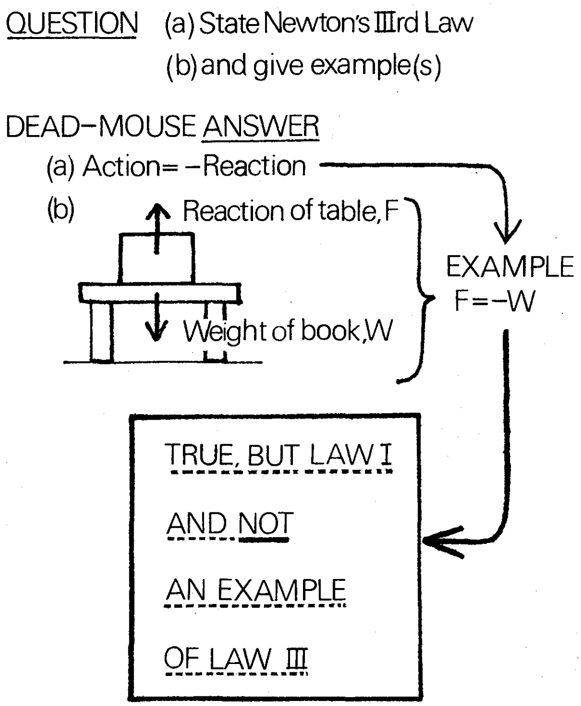
Suppose a question has three parts, the first trivial, the second routine, the third asking about clear understanding. A student who has memorized some of the relevant material may show when he comes to the third part that he does not really understand it at all. In that case, the proper mark for the whole question may well be zero. If we give his partial marks for the first two parts, we may mislead him into thinking that scraps of memorized knowledge can count as adequate knowledge.

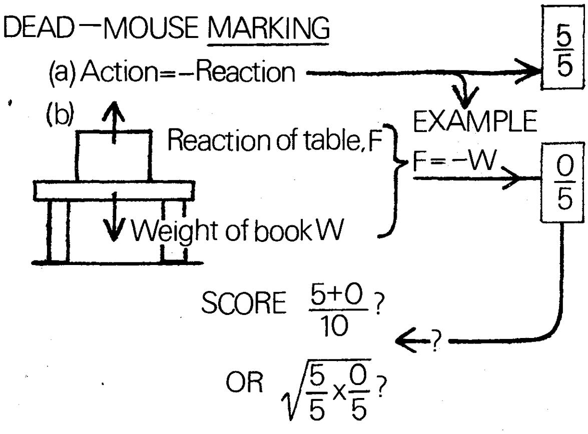
Before giving zero for an answer that is spoiled by the student showing a major lack of understanding, we should warn students of this possibility. Sometimes, I give the warning in the form of the following story—which leads to the strange title for this marking treatment.

The pickle-factory story Let us imagine an investigator visits a pickle factory to evaluate the quality of its product. He measures the quality of the vinegar and gives it 15 out of 20; he examines the cucumbers and gives them 8/10; the cauliflower, rather poor, 8/20; . . . and so on, for all the ingredients. Suppose the total adds up to 75/100. The evaluator may be unwise to say, 'The pickle is 75% perfect: a very good mark'; because if one dead mouse is found in a jar of pickle, the factory is ruined.

So the 'dead-mouse principle' warns students that they should not assume that they can collect a useful total of partial marks for various pieces of information in an answer, if in response to the major part of the question they show that they do not really understand the matter. As in an interview, a serious revelation of inability contaminates the whole answer.

For example: suppose a student, asked to give an example of Newton's *Third* Law of Motion, gives an example of the *First* Law. This suggests his statement of the Third Law is only parrot-repetition. If we offer 5 points for each part, I think we should be as unwise as the student if we just add 5+0 and say he is 50% correct. Instead we might multiply the marks.





NOTE 2
OBJECTIVE TESTS

Objective tests have a curious history: starting with an honest revolt, they presently appeared to offer an egalitarian virtue; then they came to be served by machines—and perhaps to be modified by machines too—and now economies of time and labour are often claimed to make them essential as part or all of an examining system.*

Early history Originally, 'objective testing' described the breaking up of an examination question into separate parts, each of which made a definite request and had a definite expected answer. That arose from a revolt against 'essay' questions which left the candidate uncertain of what was required and allowed examiners to disagree about what they expected—so that the marking was not *reliable* (in the technical sense).

For objective tests, examiners were urged to think out carefully all the things they wanted the candidate to tell them and then place each of those expected items in a separate question. Since each such separate question had a definite expected answer, it was possible to put the examination in a format which could be marked by a machine, or by a human examiner working with the reliability of a machine.

* There are doubts as well as uses on both sides of the Atlantic.

In examining Nuffield physics, one of the two O-Level Papers set by the Examining Board is in modern objective-test form; while the other Paper remains a mixture of short-answer questions and essay questions. The first Paper serves a good purpose by its wide coverage. At the expense of great care and skill in its construction, it does ask, in its own way, for understanding. But if the second Paper ever lost its pattern of open enquiry and free response, the public examining of Nuffield physics would exert a stranglehold on the teaching, as seen by teachers and as felt by pupils.

The machines, unlike Nuffield Examiners, would never give bonus marks for extra insight or a good suggestion.

In American practice, it is many years since the Examiners for the College Board's 'Advanced Placement' physics (somewhat like A-Level) voted unanimously to omit the five-answer objective questions as unsuitable for assessing the qualities needed for advanced placement in universities.

Also in American practice, the English essay or composition paper was eliminated long ago from examining for university entrance, on grounds of *unreliable* marking; but it has now returned, in a modified voluntary form, at the insistence of universities—in spite of objections about the great expense of marking.

It is strange that although a small class, a small college, or a small country can find enough examiners for thoughtful marking, large communities complain they have too few—the simple pattern of proportionality that we often use in physics seems to lose its appeal.

The modern form For machine marking, the candidate chooses the 'best' among five printed answers. Other forms have developed also: true-false, matching parallel lists, and multiple-choice questions in which *several* of the answers offered may be correct and all the correct ones are to be chosen for successful credit.

With the skills of modern machines in mind, we might envisage such tests receiving more elaborate marking: highest mark for a specially advanced choice of answer, a good mark for one or more reasonable choices, and perhaps a negative mark for choosing enticing nonsense.

The egalitarian virtue Whether we like it or not, public examinations are political; they play a defining part in the government and development of a country. When public examinations are extended to a wider geographical area or to a wider range of social, cultural, or economic backgrounds, there are obvious dangers of some examination questions being unfair or seeming unfair. Doubts crystallize into a picture of a biased examiner or an unfair examination. Objective tests come to the rescue. Such tests, and their marking, *seem* free from bias. Also they combat anxiety about putting sole trust in careful continuous assessment by individual teachers.

Yet we all know of tests where claims of high *validity* and lack of bias have proved untrue.*

The pressure of economizing As machines (and stencils) for marking were developed, examiners were tempted to adopt objective tests; and many found intense satisfaction in devising their own questions. However, they soon found that the framing of 'good' objective questions is much more difficult than they expected. Where the teaching is aimed at giving understanding or encouraging creative thinking it is hard to keep the tests directed at those aims—it is tempting to shift towards tests of facts, or of routine problem-solving. There is also an odd danger of

* For a brilliant critique of the tests themselves and an account of pitfalls in constructing them, see 'The Tyranny of Testing' by Banesh Hoffmann. The author is an American physicist who has also written on quantum theory and is one of the biographers of Einstein.

choosing items that fit the test format easily, whether they are important or not.*

In recent years, two developments have pressed examining even more strongly towards objective tests in some parts of the world:

(a) Education has been extended to later years for a larger fraction of the population. Thus, more testing and examining is being done, or felt to be needed, without a corresponding increase in the number of examiners available.

(b) Labour costs—in this case, the salaries of examiners—have increased much more than the costs of materials and machinery. With the development of computers, machine marking has become increasingly quick; it has become increasingly amenable to easy statistical analyses. And we hope that in the future it will become more flexible.

Present uses For testing simple knowledge, objective tests promise to be very useful. (For example, in language teaching they can measure progress and skill in spelling and grammar.)

To measure deeper values of understanding—in language teaching, literary skill or appreciation of poetry—objective tests show more doubtful promise.

In science, although objective tests *can* be constructed so that they aim at measuring understanding, there are three difficulties:

(i) A question for understanding requires very careful construction, compared with the ease of making a test for information (cheap recall); so that the intended demand for expensive recall is easily displaced.

(ii) Choosing the single 'best' answer has often proved unfair to the most able students. While average students will select the correct answer as envisaged by the test-makers, students with exceptional knowledge or insight may see that another of the offered answers is even better—yet the marking-machine will call that choice a failure. This danger has received considerable attention in recent years. With questions asking for cheap recall there can hardly be any doubt; but it is difficult to make sure that questions that ask for thorough knowledge are safely framed. And if an element of imaginative guessing is involved, the difficulties of sound construction are extreme, for this type of test.

It is unfortunate that objective tests for understanding are sensitive to the manner and material of the teaching: what is a request for expensive recall for one class may ask another for cheap recall.

(iii) Even with the best and most skilful of objective tests—which can indeed test for understanding *and* tell candidates that they are doing so—students in answering the questions soon lose the feeling of talking to an intelligent examiner and develop an attitude that may be very damaging to education. However wise and clever the test, it appears to the candidate as a sort of game, rather like filling in a crossword puzzle. Students become accustomed to a rapid series of choices, using common-sense to weed out unlikely answers and guessing skilfully but without stopping to draw on full understanding.

Thus the process of taking many objective tests may itself modify the picture that students hold of the field of study. Other forms of examinations can impress their candidates as being much nearer to good teaching and learning. And for that reason we may well hope to see other forms continuing to be powerful agents in curriculum renewal.

* A question used *ad nauseam* at one time asked which characteristic of electromagnetic waves is *not* shared by longitudinal sound waves. The five-answer question offered 'polarization' as the answer to be chosen. True; but not very enquiring as the sole question on Sound.

NOTE 3
EXAMINING OVER A WIDE RANGE OF ABILITY

Pupils with less ability or less *interest* in the field deserve the satisfaction of success in cheap recall and simple recall. They too should have prizes.

At first thought, a long ladder of objective tests ranging from cheap recall to expensive recall and imaginative reasoning would serve a group of pupils with mixed abilities and interests. On second thoughts, that would be a cruel mismatch at both ends of the intellectual spectrum.

Pupils with least interest or ability would be frustrated by finding they could climb so few rungs; ablest pupils would be frustrated too, either fatigued by working through the early rungs or worried by anxiety if advised to omit them.

Short-answer questions would be better, giving each pupil a chance to express his answer at his own level, in his own way.* Yet the essential defect is still there, the spreading of candidates' scores over a wide range—sought after by administrators, regretted by many parents and children and teachers—a result for which examinations have received strong criticism in the past.

Yet we cannot do without assessment altogether, for several reasons such as the following (I give suggestions of solutions in brackets):

(i) Each pupil wants to know how he is progressing. (Then give '*mirror tests*'.)
(ii) For advanced studies or for employment, colleges or employers ask for estimates of either learning ability or training. (Use teachers' assessments; give *'I' and 'U' tests*—described below.)
(iii) Administrations, employers, colleges choosing applicants all ask for calibrations to enable them to compare assessments by different teachers or different schools. (*'C' test* added to teachers' testing.)

* In early trials of the Nuffield O-Level programme teachers were offered, for each Year of the programme, a 'December Paper' and a 'July Paper' to test their pupils. When those were given, pupils in some Secondary Modern classes failed miserably when teachers applied the suggested marking policy. But on re-reading those pupils' answers we realised that the examiner needed to adjust to a different relevant vocabulary; and then we saw encouraging signs of good learning, at least in the first three years.

'C' Tests: an Offer of Calibration

In Sweden, and in some examining in England, each teacher conducts his own 'continuous assessment'* of his pupils, leading to a rank order *which the teacher is not required to alter*.

But occasionally, say once a year, a test is provided by a central board and used *only* for calibration. *No record of pupils' names and scores is returned to the board.* The only use made of the scores is to tell the teacher whether to raise or lower all his marks, to make them comparable with a national scale.

'I' & 'U' Tests, for Two Incommensurable Qualities

Let us be realistic; we do teach science, and pupils do learn science, in two different ways—as different from each other as learning French grammar and spelling is from studying French literature.

To a pupil with intellectual interests and abilities, doing and thinking in physics to build understanding is a pleasant occupation, willingly to be exhibited in a test. To many pupils with other interests, the demands of 'understanding' are difficult or unwelcome, but careful acquisition of facts is feasible, and testing of factual knowledge would be pleasant if it could be well rewarded.

Two such different activities need two different tests. Provided the marks of the two are never added and averaged, but are always recorded separately—as with marks for algebra and marks for French literature—each will contribute a sensible record.

I suggest that each time there is a test or a formal public examination there should be two forms, 'I' and 'U', given on different days.

TEST 'I' for Information (A more polite name: 'physics knowledge'.)

TEST 'U' for 'Understanding' (More politely: 'creative thinking in physics'—and there is a warning to candidates in that.)

Each candidate would be free to take either test or both, and the scores on the two tests would be recorded separately.

* This involves a wealth of judgements, but it does not mean *continual* or *ceaseless* assessment!

Test 'I' would be constructed to reward industry rather than special ability. A high mark would indicate praiseworthy knowledge, which, if enjoyably gathered, should have some lasting value; so that pupils as they grew up to be parents themselves would speak well of science to their children.

Pupils who are bright enough to do well in Test 'U' are bright enough to know the value of what they gain. Employers and institutions for further education would emphasize Test 'U' marks where they consider understanding is needed. And teachers might sometimes have to compare the functions of Test 'I' and Test 'U' in discussions with parents.

Then we would still have a divisive effect of examinations, but we should at least have done our best to make a dual* system that is humane and honest.

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* To the suggestion that the two kinds of test, 'I' and 'U' should be mixed in a single examination there are two objections:
(i) statistical The statistical pre-testing of a mixture of 'I' and 'U' questions is fatal: the statisticians reject the 'U' questions as less *reliable* despite their good *validity*. They obtain a trial group of candidates and first make an overall assessment of abilities—perhaps by using all the tests that are under review. Then they find that the members of the trial group treat the 'I' questions consistently with their abilities. But with the 'U' questions there are arbitrary variations from expected success. Of course there are. The sampling of understanding is more tricky; as in a personal interview, the question has to touch the candidate's fancy if he is to do himself justice.
(ii) We would be back again at enforced discouragement. We should have lost the advantage of 'separating the variables'.

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This volume provides an essential introduction to the revised Nuffield Physics programme. It surveys the original programme and sets out the changes in the new edition. Among the subjects discussed are the setting and marking of examinations (also treated in an appendix), the teaching of Energy in the programme, changes in school structure affecting the teaching of Physics, and some practical aspects including the preparation of experiments and laboratory organization. It also includes an invaluable appendix on teaching science for understanding.

The other volumes of the programme are:

Pupils' Text Years 1 and 2
Pupils' Text Year 3
Pupils' Text Year 4
Pupils' Text Year 5

Teachers' Guide Years 1 and 2
Teachers' Guide Year 3
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Teachers' Guide Year 5

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