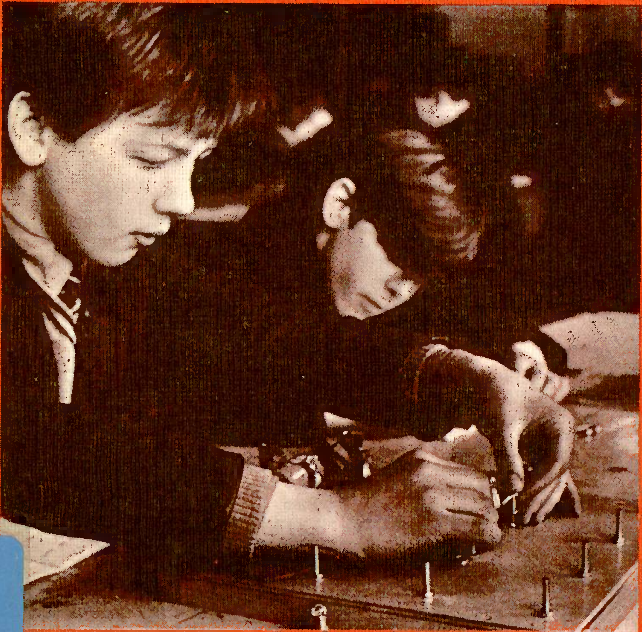
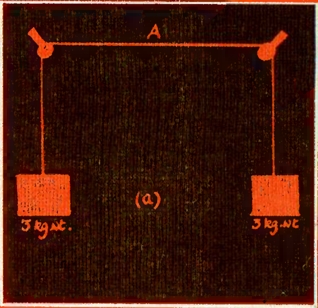
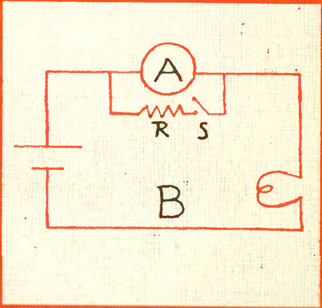
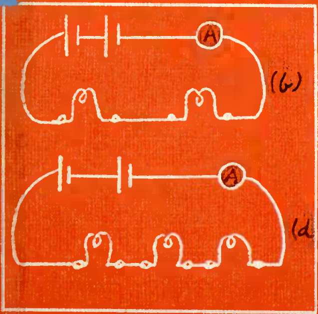
PHYSICS

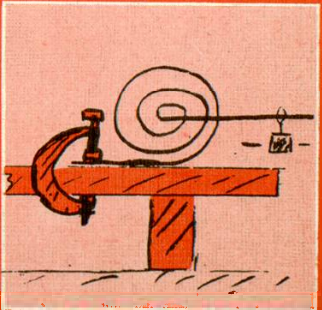
Teachers' guide II











NUFFIELD PHYSICS TEACHERS' GUIDE II

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FOREWORD

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

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

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

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

Brian Young
Director of the Nuffield Foundation

CONTENTS

ESTIMATED ALLOCATION OF TIME

YEAR II

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

Chapter 1	4
Chapter 2	13
Chapter 3	8
Chapter 4	8
Chapter 5	10
Chapter 6	9
Chapter 7	8
	60

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

KEY TO MARGIN REFERENCES

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

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

PREFACE TO YEAR II

This is a year of growing acquaintance with physical phenomena and some more instruments, with a little more emphasis on organizing the knowledge in a scientific way – by looking for general rules of behaviour and by using imaginative models.

Connections with Adjacent Years
Before thinking about the content of Year II, look forward to Year III and look back on Year I to see where Year II should lead and what it can build upon.

Year III will want to draw on the following topics‡ treated in Year II:

a. A good idea of forces and their measurement;

b. Clearer knowledge of *forms* of energy, and much discussion of *changes* of energy (with the idea of conservation taken for granted at this stage);

c. A confident working knowledge of simple electric circuits (currents and ammeters, but *not* voltmeters); also a little knowledge of electric charges and their forces;

d. A growing use of the picture of matter consisting of atoms or molecules in motion.

Year I should have established a general tradition of independent experimenting and of some critical thinking. It should have given an informal introduction to several concepts that will be developed and used in later years. A first acquaintance with these concepts in Year I, with a few illustrations and simple use of them, will start a growing sense of familiarity. After further use in later years, a formal discussion with experimental tests and illustrations, will raise the concept to the level of scientific knowledge.

And in Year I, children will have done several experiments that provide essential preparation for the following years.

‡ See later pages for a more detailed discussion of connections between Year II and Years III and I.

Here are the most important of those provisions made by Year I:

a. Concept of forces as pushes and pulls, measured by springs, etc.

b. Concept of energy, 'something provided by fuel or food; to do "useful jobs" '.

c. Concept of work as measure of *energy-changes.*

d. Concept of atoms and molecules as particles of which things are made; gas molecules in rapid random motion.

e. Class experiment to measure the *length* of an oil molecule.

f. A look at the Brownian motion of smoke particles in air (class experiment for every pupil).

g. Class experiment with a seesaw to look for a lever law.

h. Experiment to investigate one pulley system.

i. Discussion of seesaw and pulley system as machines to 'multiply' force and as machines to transfer energy without any increase. Comparison of input work and output work.

Content and Teaching of Year II

As in Year I, class experiments play a very important part in Year II. They provide new knowledge and they give children experience of working as scientists. We must give children plenty of time to arrange their experiment, to try it out; to change things round to make it go better; above all, to enjoy doing it with a feeling that it is their *own* experiment. In fact, when a child asks whether the experiment is going well enough, or whether something is 'right' the wise teacher will often reply, 'It's *your* experiment. You are the scientist today.' This can be put to children in a class with such success that they have a strong sense of delight and personal ownership. Some teachers in trials report that pupils are seriously disappointed when they find that the law of springs which they have just discovered in their own experiments was discovered and stated clearly by Hooke three centuries ago. When they see that history in a book or are told it by the teacher, it is an anticlimax. Yet other teachers report great interest when such a historical study is added to the story that emerges in the laboratory. The choice between leaving the result the pupils' own and bringing in the historical commentary must be an individual one for teachers to judge in terms of their own tastes and those of their class. In any case, we urge teachers to give open, undirected, work in class experiments as much encouragement as possible.

For such work in class experiments it is very important to have plenty of apparatus and materials available. In a later year, we can tell pupils they should ask for extra equipment that they need, or even to fetch it from the proper place. But here we are still leading strangers in this land of physics so we must make the general topography obvious.

Beginning the Year with some revision and extension of Year I's study of Forces and Energy, should not take long. Even if pupils seem to have forgotten a lot, or seem to have missed it all in some mysterious way, a quick look at those things will suffice to start them thinking about such matters again – then we shall come back to them seriously later in the year. The only essential points about forces now are:

to see and feel the forces between magnets;

and to discuss briefly 'turning effects of forces'

both these, of course, as class experiments.

Electric Circuits. Then, within the first two weeks of the term, children should embark on the long series of simple class experiments with electric circuits, using the Worcester Electric Circuit Kit. At this stage, work in the laboratory should be constructive play, with a large share of the planning done by the children themselves.

If the teacher draws circuits, any child can soon follow the drawing obediently without knowing what he is doing; and if the teacher gives a short talk before each experiment the work will proceed quickly and efficiently, but the children will miss a lot of the fun of doing experiments and they will not have built the capable lasting knowledge – 'I can make electric circuits work' – that they can gain from doing the experiments on their own.

These electric circuit experiments can profitably continue for many weeks. Only occasionally should we interpose a demonstration. Instruments, such as the home-made ammeter and then the commercial one, should come in as things to use and not, at first, as things with a mechanism to be explained – we should remember how we use a stopwatch without opening it, and without teaching anything about S.H.M. or compensated balance-wheels.

Many simple questions for homework or class discussion will help pupils to proceed to the next stage of thinking and doing, and will give them a sense of advancing knowledge. We may even remind a pupil 'You couldn't have answered that a month ago'.

Running from the simplest circuit with a battery lighting a lamp to the first glimpse of a cathode ray oscilloscope, this series of experiments can contribute an enormous advance in knowledge. *We must give it time.* The outcome we hope to achieve is a cheerful sense of confidence with electric circuits rather than clearly organized sophisticated knowledge that can be produced in an examination. There will be more work with electric circuits in the later years.

Force and Energy continued. We look at further examples of forces, including a quick look at solid and fluid friction in class and demonstration experiments: all of this is to give a sense of familiarity and a clear picture of forces as pushes and pulls that can be measured by springs or stretched rubber threads. Repulsions must take their place with attractions, which somehow seem more natural to most children.

With a fast group the idea that a collision involves repulsions that grow steeply at close approach might begin to modify the natural view that a collision must have a smash of 'contact'.

The effect of adjustable fluid friction in bringing a falling object to a terminal velocity should be explored, in preparation for Newton's laws in later years. (To children as to adult Greeks, constant velocity is the *natural* result of a steady force; and we need to face this before we can say that Newton's First Law tells the true story.)

This should be a short review of forces, with newtons suggested for measurement and weight described as 'the pull of the Earth'. It might even include a first look at the idea of gravitational field-strength measured in newtons per kilogram. Throughout this we should try to use 'mass' in the proper places without much comment on it. We insist that *weight* is a *force* (with the peculiarities that it is 'vertical and unavoidable'). We suggest that *mass*, unlike weight, is a stodginess of stuff that stays the same everywhere. We shall look at motion force and mass informally in Year III and we shall study Newton's Laws in Year IV; so there is no need for more than glimpses now.

The discussion of energy in this Year should be fuller and more mature than in Year I. We should use [work] calculated as [force] × [distance] as the measured *transfer* of energy from one form to another form. (See the special Note on Work in the General Introduction.)

We should carry children through many examples of energy changes in great variety. Although some changes can now be measured by work, this should still be a light-hearted tour to get acquainted with the very important foreign country called Energy. It should be a holiday trip, crowded with exciting events. We should not spoil the fun by expecting formal descriptions at this stage.

In those many examples where a human being or an animal does a job we should continue to pay attention to the source, chemical energy from food.

Heat. In this Year we touch upon heat, measured by a weighed mass of water and a thermometer; and then we hand calorimetry over to the Chemistry Course.

Children see some of the effects of heat – if possible in class experiments – but should not spend long on them.

'Circus' of Heat-transfer Experiments. The Year ends with class experiments to look at convection, conduction and radiation. These experiments have clear instructions like a cookery book, but leave the children on their own in drawing conclusions: 'You are the detective. Look for clues in the experiments you do, and see what you can extract from the clues you find.' That is an attitude to science which we put now in a cheerful informal way; but we shall try to continue it through the years.

Notebooks. During this year we should keep the experimenting informal and exciting. Children will need to make notes; but they should not fill their notebooks with definitions or long records. It is still their personal memory that matters most.

Outcome of the Year. By the end of this year we hope the children will have a fund of skill with simple electric circuits, a surer acquaintance with energy, some knowledge of heat and its effects – all in the form of a confident view that science is interesting and worth doing. We are continually aiming at a feeling that 'Science makes sense'.

Connections with Year III (a more detailed discussion)
Year III will start with wave motion and light, leading to optical instruments; and that will need no preparation now.

Year III will provide new apparatus for simple class experiments to investigate motion; those will lead to ideas of velocity, constant velocity, changing velocity, acceleration, constant acceleration. With this preparation, pupils will have a first look at the ideas behind Newton's Laws of Motion – little more than a rough qualitative look at that stage, illustrated by class experiments. Falling bodies and projectiles and satellites will enter into that informal treatment; and the idea of a gravitational field with a definite 'strength' may be introduced as a formal concept. All that will prepare for more mature and fruitful studies of dynamics in Years IV and V. Year III will need to draw upon a good knowledge of force, treated anthropomorphically as a push or a pull experienced by muscular sense and measured by the stretching of springs or by groups of standard springs in parallel. So Year II should build up a comfortable, clear picture of force so measured.

In Year III we shall refer to energy from time to time, particularly in a qualitative continuation of kinetic theory; but we shall not continue formal development of energy, and discussions of energy conservation, until Year IV. In Year II we proceed from a study of force to the idea of energy change measured by [force] × [distance]. This repeats and continues the discussion of energy from Year I.

In Year II energy of motion will be an important form in our discussions. We may name it kinetic energy but we shall not arrive at the expression $\frac{1}{2}mv^2$ until Year IV.

Heat will be an important form in Year II – but as something measured directly and only vaguely suggested as a form of energy.

In Year III we shall use a new kit to continue the series of class experiments with electric currents, magnets, etc., started in Year II. So, in Year II pupils should acquire skill and familiarity with the first electric circuit kit and learn by experience the use of ammeters, rheostats, etc. They should be ready to proceed to magnetic fields and motors and electromagnetic induction in Year III. Voltmeters come into proper use in Year IV. For that future work, pupils need confident command of the simple class experiment apparatus; therefore the experiments in Year II deserve plenty of time.

Years III and IV also need preparation, through our treatment of energy, for appeals to energy considerations in discussions of voltage and the phenomena of electromagnetic inductions.

In Year III there will be a short discussion of electrostatic induction and demonstrations of electric fields, for which Year II should prepare by giving simple knowledge of charges and forces exerted by charges – but complicated electrostatics experiments should be postponed.

In Year III pupils will return to the picture of gas molecules in motion from Year I and the general atomic and molecular picture of solids, liquids and gases used as a *model* in Year II. In Year III temperature will be linked qualitatively with kinetic energy of gas molecules and there will be simple demonstrations and experiments on gas laws and a discussion of absolute scale of temperature in terms of kinetic theory model.

Note to Teachers. Please see the General Introduction to Year I for important notes on:

The role of the word 'constant' in science
Work Conservation of Energy Perpetual motion

Notes follow on:

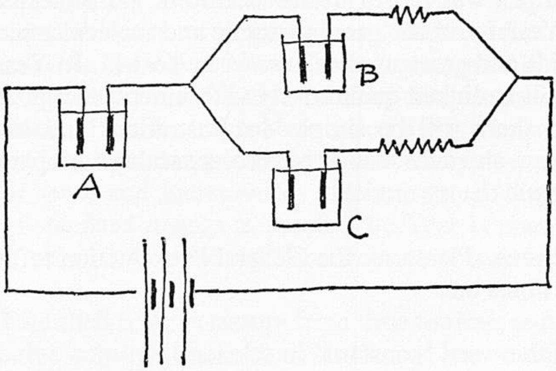
Energy in Year II Current and the flow of electricity

NOTE ON ENERGY TEACHING IN YEAR II

In the *Teachers' Guide* for Year I, there is a section dealing with energy and energy changes. Before teaching energy in Year II, teachers should look at that treatment in Year I. They will find considerable duplication between Year I and Year II. That is an intentional overlap to provide for differences in pace. There should of course be some overlap – to teach in several overlapping stages is one of our main principles in constructing this course – but there should not be as much duplication as the full teaching of our suggested Years I and II would make.

NOTE TO TEACHERS: CURRENT AND THE FLOW OF ELECTRICITY *(this is a note from one physics teacher to another)*

The words 'current' and 'flow' were introduced in electrical studies long before electrons or any other things were known to be really there and moving. Those words were used because there is *something which is the same all the way round the circuit*; and, because, when a circuit divides into two branches which later reunite, the values of that something in the two branches add up to the value of that something in the main circuit before and after the divided part. That something could be the strength of magnetic field on a standard coil, or it could be the rate of producing hydrogen in a standard electrolytic bath or the rate of carrying copper across in a copper-plating bath.



Thus we might insert a copper-plating bath A before the circuit divides, and then two similar baths B and C in the two branches, and we should find that the masses of copper carried across added up, $m_A = m_B + m_C$.

However, if instead of copper-plating baths we inserted three equal pieces of high resistance wire, each immersed in water to catch the heat developed, we should not find that heat developed in A = heat developed in B + heat developed in C, $H_A = H_B + H_C$. We should not find an additive property, unless we made the surprising move of taking square roots. That was one reason why the heating effect was not adopted as a simple measure of electric current.

In a way, then, early electrical investigators chose, for their own convenience in measurement, a property (magnetic effect or chemical effect) which does give additive effects where a circuit divides into two branches. So those early electrical scientists had no clear reason to believe there was a real flow; but having chosen their system of measurement to give the same properties as flow of a conservable fluid, they spoke of electric currents flowing.

It was some time before the properties of electrolysis made it seem quite likely that there are discrete electric charges moving in solutions; and it was much longer before there was evidence of electrons; and longer still before we could be at all sure that currents in solids are a flow of electrons.

We now know that currents in solids are not always just a flow of negative electrons: in some solid semi-conductors, there is a flow of positive 'holes'; and in some solids, positive ions can be driven to flow. When a gas conducts, as in a spark, there is usually a complex mess of positive ions, negative ions and free electrons, each moving in an appropriate direction. When a liquid electrolyte carries a current, both positive and negative ions move; and in *some* cases we can even see their motion.

We feel sure that a current in a metal is a flow of negative electrons, but in the last quarter of a century we have modified our detailed picture of that considerably. Forty years ago, the 'free' electrons in a metal were thought of as behaving just like a gas, moving at random with the appropriate kinetic theory speeds for 'molecules' of their small mass. Nowadays, our knowledge of atomic behaviour, summed up by quantum conditions, makes us picture those electrons moving at much greater speeds still; they behave as if they were squeezed up to far higher regions of temperature and held there with no way of taking a more reasonable speed. And they can travel through a well-ordered crystal lattice for great distances without making a collision. (The former peculiarity shows why free electrons do not contribute much to the specific heats of metals; and the latter peculiarity suggests why they help so much in the conduction of heat.) Then, when we apply a potential difference to, say, a copper wire, the electric field which is thus applied imposes a very slow drift on this rapid random motion of electrons in the metal, in practical cases a drift of a few inches per hour.

With this complicated picture of metallic conduction in mind, one easily feels hesitant about saying 'A current is simply a crowd of negative electrons driven along the wire, and therefore let us reverse the traditional arrows, paint the red knob of the battery black, and perhaps even interchange the names *positive* and *negative*'! In view of the enormous investment in instruments and books, and the whole tradition of training in electrical engineering, most physicists hesitate to make a change of conventional arrows of circuits, etc., in order to be 'true' – where that new 'true' statement would apply only in some cases.

So in this programme we shall follow the standard traditional arrangement of calling the charge of glass rubbed with silk positive – a convention instituted by Benjamin Franklin – and the red knob of the accumulator (with brown plates), or the carbon of a dry cell, positive.‡ And we shall draw arrows on circuits pointing round the outside circuit from positive to negative.

We know quite well that negative electrons in metals flow the opposite way from that arrow; and we shall presently expect students to know that and remember that without being muddled.

Sometimes when a colleague argues strongly in favour of a reforming change we may offer him the story of the Army receiving in the middle of war a large packing-box which arrived at the battle front with a letter which explained 'This box contains delicate scientific instruments. It is essential for their safety that the box should be opened at the bottom first. In order to avoid confusion, the bottom will be labelled "TOP".'

‡ Until recently, dry cells have followed the pattern of their obsolete ancestor the Leclanché cell, and have been made with the positive carbon in the centre. Now, some makers are beginning to place the carbon in the outer shell, making the central rod the negative pole of zinc.

Chapter 1

FORCES

Turning Effects; Magnets

Programme. *We begin the Year with a series of class experiments on electric currents; and later in the Year return to discussions of force, work and energy. However, the first lesson of the Year should go back to ideas of forces, to provide just enough knowledge of forces to enable us to introduce a simple 'straw' ammeter for electric currents.* * * * * *

MORE ABOUT FORCES

This first lesson (which may well spread to two periods) should be a mixture of demonstration and class experiments. Start by asking the children what forces are, and accept all the suggestions which are concerned with forces pushing and pulling and having effects such as stretching, twisting, bending, etc. Point out that the easiest forces to know about are the ones that we feel ourselves when a muscle helps us to pull up a weight or hold a load, or when a pencil makes a dimple in our cheek, or when someone pulls our hair. T

Teachers may like to ask some questions about the ways in which a force can be exerted. Some are suggested in the box (Specimen Problem A). These will enlarge pupils' knowledge as one pupil suggests things to others, and they will promote discussion. A teacher in preliminary trials reports that he considers this collection too hard and too long for use in class as it stands. He used half a dozen parts successfully, but even then not every pupil had a chance to answer. If these questions prove really fruitful in promoting discussion, teachers may want to devote considerably more time to them – regarding the questions and discussions as a very important part of the teaching. That is why we suggest so many questions in the box.

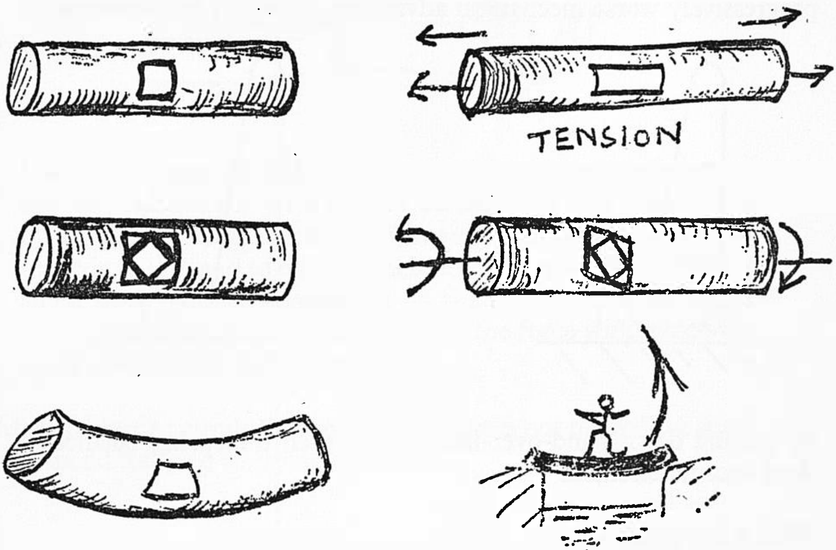
If you like, ask, 'Which is the force you feel: the force you use against somebody else, or the push of somebody else against you?' Do not continue into what would seem a very puzzling, and unnecessary discussion of Newton's Law III at this point. This is a casual question to be left dormant.

Then give pupils an assortment of things – rubber bands, shirring-thread, a steel spring, a piece of thick rubber tubing to try forces on, a piece of latex foam for compression, and a piece of plastic foam for inelastic compression. These could all be in a small tray, containing the assortment for each pair of pupils. C1

> 'Instead of judging forces by how far the pencil pushes into your cheek, or how much it hurts when some force twists your ear, have a look at forces doing things to rubber and springs. Fifteen minutes to find out anything you can, without other apparatus.'

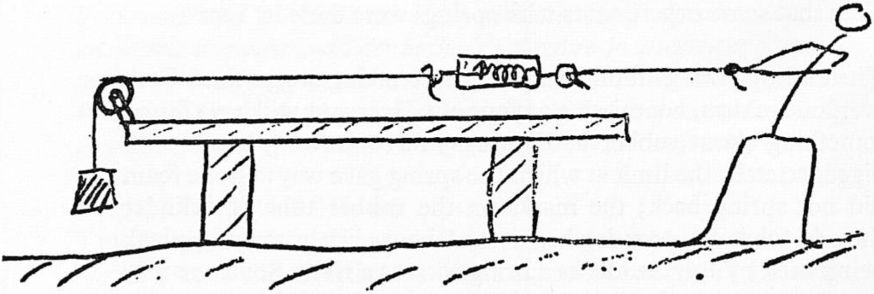
Note that some experiments with springs were done in Year I.

Then ask for things found out, of course taking suggestions from everyone in turn, not missing anyone out. Everyone will have found something about rubber and springs§ force growing bigger with bigger stretch; the limit at which the spring gave way; plastic foam did not spring back; the marks on the rubber tube or cylinder showed what happened when it was bent, like a sagging plank being used by Boy Scouts as a bridge across a river. Someone may even have found what happens to the tube when it is twisted. To encourage such observations there should be some ink patterns already on the sample of rubber, preferably a set of squares.

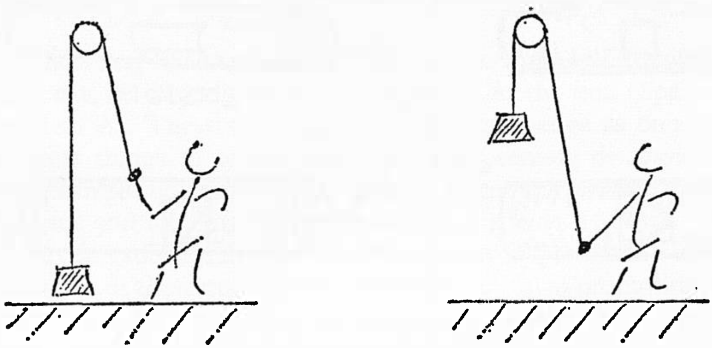


Ask if forces always get bigger and bigger when you go further. D2
Asked in this vague way, the question will probably get the answer 'Yes'. If so, offer an experiment on the lecture table in which a load (a small bag of sand, or a half-kg weight) resting on the floor is attached to a cord which goes up and over a pulley held firmly so that pupils can pull it and go on raising the load while they pull the string a considerable distance. If there is time offer any unbelievers a spring balance for that.

§ A teacher in trials reported: 'Yes, but many are much more elaborate than I had expected. And this takes a long time.'
Another said: 'The wide steel springs, compressed on the bench and released, will reach the ceiling. A discussion on energy changes followed.'



The horizontal arrangement is probably better than the more obvious vertical one in which the weight does get more difficult to pull down as it rises because the arm muscles are being used at a progressively worse mechanical advantage. This can be overcome



by pulling down hand-over-hand – and then the spring balance does become essential.

With a fast group ask: T

'How do you suppose the marks were put on this spring balance? Would you trust them? Could you test them?'

(Leave those questions unanswered.)

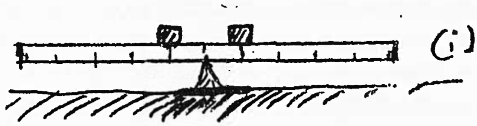
Sometimes a force has no visible effect at all.

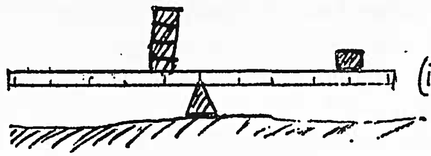
'Suppose you sit on the table. Do you push on the table with a force? Does the table move? Does it go on moving? Does it stretch, or bend? Well, are you *sure* it doesn't stretch or bend? Suppose we made a table with a very thin plywood top and you sat on that? ... Even with a thick table, I suspect, we should find that while you are sitting on it you make a dent in it, but it is a very small dent and you would need special apparatus to see how much you pushed the table down.'

TURNING EFFECTS OF FORCES

(A brief treatment, needed for electric experiments.) C3a

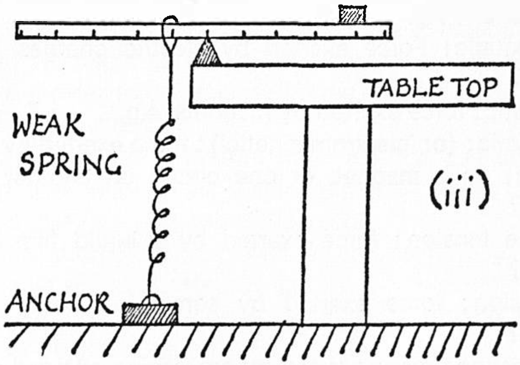
Provide the simple lever and fulcrum or pivot from Year I for a class experiment. In this case, do not offer it as an open experiment to play with, but ask pupils to do the following:





'Balance the seesaw empty, then place a load 1 one space out on the left; balance that with a load 1 on the other side. Then build up a bigger and bigger load one space out on the left by changing to loads 2, 3, 4, and so on; and each time balance that load with a single load 1 placed somewhere on the right. Here you have a sort of weighing machine for weighing the force with which the earth pulls the left-hand load down.'

Make it clear to pupils that an *exact* balance is not needed: or some will spend too long worrying about this.



When the children have tried that, replace the big variable load on the left by a spring. For that, they should place the seesaw with the C3b

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

A. Kinds of forces. Friction forces. Gravitational forces.

This question to be answered orally, round the class.

Notes to teacher:

1. If some of these are too difficult, omit them.
2. If there are not enough to go round the class, go round again with the same questions but asking for different examples.

The list below gives a number of ways in which a force can be exerted. For each of these *give*, in one sentence, *an actual example of the kind of force mentioned.* (For example, under *a* I might say 'e.g. when I start to walk I push backwards on the ground with my foot'.)

a. Motion: force exerted by something starting to move (or accelerating) e.g. . . . ?

b. Motion: force exerted by something slowing down (or stopping) e.g. . . . ?

c. Motion: force exerted by some moving thing whose direction of motion is being changed (without noticeable change of speed) e.g. . . . ?

d. Tension: force exerted by a stretched solid material, e.g. . . . ?

e. Compression: force exerted by a compressed solid, e.g. . . . ?

f. Compression: force exerted by compressed liquid, e.g. . . . ?

g. Compression: force exerted by compressed gas, e.g. . . . ?

h. Friction: solid moving over another solid, e.g. . . . ?

i. Friction: solid moving over, or through, a liquid, e.g. . . . ?

j. Gravitation: e.g. . . . ?

k. Electrostatic: Force exerted by electric charges at rest, e.g. . . . ?

l. Magnetic: force exerted by magnets, e.g. . . . ?

m. Magnetic: (or 'electromagnetic'): force exerted by current (in a wire) on a magnet, or one circuit on another circuit, e.g. . . . ?

n. Surface tension: force exerted by a liquid film or skin, e.g. . . . ?

o. Expansion: force exerted by something being heated, e.g. . . . ?

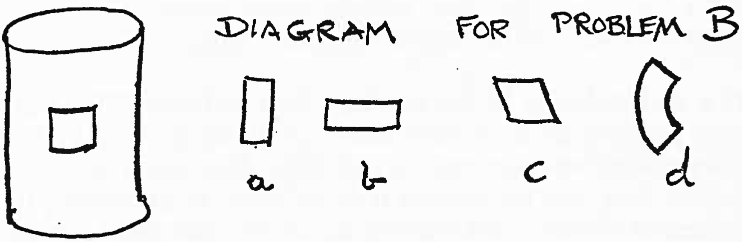
p. Contraction: force exerted by something allowed to cool, e.g. . . . ?

q. Any other sort of force that does not come under any of the above.

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

B.

The sketch shows a square drawn in ink on a short piece of thick rubber tubing. The tubing is upright (vertical) and is fixed firmly to the table at the lower end. Some kind of force, a pull, a push, or a twist, is applied to the upper end and the square is pushed out of shape into the rectangle (*a*). Remember that the tubing is vertical (upright) and is held fast at the bottom. Then that force or twist at the top is removed and another kind of force is applied, to produce the shape (*b*). Then (*c*); then (*d*). For each case, say whether a push or a pull or a twist is applied. If a twist, say whether the direction of the twist on the upper end is clockwise or anti-clockwise.



C.

Five effects, or results, that a force can produce are listed below. Copy the list and add one example to illustrate each, e.g. after (*a*) we might add 'A sailing yacht: the wind freshens and exerts a greater force (pushes harder) in the sails so that the yacht moves faster'.

a. Acceleration in a straight line: a force can start a body moving and increase its speed, e.g. . . . (give an example different from the one about the yacht).

b. Acceleration in a circle: a force can start a body rotating and increase its speed of rotation, e.g. . . .

c. Slowing down or stopping (of objects moving in a straight line or of objects rotating), e.g. . . .

d. Opposing other forces so as to keep a body at rest, e.g. . . .

e. Overcoming other forces so as to keep moving with constant speed, e.g. . . .

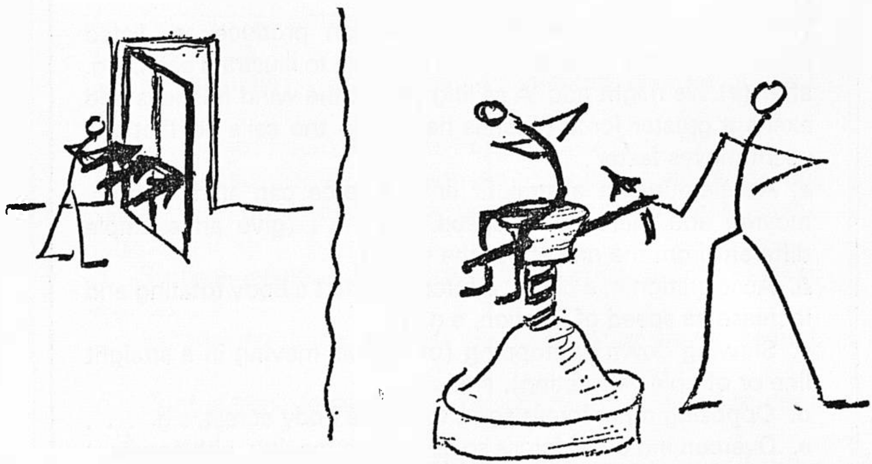
f. Deformation of size or shape or both, e.g. . . .

D.1

A man steps off a moving bus and falls heavily. In what direction does he fall and what force or forces caused him to fall? (He is a rather silly man, but you can assume he was sensible enough not to hold on to the bus as he stepped off!)
This man provides *two* examples of effects of forces listed (*a*) to (*f*) in question C. Which two?

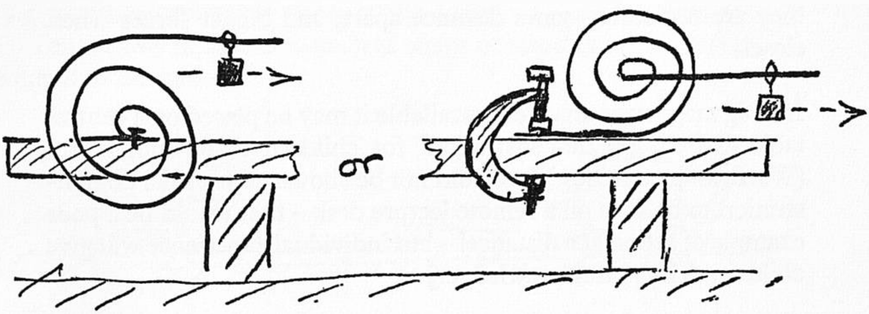
left-hand arm overhanging the edge of the table; they should tie a thread round it at one space out to the left and attach a weak steel spring to that thread; stretch the spring so that it has a small tension by hanging on it a big weight that rests on the floor keeping the spring at a more or less constant stretch. Show pupils how to arrange that and then ask them to measure the pull of the spring by moving a load along the right-hand side of the seesaw until it balances. (Obviously, a teacher will need to practise this so that he can give hints to get this done with the actual spring.) This gives some practice with the use of forces to turn things.

Give a demonstration of the turning effects of forces. That was shown, perhaps, by the seesaw class experiment in Year I, but turning effects were not emphasized then. Now use a squeaky classroom door, and try pushing it at the hinge, at the handle, at intermediate distances. Ask whether a push or a pull has the same effect if you apply it near the hinges, half-way out, or all the way out. D4



Or place a heavy object such as a boy on a builder's screw jack, or on a chair containing a spiral support to adjust the height. Raise the load by pushing gently on the side arm of the jack, or on a pole through the arms of the chair. Ask the same question. D5

Finally, show a demonstration of a spring like a giant hair-spring being twisted by a force applied to an arm. This may be a large clock-spring, released into an open flat spiral with one end fixed and the other end carrying a horizontal arm along which a weight can slide. This is just a qualitative experiment to show how, with the help of a spring, one could measure the effect of forces twisting something round an axle. D6



Magnets and Forces

'Most of the forces we have thought about so far come from our muscles or other springy things; and other forces come from the pull of gravity as we call it – the weight of things. But there are other kinds of forces. Try some magnets.' T

Then the teacher should give the children magnets for class experiments: two cylindrical magnets, two horseshoe magnets, some iron filings and nails or some other scraps of iron. Let the children feel the forces between poles and then let them use the magnets to pick things up. Small compass needles can be available as well, but the main business here is to encourage simple play with magnets, so that children can feel the forces between them and know something about their behaviour for use in electrical experiments. The instructions are: 'Find out what you can about magnets. Have a good time with them.' Five minutes with some magnets would be too short: it would be irritating and muddling. Half C7a an hour with magnets is probably enough. More than a whole period spent with magnets, making notes and perhaps giving special names to things, would be out of place at this stage. Note-taking would do more harm than good, by delaying things. If pupils ask, say:

> 'Yes, the places where the filings cling are called "poles".'

Encourage pupils to feel the forces between poles. Ask questions such as, 'Do the ends always attract each other? Try different ends on each other.' But do *not* give a formal statement about like poles repelling, etc.

The important thing to point out is that magnets exert forces when they are noticeably some distance apart, and bigger forces when closer. T

If a big magnetron magnet is available it may be placed on a central table as a 'pupil demonstration' for children to try things on. (Warn about watches.) It should not be shown as a formal demonstration to be seen on a remote lecture desk – that would be a poor example of action at a distance! – but individual experience will give children delight and knowledge.§ D 7b

(The question of North and South poles may crop up. It can be settled quickly by hanging up a bar magnet and showing that it does point roughly North and South. Say that we call the pole that points North the 'North-seeking' pole.) T

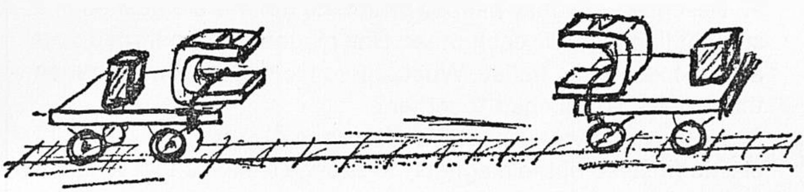
Note to Teachers on the 'North Pole Paradox'. Sometimes *
pupils get into a tangle about North and South poles when they *
learn that the Earth must be a big magnet and the pole up near the *
geographical North Pole must be the opposite type to a North- *
seeking pole. They waste time over the paradox that the Earth's *
North magnetic pole must be a 'South' pole. That is not a good *
scientific paradox that encourages thinking and makes people enjoy *
puzzling a problem out; it is merely a wrangle over wording which *
is best cleared up at once. *

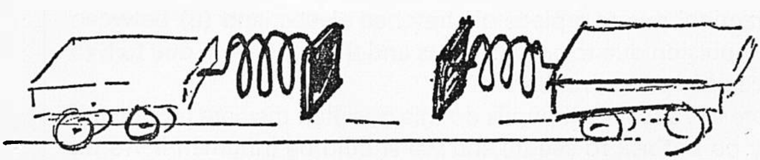
> 'We call the end that points towards the North "the North- *
> seeking pole", since it points to somewhere near Alaska, where *
> the Earth seems to pull it, the Earth itself must have the opposite *
> kind of pole there. So the Earth's pole there is a South-seeking *

§ 'This really enthralled them. They tested the "action" through table, glass, flesh, etc., with iron filings and magnets.'

type of pole. You can keep it clear by calling those poles "North-seeking" and "South-seeking", and – this is a command – no one is to shorten those into plain "North" and "South" until he is quite sure that he knows what that means: that "North Pole" is short for "North-seeking pole". Then there need be no puzzle just because the Earth does have up in Canada, a South-seeking type of pole which might be called for short a South Pole.' * * * * * * *

As a demonstration, put two horseshoe magnets on toy train wagons on a section of level track, and then push one wagon towards the other stationary one, so that they collide with the repulsion between the magnets driving them apart. (If larger trolleys or roller skates are used instead of the toy train wagons, they may slew sideways in the collision so that the magnets will cling together, unless we compel the trolleys to run on rails or between narrow boundaries, such as strips of wood or metre sticks clamped to the table.) D8





Then show a collision with something else like buffer springs producing repelling forces instead of the magnets. Instead of the magnets, clamp to the front of each wagon a small piece of wood carrying a wide spring which projects out in front of the wagon and carries a disc as buffer on its outward end. D9

These collision demonstrations are important things for children to see; but at this stage, there should be *no* mention of momentum or of Newton's Laws: simply a remark, 'Look at the kind of forces that can act in collisions.' T

Chapter 2

ELECTRIC CIRCUITS

Lamps, Switches, Ammeters

Explain that we shall come back to forces and work and energy later in the Year. (The pupils should have been through Year I. Any who have missed Year I should be given an account of the discussion of forces and work and energy of that Year.)

This raises a general question: the fate of things done and learned in earlier Years. We should do all we can to suggest that the science pupils are learning will grow and that they will use the things they have learned before – that should not be a weapon to threaten 'You must learn this and remember it', but we should use it as an encouragement, 'This is going to be important and useful later on'.

INTRODUCTORY COMMENT TO TEACHERS

We shall now proceed to electric circuits, studied by class experiments. There are three reasons for spending time and trouble on electric circuits:

1. general importance in this electrical age;

2. in our physics we shall do a lot about atoms, and these pupils will need to know about electricity before they can understand experiments relating to the structure of atoms;

3. we have a whole lot of experiments with electric circuits that pupils can do on their own, so that they find what scientific work really feels like.‡

‡ To encourage home trials by pupils as an important educational experiment, a small private fund is available to underwrite the possible loss or damage of apparatus while on loan. We hope that pupils will be able to take home a Worcester Circuit Board kit, a current balance, and perhaps electrolysis experiments. We hope even magnets will be taken home – despite their reputation for disappearing. Where a school lends such items of apparatus to a pupil to take home for experiments and finds that they cannot get them back or the apparatus comes back damaged or broken, they should apply to:

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

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

These are obvious reasons which all of us teaching would certainly *
have in mind; but we should also give these reasons to pupils if *
occasion arises – it is often good for the patient to know why he *
receives the medicine. *

CLASS EXPERIMENTS WITH THE WORCESTER ELECTRIC CIRCUIT KIT

We should do our utmost, particularly in early trial years of this *
part of the Nuffield Programme, to enable children to work on their *
own with this kit. That means that we must make sure they have *
enough apparatus to work in pairs, and we must give them plenty *
of time. Hurrying pupils through, to get an expected result or to *
'finish the experiment today', will spoil things; time can be gained *
by some demonstrations instead of class experiments in another *
part of the course. *

We must also be careful to give help and encouragement without *
giving 'cookery-book instructions'. For these young beginners, it *
would be useless just to provide an assortment of apparatus and no *
instructions. We certainly must tell them what to do, and what to *
do next, and next after that, and so on. But we do not need to tell *
them what to find, what to expect; nor do we need to tell them *
exactly how to carry out the experiment. *

Simple Circuit

On the first day with the Kit, the teacher must explain how the T
pegs and connectors are to be used and should point to the proper ends of the battery: but he should *not* draw circuits, nor even ask for notebook records yet.

In the early stages of this series of experiments, pupils should not be given a complete outfit but only those things which they will need immediately. Extra equipment can be issued as needed; and later on extra equipment may be placed on a cafeteria table at one side for pupils to help themselves as they need.

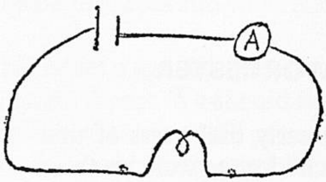
The teacher should let the children try the following simple experiment with these instructions:

> 'You will need to have wires, or something else made of metal C12
> all the way round from the battery to the lamp (or whatever else you are using) and then back to the battery.‡ Try that. Try making a break, or using a switch, which is a thing to make a break.'

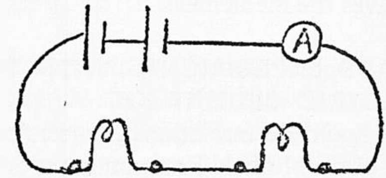
‡ Teachers must decide whether to insist on using the name 'cell' or allow each cell to be called a 'battery'.

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

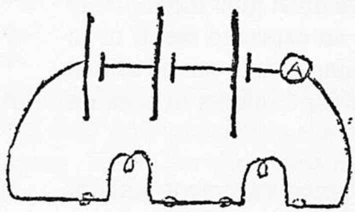
G. Electric currents — Simple currents



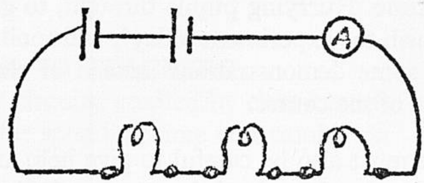
a



b



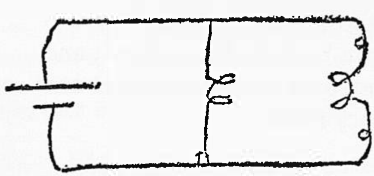
c



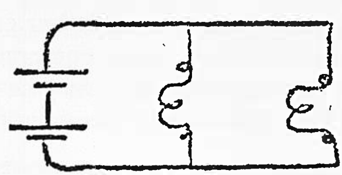
d

The four drawings (*a*), (*b*), (*c*) and (*d*) above each show circuits containing one or more ammeters, batteries and lamps.

1. Which symbol means an ammeter, which a lamp and which a battery? How is the positive end of the battery shown in the symbol?
2. Are the lamps in series or in parallel?
3. If the lamp in (*a*) is at full normal brightness, what about the lamps in (*b*), (*c*) and (*d*)? Are they brighter or less bright than in (*a*)?
4. In which circuit would the batteries run down most quickly?
5. Draw circuit (*d*) and include a switch that would turn off the lamps without any wires having to be disconnected.



(*e*)



(*f*)

H.

1. Are the lamps in circuits (*e*) and (*f*) in series or in parallel?
2. Are the lamps in (*e*) at normal brightness, or much less bright, or much more bright than normal? What about (*f*)?
3. In which circuit would the lamps run down more quickly?
4. Draw circuit (*e*) and include three switches that would turn off *either* both lamps together, *or* one lamp only, *or* the other lamp only.

SUGGESTED INSTRUCTIONS SHEET to be given out to Pupils for Class Experiment C12 with Circuit Boards.

Try the following:

1. Connect a battery to a lamp and make it light.

2. Try the battery the other way round.

3. Now try the circuit but arrange it so that it is a different shape.

4. Try the single battery, but with two lamps.

5. Repeat everything you have done already with one lamp, but using an extra battery. Remember that there are two ways of arranging the batteries – with them facing the same way and with them facing opposite ways.

6. Now try these experiments using the two batteries and two lamps.

7. Try again with three lamps and two batteries.

8. Now try with three batteries and two lamps.

9. And with three lamps and three batteries.

1. Join up (connect) a battery to a lamp and make the lamp light.

2. Then try the battery the other way round.

3. Try changing the connecting wires to make a different shape instead of a square. Does the lamp light just as well? (Give pupils a sketch of a trapezoid.)

4. Then try a battery with two lamps and see what you get.

5. When you have done that, go back to one lamp and ask for an extra battery. Try any of the things you have done, but this time with two batteries.

Leave the instructions for later variations alone, but move about among the children and encourage them to turn one battery round the opposite way when they have two batteries.

In one case with two batteries they will have a 'photo-flood' lamp like the ones used by photographers.

6. Then provide an extra lamp for 'two lamps and two batteries' in series, and again suggest turning one battery round;

7. then two lamps and three batteries;

8. three lamps and two batteries;

9. three lamps and three batteries.

Where three lamps are lit by three batteries in series, *with one battery reversed*, we might ask a pupil, 'Does it matter in this case which of the three batteries is backward?'

If in some of these experiments children say that they can see no light from a lamp, ask them to shield the lamp and look carefully for a very faint red glow.

Because of the time delay in manipulating components, the children may not notice the change from bright to 'half-bright'. If so, suggest using a crocodile lead for one of the battery connections so that a quick change can be made from one battery to two.

By now every pupil should have realized that a circuit requires a complete linkage all the way round, that a break will cause the T lamp-lighting effect to stop. On the other hand, 'short cuts' (short circuits) may be undesirable. And the picture should now be building up that one lamp requires one cell, two lamps require two correctly connected, etc., for normal brightness, in this type of cir-circuit. Suggest to children that they can use the brightness of a lamp as a measure of current.§‡

If some children say, 'This is getting too complicated to remember', we should reply: T

> 'You don't have to remember all these things that happen. Next time, I'll show you how to draw the arrangements easily. We shall call that "drawing a circuit". Then we'll make some kind of a record of what happens.'

Lamps as Informal Ammeters. At an early stage of trying different arrangements of batteries and lamps, which will include such parallel circuits as one battery lighting one lamp fully, the teacher should hold a short discussion with the children about using the brightness of a lamp as a measure of current. T

> 'Suppose you call a lamp "fully lit" when it is connected to one cell. Have you ever seen a lamp that is extra bright? Have you ever seen a lamp that is duller than fully lit? Well, let us stick to the cases where the lamp is fully lit and call that one lamp's-worth of current – whatever a current really is. Go on with your experiments, but later, when you make notes of what happened, I hope you will be able to say how big some current was, reckoned in fully-lit-lamps'-worth.'

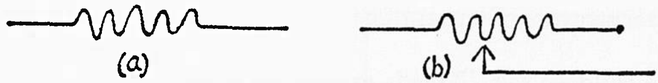
§ 'The children find the work with the circuit board most stimulating and enjoyable and they have organized themselves to give out and check the apparatus so as to spend the maximum time at the apparatus. They have swiftly and easily come to certain very reasonable conclusions and have learnt to make up circuits quickly and with understanding.'
and later:
'This work is certainly causing the most comment and excitement of any so far. This would seem to be because the children already think they know 'all about' electricity and are most engaged to find in fact they do not. They work steadily in almost silent concentration – testing, measuring and designing. They are getting more from this work and giving more than would seem possible and this demonstrates scientific investigation in a most realistic way.'

‡ The Worcester circuit board does not encourage putting cells in parallel. Nor should we encourage that in modern teaching – it is a relic of days long ago when cells had large internal resistance; and it is not done now. On the other hand, generators are connected in parallel – an essential and dangerous operation – in modern grid systems. And lamps in all home lighting are in parallel. Pupils should certainly learn about lamps in parallel.

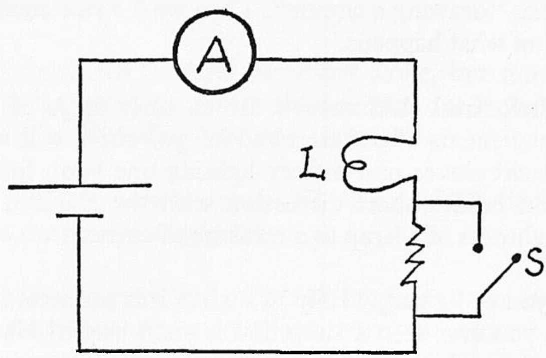
SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

I.

Here are two new electrical symbols:



What do they represent? Describe (one sentence for each) something that you have used that can be represented by symbol (*a*), and something represented by symbol (*b*).



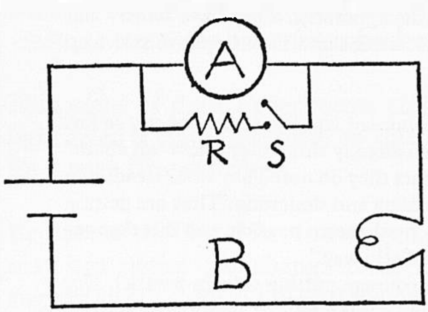
J.

In the diagram S is a switch.

a. What happens to the brightness of the lamp L and the current shown by A as the switch is opened and closed?

b. The ammeter reads 1 amp with the switch closed and 0·5 amp with the switch open. What has happened to the other 0·5 amp? Has it gone anywhere?

K.



a. In the circuit shown, the ammeter reads 1 amp with the switch open (off), and 0·9 amps with the switch closed (on). What has happened to the other 0·1 amp? (In this case the resistance of R must be quite small because the resistance of the ammeter is very small anyhow.)

b. A second ammeter is joined in the circuit at B, next to the battery. This ammeter does not noticeably change its reading when S is opened and closed. Why not?

Heading and Magnetic Effects. At this point, teacher should give a short discussion: T

'This is one of the things that electricity does: something happens when we join the battery with metal to the lamps that makes the lamp filament hot. When you go back to your experiment, try that with a short piece of very thin bare wire and see whether the electric effect makes that hot. ... That is one of the things that an electric current does (why we call it an electric current will be clearer later). C13a

'Now I want you to try another thing that an electric current can do. After you have tried the thin wire, take a long piece of wire and wind it in a coil round an iron nail. You had better use some wire that is flexible, easy to bend. It must be covered with some protecting stuff so that when you wind it into a coil the electric current has to go round and round the coil and not just through a solid lump of copper made by the wire touching its neighbours. Wind it like this. ... Then connect that coil with the nail inside it to the battery instead of a lamp and try to see whether it is a magnet.' C13b

Children will have found magnets picking up iron filings or chips of iron in the first lesson on forces. Explain that: T

'this "magnetic effect" is another thing that electric currents will do. And there are some other, different, things that currents will do. And these things are all we really know currents by.'

Electric Currents: Theoretical Knowledge. (A note for specially enquiring classes.) T

'You cannot see an electric current, or hear it, or know about it by anything except those things that it *does*.

'How do you know that your Uncle George has a bad temper? Because he talks very crossly when you annoy him; or, when something goes wrong, he soon begins to shout or say unkind things. You only know he has a bad temper by its effects. You cannot see a knob on his head labelled "bad temper", or a tribe of little demons dancing in his stomach to keep him irritable. Some of you have heard that when there is an electric current there are little electrons running along in the wire, but you cannot see them any more than you can see the demons in Uncle George's stomach; and for the present we will be good scientists and be guided only by what we see. We shall say "I see a lamp that's lighted, a wire that's hot, or a coil that does something magnetic. That's an electric current, that is."

'Later on, we may decide we know there are electrons running through the wire; but at present that would be a mistake rather like a savage saying that he knows there are demons dancing in Uncle George's stomach.'

Measuring Current: Making a simple 'Current-Balance'

'If heating and magnetism are all we know about a current, we must judge it that way. You were very sensible to use the brightly lit lamp to tell you that you had a current of some definite size. Now, we are going to try to use the magnetic effect of a current. You can make a little machine to show how big a current you have.' T

The teacher should show the arrangement of the Worcester 'current-balance'. Then the children should make it. (See *Experiment Guide.*) The assembling will take time – at least one period – but the whole point of this is to let children make the meter and adjust it themselves, whatever the cost in time. C14a

Children should try this meter in circuits in which they know the current is 'one lamp's-worth', and see what they find. C14b

They should also try this meter in a circuit in which they know the current is less than one lamp's-worth (dull glow) and in a circuit in which they know the current is more than one lamp's-worth (photo-flood). They should be encouraged to arrange these by using an extra battery or an extra lamp and not by inserting resistance wire or a rheostat – these come a little later. C14c

With average or slower groups it may be better to avoid moving the rider along a scale of currents, and just keep it a 'one lamp's-worth'. Then the pupil can classify currents as more or less than that.

They should next try the ammeter with several lamps in a parallel circuit. But first they should repeat the experiment (C 14b above) in which the meter is used in a circuit of 1 battery and 1 lamp where the current is 'one lamp's-worth'. Then a second lamp is added in parallel with the first so that the current becomes 'two lamps'-worth' and the rider of the balance has to be shifted appropriately. Lastly, a third lamp is added in parallel with the other two. C14d

Notebook Records

Up to this point, a careful recording of experiments in a notebook T
would have two disadvantages: first, it would delay the experimenting so much that some children would lose the thread; second, it would make the children ask what to record and how to record it and bring the teacher into the business, and thus spoil the atmosphere of open experimenting. Now, however, when some skill, and some half-understood knowledge, have been acquired, the teacher should give a blackboard talk on how to draw circuits neatly, and how to show lamps and batteries, etc., by symbols.

Then, he should ask the children to draw in their notebooks the C15
circuit for a battery and a lamp, then two batteries and a lamp, then two batteries and two lamps, and so on. Then the pupils should try what happens in each of those, all over again, and make a very short note of what they see.

It is much quicker, but not nearly so good, if the teacher draws all *
these circuits on the blackboard. At a later, much more sophisti- *
cated, stage a drawn circuit is simply a quick piece of codified *
communication between teacher and pupils; but at this stage it is *
nearer to the teacher doing the thinking for the pupils; so it is *
better to let them draw their own circuits. Drawing neatly with *
rulers will take more time than is justified: the drawings should be *
neat but not meticulous. *

Currents and Conductors

Pupils should insert some samples of materials in a circuit to see if C16
they can carry currents easily: a stick of wood, a strip of paper, a strip of copper, a thread of nylon, a piece of aluminium leaf, a pencil lead (which must be of *soft* lead).

Ammeter

When the children are used to 'weighing the current' with the C17a
little 'current-balance', each pair should be offered an ordinary moving-coil ammeter for class experiments (*not* a moving-iron one, whose high resistance is likely to lead to difficulties).

'This is called an ammeter. It does the same job as your magnet-and-coil that weighs the current, only it is factory-made by the thousand and it is marked in the units that all electrical engineers use, amps (short for ampères) so that all ammeters agree.

'You can use this instead of your simple current-balance. Go and try this ammeter with a battery and a lamp, and then with a battery lighting two lamps fully lit, and see if you think it does well as an instrument to measure currents, instead of lit lamps or your simple current-balance.'

If the laboratory already has a demonstration model to show the working of a moving-coil meter with hair-springs, the teacher should show this, but the explanation should be kept brief and should not be laboured – we are anxious to get ammeters into *practical use* here, and shall return to *explanations* with new apparatus in Year III. T

With a very fast group who ask, we might offer the following explanation, but even that should be given lightly, without dictated notes or long discussion – otherwise we shall prejudice the development in class experiments in Year III.

'With your current-weighing machine, the coil pulled the little magnet in, against the counter-pull of the little rider on the other side. In this ammeter, the coil does the moving instead of the magnet. The magnet is a strong horseshoe magnet that stays fixed to the case and the coil is free to turn on an axle.

'When a current flows through the coil, the coil acts as a magnet and it is pulled round by the horseshoe magnet. It tries to turn round to a neutral place between the arms of the magnet, but it is twisted the opposite way by a little hair-spring, like the hair-spring of a watch.

'So, instead of the opposing pull of the little rider-weight, this ammeter has the opposing twisting force of the hair-spring. The stronger the current, the bigger the twisting force made by the current's magnetic effect and the horseshoe magnet; and, the bigger that force, the farther it pulls the coil round *against the increasing opposition of the hair-spring*. The pointer is attached to the coil, so it shows how big the current is.'

Some children may want to continue with the current-balance rather than with an ammeter. We should not discourage that if it is a matter of pride in their own instrument; but if it is due to unthinking habit we should encourage them to move to the modern instrument that can be used so quickly and easily.

Some pupils will then use the ammeter to try more complicated arrangements of batteries and lamps. However, that should not be allowed to delay the general progress.

Switches

Some kind of switch will certainly have been put in the circuit before now; if not, that should be tried. If time permits pupils may try several switches which, with an ammeter will show some interesting things when there are branches to several lamps. (See C22) C17b

Current all round a Circuit

This is an extremely important experiment. Ask pupils to try putting their ammeter in different places in the circuit. C18

> 'Take two lamps and two cells and connect your ammeter in this circuit in a number of different places, between the lamps, between the cells, between the cells and the lamps. Each time, notice the reading. What does this experiment tell you?'

The result may well be surprising, because this idea of resistance is there in common talk, and many people think the current will come out of the lamp smaller than it went in. Even when pupils have seen this for themselves, they will sometimes forget that the current is the same all round the circuit. If we want them fully to appreciate this very important property, we must leave them to absorb it, and not dictate it as obvious knowledge from the teacher. * * * * * * *

Problem. At this stage it might be worth showing a simple problem circuit: conceal a $4\frac{1}{2}$ volt battery in a box and connect it to a circuit of three lamps in series with a current-balance with its rider set at the one lamp's-worth position. Let the children observe the deflection and ask. 'What do you think is inside the box?' Then show the contents. T

'Direction of Current.' The circuit board is useful in predicting where the red and black leads should go to in the circuit and then showing that the prediction does in fact give a downward pull. Of course the current-balance does not tell us which way the 'electricity' really moves: but it does provide an arbitrary reference standard. T

Discussion of Current. Then we can say: T

> 'There *is* something the same all the way round the circuit, the same reading with this simple ammeter, or the same brightness of lamp.'

(One of the two lamps can be moved to a place between the two batteries in series and will still be just as bright.)

'That is why scientists say "There is a current; there is something running round the circuit which stays the same all along, just like a current of water in a river." If a river is carrying 1,000 gallons a minute past one place, it must be carrying 1,000 gallons a minute past any other place farther down the river – unless there is some side-stream, or a mysterious hole in the ground. Some scientists like to think of this electric current story as rather like water being pumped round a closed ring of piping.'

The teacher continues with a description of a water circuit‡ and shows a model, and points out that the flow would be the same all round. D19

He should ask:

'Is there really something that moves round through the copper wires and through the lamp, and makes the lamp light or pulls the magnet? T

'As far as you or I can tell now, we can only say "This electric behaviour is *rather like* the behaviour of a current of water flowing, that makes the same thing happen all the way round. But we do not know whether anything is really flowing, and certainly not what it is." If it flows it might be some kind of "juice"

‡ A demonstration water circuit needs a small spinning pump, a section of narrow tubing to show high resistance, and a simple flowmeter or a rotameter to indicate the rate of flow. The meter should be a home-made one. The water can flow into a funnel in which a small floating cork serves to show the flow-rate by the speed at which it is carried swirling round.

As an alternative to the flowmeter described above, some teachers may wish to try a home-made model of a 'Rotameter'. In this device the fluid flows upwards through a vertical tapered tube which gets wider and wider towards the top. A small spinning-top inside that tube is carried up by the flowing liquid or gas to a height at which it is just held stationary. The faster the flow the greater that height, so that there is more space round the spinning-top for the fluid to get past. Commercial models are in widespread use for measuring fluid flow; but they are very expensive. For a home-made model, a glass tube about $\frac{3}{4}$ inch in diameter is pulled out so that it tapers in length of, say, one foot to about $\frac{1}{2}$ inch diameter. A glass marble or steel ball is inserted instead of the spinning-top.

The water circuit should *not* have a pressure gauge at this stage. We suggest it should be shown again in Year IV with a pressure gauge, measuring the pressure difference between the ends of the 'high resistance pipe'.

flowing this way round the circuit, or it might be some opposite "juice" – we should say negative instead of positive electricity – running the other way round the circuit. Or there might be both of those, each running its own way.

'Instead of some smooth "juice" flowing like water in a pipe, the current might be a movement of little particles, little bits of electricity, moving along like a line of rabbits in a burrow or an army on a road. Again, this might be a row of positive bits travelling this way, or negative bits travelling that way; or both kinds, each travelling its own way.

'Which of all these things do you think is right? Nothing travelling at all, or "juice" travelling one way or another, or little bits of electricity travelling one way or another?'

Direction of Current (continued). Whatever the answers – which the teacher should accept quite happily at this stage – the teacher should say: T

'We must wait for further evidence. Nowadays, we think we know that there are things that move when an "electric current" happens, in some cases several kinds of things; but we cannot show you that yet.'

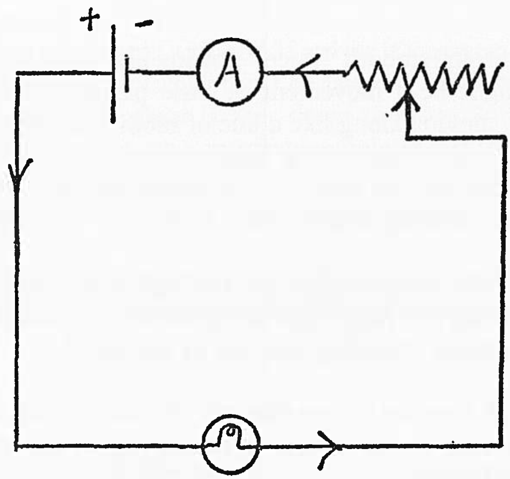
(In fact, contrary to wishful hopes, nothing we do in elementary physics teaching – even though we include cathode ray demonstrations and a photoelectric experiment – requires a view that electric charges come in small particles. Continuous (negative) juice would do just as well! Only when we come to Millikan's experiment do we meet clear evidence that requires 'particles' of electric charge.) * * * * * *

'For the moment we shall stick to the standard agreement, used by all electrical engineers, which is the idea of bits of positive electricity coming out of the red knob of the battery and going round the circuit in one direction to the negative end of the battery.

'That was settled long before anybody knew about "electrons"; and now that agreement, which is used to put arrows on the electric circuit drawings, is used so much that it would not be safe for us to make a muddling change. Later on, you will be able to decide for yourselves what is really going on – and you may find it even more complicated than you think.'

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

M.



So far in these problems we have not bothered very much with direction of current. In future we shall adopt a universal agreement made a century ago. We shall say that something which we call 'the current' runs from the ' + ' terminal (the red one) of the battery, round the circuit to the ' – ' terminal (the black or blue one) of the battery. We put arrow heads on the circuit diagram to show the direction of that current.

Suppose there is some 'positive (+) electricity' that is stored up at the + end of the battery, ready to move round the circuit. Then *if* that positive electricity does move round the circuit it must travel in the direction shown by the arrow heads.

a. But *perhaps* the current in the wire is NOT really a flow of that positive electricity. What other kind of current can you imagine instead? There are two other possibilities, besides the flow of positive electricity we have just described. Can you think of both? What arrow heads would you put for each of those suggestions? (One of those suggestions is what we now think happens in real wires but electrical engineers and scientists agreed long ago on the arrow heads pointing from positive to negative, that we have shown in the diagram here. It would be too confusing to change over to some other arrangement now.)

b. In the diagram there are *four* arrow heads. Three show the correct 'direction' for the current, the fourth does not. Which is the fourth arrow head and what is it doing in the diagram?

Resistance: Circuit with a Dimmer

Pupils will have tried inserting some pieces of wire that seem to have 'resistance' and make a lamp in the circuit duller. If not, they should try that now. C20a

With such a wire inserted, pupils move a crocodile clip along it to vary the resistance. C20b

Then give pupils a fixed resistor to try. C20c

Pupils should now insert a variable resistance, a rheostat, and try making the lamp brighter and dimmer, watching their new ammeter at the same time. C20d

Resistance and Temperature
(buffer option for fast groups)

In switching on a lamp with an ammeter in the circuit, some pupils may have noticed that the current is momentarily bigger at the start. And as we know, any attempt in later experiments to look for a simple linear relationship between current and voltage fails for electric lamps. We know that metal wires do obey Ohm's Law; and we know that the simple behaviour is obscured by temperature-changes. We should not teach that at this stage; but we should let pupils find that there are considerable changes of resistance when the temperature of a (pure) metal is changed.§ For that, offer them a fine piece of iron wire, taken from steel wool. T

Effect of Cooling. A strand of steel wool 2 or 3 inches long is pulled from an ordinary steel wool cleaning pad (or, better, a pad of grade 2), clipped with crocodile clips and connected in series with 3 cells, an ammeter and one or two lamps. Blowing on the wire is sufficient to increase the current considerably. Mounting the wool in clips may cause some difficulty, in which case use a paper clip to anchor the steel wool in the first place and then clip on to that. Holding the wire between the fingers has the same effect and gives the children a clue as to what is happening. C21

Fuses. The same wire can be used to show fusing, but now the lamps should be removed or they will fuse first! By sliding the clip down the steel the point will be reached where it fuses quite spectacularly. C21

§ 'Both experiments 20 and 21 were very valuable in making them think out their circuits, be deft with their fingers and reasonably careful in their recordings. These take time – far longer than one anticipates. Their enjoyment was very marked.'

Note to Teachers: 'Resistance' as the name for a Constant. Resistance is a word that comes from the water-flow analogy. That idea was so strong in Ohm's mind when he started on his researches that he said he was looking for electrical 'resistance' and trying to find its properties. When it was found that metal wires give a constant ratio for p.d./current, that constant was given the name 'resistance' which Ohm had ready for it.

In contrast with this one case, the order of events in most physical discoveries is the other way round; we first discover experimentally that some ratio has a constant value and then coin a name for it because it is constant, e.g. we find [stress]/[strain] constant for a wire and then call that Young's Modulus.

Sometimes when we are teaching, this logical order gets obscured: some pupils grab the name of the constant and somehow take it for granted that the name itself assures the constancy and thus takes away any need for experimental investigation. Then the practical experiment becomes a scheme for making one accurate measurement of that assured constant instead of an interesting investigation to see what relationship is there. Examples: single measurements of resistance, Young's Modulus, 'J', specific heats. ... Of course, there is nothing wrong in making these measurements: each has its importance in professional physics; but an organized series of such experiments can give beginners a wrong-headed picture of science.

We shall not deal with Ohm's Law until Year IV, and even then only briefly, for this is the transistor age, in which *non-linear* devices are of great importance.

Comment on Notebooks

At this stage, a pupil's notebook should have a drawing of each circuit – neat *but not meticulously ruled* – and a note *in his own words* of what happened.

(There should be no pressure, in these experiments, to draw conclusions. These young people are getting acquainted with electric circuits, and we hope they are enjoying that and building up some sense of knowing their way around among electrical things. Insisting on formal conclusions would be artificial and puzzling; and in many cases the teacher would have to end up by dictating a conclusion. After all, when you have been to the circus and come home and have given a glowing but inaccurate description of it, the only *conclusion* that could be added would be 'I enjoyed it' – or, if you are being trained to write unnaturally formal reports, 'The performance of the circus was enjoyed by me'.)‡

Encouragement

Those of us who have not tried teaching elementary electric circuits with young pupils working on their own like this will be surprised at the difficulties and the delights. Trying things that seem obvious and quick to us will take the children much more time. And the simplest and most obvious mistakes seem to make them feel puzzled – then they need encouragement, but not always quick help in putting things right. Simple experiments that seem to us dull and obvious seem to them a delightful part of growing knowledge. * * * * * * * * *

Buffer Experiments. We hope that in the series of class experiments with the Worcester kit pupils will be able to go at their own pace, some moving ahead fast and others even going back to repeat an experiment that they did not understand. Any such plan raises difficulties in running the class; and we therefore suggest to teachers that they should have 'buffer experiments' up their sleeves for abler and faster pupils to do while others are catching up. Such buffer experiments will give faster pupils new things to think about and do. A few are suggested in the *Experiment Guide* under experiment C 22. * * * * * * * *

What practical use: Some pupils may well say 'Well, I can make the lamp brighter and dimmer, but what does that lead to; can't I do something definite?' We should offer them a fuse, telling them the maker's rating for it, and ask them to find out if the maker is right. This seems to them a definite job and the result is interesting and surprising. C22b

Simple Voltmeter as a 'Cell Counter'

(To be omitted by slow groups.) In Year III, we shall introduce voltmeters as empirical instruments and in Year IV we shall use them with a clear definition of potential difference, in terms of energy transfer, but we can, with faster groups give a first hint now of voltmeters and their uses as follows. * * * * *

Provide either a commercial voltmeter or a milliammeter with a suitable high resistance so that it will cover a range of 4 or 5 volts. Then ask pupils to connect three lamps in series with three batteries, C23

‡ The new Edition (1965) of Fowler's *Dictionary of Modern English Usage* offers a strong comment on that passive style: page 689.

in series. (At this stage, it is fair to draw the circuit on the blackboard, because the problem is not to get this circuit set up and understood but to set it up quickly so that we can use it to examine and understand something much more difficult.) Then, ask pupils to connect the wires from the new instrument they have been given across one lamp, then across two lamps, then across three lamps. Ask:

> 'How many cells are needed to run one lamp? How many cells are needed to run two of your lamps together? How many cells are needed to run all three lamps? *This new instrument is counting something for you.* What does it count?'

We hope to elicit the idea that this new instrument acts as a 'cell counter'. It counts the number of cells in use for the particular lamp or group of lamps that we apply it to.

Counting in Science. We shall have described an ammeter as a *
counter of lit lamps (in parallel); and some fast pupils will now *
meet our description of a voltmeter as a counter of cells (in series). *
If pupils comment that counting is a queer job for an electrical *
instrument like this, we should treat this question gently and use it *
as an opportunity for a very general piece of science teaching. *

> 'Are you sure that is strange? Don't we often have to count when we make a measurement in science? Suppose I measure the length of this piece of paper with my centimetre scale. I just put the edge of the scale against the paper like this, move the scale till the top of the paper is at nought and then I see the bottom of the paper is at 20·6 centimetres, so I say the length is 20·6 cm. But I could do it like this: I could get something just one centimetre long and mark one centimetre from the top of the paper to this mark, and then 1 centimetre again, and then one centimetre again, and so on, like a man pacing off a distance in paces. Then all I have to do is to count the number of times I mark off another centimetre on my way down the sheet. Of course, when I come to the end there is a bit left over and then I had better mark one millimetre, and then one more, and so on, and then count how many millimetres. T

> 'What does a clock really do when it keeps track of the time for you?'

Elicit the answer that somehow the clock counts seconds and does that, if it's an old-fashioned pendulum clock, by counting swings of the pendulum. Ask what a watch does. If the question of electric clocks crops up, ask whether they too count something, not swings of a pendulum but perhaps swings of the electric current to and fro to plus and minus. (And we might go further and suggest the clock counts revolutions of the dynamo.)

Yet we point out that ammeters do not seem to be counting anything in the wire.

> 'The ammeter seems to just measure a steady force when there's a steady current; but if it were a current of water, you could certainly measure by counting how many gallons go past any point that you watch, in every second, or every hour. (In fact river-flow is measured in thousands, or even millions, of gallons per hour.)
>
> 'Is there anything corresponding to that with ammeters?'

(Wait for electrolysis to offer an answer to that.)

Chapter 3

ELECTRIC CURRENTS

Conduction in Liquids and Gases, Electron Streams

ELECTROLYSIS

We shall not treat electrolysis in great detail in this course, either *
now or in later Years. *

In schools that are also following the Nuffield Chemistry Pro- *
gramme, pupils will study electrolysis fully in Chemistry. *

In other schools, it may seem unkind to do little justice to some- *
thing so important as electrolysis. Yet it is probably better, in this *
physics programme, to spend only a short time on electrolysis *
and then in a following Year repair any serious damage done by *
omission. *

Before starting on electrolysis, the teacher should consult his col- *
leagues in Chemistry very carefully to find out what the pupils have *
already done or are likely to do soon in Chemistry. In the Nuffield *
Chemistry Programme, pupils meet electrolysis in Year I, seeing *
or doing some of the experiments suggested below. However, they *
are likely to find the electric circuit already set up for them; so *
our experiments may represent new work in connecting up an *
electrolysis circuit and making it go. If the teacher decides to keep *
some electrolysis experiments in his Physics Programme for that *
reason, he should certainly hurry them. *

When pupils have tried to send electric currents through samples C24
of various solid materials, we should offer them liquids – obviously water to begin with. They can use a lamp or a meter to test for current. Run two wires from the break where pupils have been inserting samples into a beaker. Fill the beaker with distilled water. Then offer common salt or copper sulphate to be added to the water. Pupils should be asked to look and see what happens to each of the wires dipping in the water, but this should not have much emphasis now.

Then wash the beaker and go back to distilled water and offer a little dilute sulphuric acid. 'De-ionized' water will do.

Also try sugar in water; then another liquid such as oil.

Finally, start again (always washing the beaker) with tap water. Ask pupils what they see happening with tap water and what they think that means. This is asking them to 'explain', to interpret some new observation in terms of older ones which seem more familiar. Of course, all they can say here is that they have seen that specially pure water does nothing and that adding salt or acid seems to make the water able to carry current, and since their tap water carries some current, it probably has things added to it. This is just a guess, but it is worth encouraging as a beginning of a scientist's treatment of things – explaining in terms of what else he has seen and knows rather than quoting an authority, such as a book, for an explanation.

In all this we should *not* dictate formal conclusions: we should just let pupils see what happens and accumulate knowledge. Even if it is forgotten, it can be regained.

Copper plating

Pupils should try copper plating. For this, they should use a C25
solution of copper sulphate, being told that this is a chemical compound containing copper (and sulphur and oxygen). They should use small strips of thin copper for the two electrodes and let a current run for some minutes, and then look at the strips to see if they can see any difference. Then they should try the same thing using carbon pencil leads as electrodes. That will suggest that copper is being deposited on one side and may raise the question of what happens on the other side. Then they should go back to the experiment with the little strips of copper.

There will also be the question, 'Can we copper-plate other C26
things?' The answer is 'Go ahead and try'. (But we must be careful to avoid having objects of zinc or iron put into the bath to be plated, because those metals will displace the copper from solution and will confuse the story badly. Therefore, the teacher should censor the materials and try them himself beforehand. Nickel-plated iron will show this substitution.)

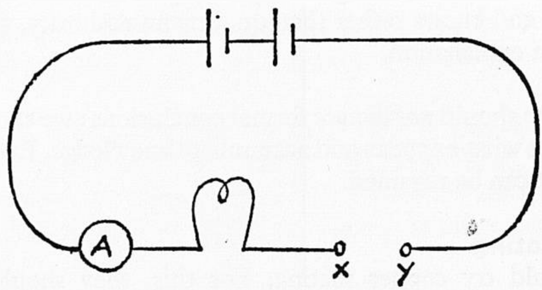
Note to Teachers. This work of playing with electrolysis may seem to you too childish, but if you will let children try it, you will be surprised at the delight, and sense of knowledge, that it gives: and you will also be surprised at the time it takes. No one can tell before by guessing how long a group of young people will take over this until they have tried it: but once they have tried it, they will be willing to give it the full time that it needs.

We shall not do any experiments with accurate weighing or embark on discussions of equivalent weights and Faraday's Laws. Those will go to Chemistry.

Suggestion of Carriers. With carbon rods, reversing the T
current will show that copper does leave one electrode ('the in-

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

N.1



Draw the circuit shown and add to it two wires leading from the pillars X, Y into a liquid in a beaker. Say what you saw happening.

a. When the liquid was pure distilled water

(*b*), (*c*), (*d*) when you used three other liquids (say which).

Also, (*e*) Why is it important that the wires in the beaker should not touch each other?

N.2

Look back to your answer to the previous question.

a. Now redraw your circuit diagram and add arrows to it, to show the 'official' direction in which 'positive' current flows. Does it flow, according to the standard agreement, from X to Y or from Y to X.

b. Does the fact that we use this agreement mean that it must be true; that is, does it mean that there must be actual positive particles of electricity (or perhaps positive 'juice') flowing round the circuit? If not, why do we use it?

going wire' is a safer term for beginners), and that copper is plated on to the other (outgoing wire). We may suggest that some form of copper is travelling across: and also that the thing which we call electricity is also travelling across. And if it is travelling in that direction, coming from the positive knob of the battery, we may call it probably positive electricity. So we say in a discussion with pupils:

> 'There may be some things made of copper, carrying electric charges across. Scientists believe that there are charged carriers; and they give them an old Greek name for travellers: "ions".'

Lead Tree (*optional but delightful*). If possible, give a demonstration of a lead tree being formed by electrolysis. Put a solution of lead acetate in a small glass bath with a wire hanging in the centre as the negative electrode and a wire down round the edge and bottom as the positive electrode both preferably made of platinum or something else inert. Place the cell in a projection lantern and send a small current through it. With a small current a beautiful tree of crystalline lead will be grown. It can be made to dwindle away by reversing the current, and this will clean the wire ready for future use. D27

Electrolysis of Water

Give a demonstration of water being electrolysed. This could be done as a class experiment, using 4 volts or more and carbon electrodes. The appearance of bubbles at both electrodes suggests that there may be ions travelling both ways. Explain clearly that this is only a guess, an imaginative suggestion, but one which other experiments, particularly in Chemistry, support strongly. D28

Avoid plain copper wires, because the reactions at the electrodes then spoil our simple story: we see hydrogen emerging at one electrode, but there are no bubbles at the other. That is because the SO_4^{--} ions arriving there attack the copper and form copper sulphate, which again forms ions. In fact, this is used as a way of separating radioactive copper from radioactive zinc in a piece of copper that has been bombarded with protons. As the electrolysis proceeds more and more copper ions join the solution and presently instead of hydrogen being released at the other electrode copper is deposited there. * * * * * * * * * *

(If you like, borrow from Chemistry a demonstration of the migration of coloured ions. This is a delight for us to see – though it would be a much greater delight if the ions were to migrate faster – but it is probably not a very satisfying demonstration for young T

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

O.

For the purpose of this question let us forget about the conventional current direction (question N.2) and speculate about (wonder about) what *actually* happens in some of the liquids we have used in the beaker containing the wires from X and Y.

a. First, say what is observed when the beaker contains copper sulphate solution. Does the copper get deposited on the wire joined to X, or on that joined to Y? Which way is the copper going through the solution?

b. Suppose the copper carries electricity with it. Which way is the electricity going, in the direction of the arrows you have already put on the wires, or against that direction? Which sort of electricity, positive or negative, is carried by the copper?

c. Next, what happens when the beaker contains water acidulated with a little sulphuric acid? What comes off at X, and what at Y?

d. What does this suggest about the way in which the electricity is carried in the acidulated water? Which sort of electricity, positive or negative, is carried by the hydrogen? By the oxygen?

Important Note. We now have the suggestion that, in some solutions that carry current, the current may consist of positive and negative electricity carried by material substance in the solution (such as copper, hydrogen, oxygen), and travelling in opposite directions at the same time. However:

1. This is only a suggestion, which certainly fits the very small amount of experimental evidence we already have; but we need a great deal more evidence before we finally accept it.

2. It still tells us nothing about what goes on *in the connecting wires.*

3. Even if we adopt this suggestion as a useful one we still shall not abandon the conventional 'positive current' that you wrote about in answer to question N.2.

P.

What name is given to the particles which we suppose to carry the current in some solutions (e.g. copper in copper sulphate solution)? What does the name mean in the original Greek? Why do you think this new name is chosen, rather than just calling them 'copper atoms' or 'copper molecules'?

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

Q.

a. Describe very briefly some observations you have made on electric currents passed through strips of paper moistened with various solutions. (Write a sentence or two about the apparatus used, and a sentence to describe each observation.)

b. These experiments are interesting though not very important – however, pieces of 'moistened-paper' might serve some useful purpose – what do you suggest?

c. What do 'd.c.' and 'a.c.' stand for? How do you think a.c. differs from d.c.?

R.

a. How do you know, without doing any further experiments, that air must be a very good insulator? Mention two or three of the curious things that would happen if, by a waving of a wand, the air around us suddenly became conducting.

b. Freddie Jones says 'Yes, that's all very well for air, but it doesn't prove that other gases are insulators'. How would you discover whether carbon dioxide is an insulator, given a cylinder from which the gas could be obtained?

S.

Air and other gases are very good insulators under ordinary conditions, that is, room temperature, and with batteries or the electric mains as sources of current. Under other conditions gases may become conducting. Describe experiments which demonstrate air or some other gas carrying electricity. (Show the apparatus in a sketch and then write a sentence or two to say what happened.)

T.

Two types of electric lamps are in common use in houses and in larger buildings: the 'tungsten-filament' lamp and the 'fluorescent' lamp. Find out what you can about these lamps, both by looking at some, and from diagrams in books (do not trouble with any of the more difficult information given in the books). Now write about six sentences comparing the two types of lamp, and answering questions such as: where does the light come from, does the current go through solid, liquid or gas, how do the colours of the light from the two lamps compare, what about the temperature of other bulbs as felt by the hand?

pupils. By projecting such a demonstration, we can magnify the speed.)

Wet-Paper Demonstration of Electrolysis: d.c. and a.c. C/D 29
There are some very pretty experiments with electrolysis in wet blotting paper (or filter-paper or white cloth) containing indicators to show the products of electrolysis. They should be done very quickly. These involve too much chemical knowledge to be of use here to illustrate ideas of ions; but they do serve as indicators for electric currents. We shall find them useful with alternating current.

Although a special 'pen' is manufactured and available for this, all the apparatus for this experiment can be made and assembled very easily by any teacher who wishes to turn it into a class experiment. The 'pen' consists of a stick of wood, such as a ½ inch dowel about 6 inches long with two small screw eyes screwed into one end about ¼ inch apart. Two thin insulated wires are connected to the screw eyes and run up along the sides of the dowel, strapped to it by tape, and go to the supply: a battery or a small transformer. The experiment needs only a few volts so it is quite safe.

If we break an electric circuit and carry the wires to a piece of paper soaked in potassium iodide solution, iodine will make a brown stain where its ions arrive. If we add phenolphthalein (dissolved in alcohol) to the solution, a crimson stain will appear where the potassium ions arrive. An easy method is to place the wet paper on a sheet of metal to act as a conducting back, and 'write' on it with a 'pen' consisting of two electrodes and connected to a battery. Draw this pen quickly across the wet paper. Ask pupils what will happen if the battery is reversed. Ask what they guess would happen if we connected it to an alternating supply. They do not yet know from their physics lessons what a.c. is; but they can guess what it is and they can guess at the answer to this question. It might be good to ask them to make a sketch in their notebook to show what they expect. Then provide an alternating supply of a few volts and let them try the experiment. (Make sure the transformer core is earthed.)

(Warning: some blotting papers contain bleaching agents, some *
paper contains starch. Either will alter the story. And some metals *
used for the backing sheet can spoil the effect). *

This may seem to us little more than playing for fun; yet it seems *
to give young people a feeling of good sense about electric currents *
as well as entertainment. *

The only danger in all this, at this early stage when it is only a matter of looking at things, is of electrolysis taking too long at the expense of many other important matters that lie ahead of us in this Year. * * * *

CONDUCTION IN GASES

Conduction through gases is more difficult to show and should be done by demonstrations. The teacher should point out that we have seen currents carried by metals, and some non-metals (e.g. carbon), and solutions (e.g. salt water), and some other liquids such as oil or sugar-solution failing to conduct. T

> 'Can gases carry currents? Does the air carry currents? Suppose the air carried electric currents as easily as copper, what would happen to the electric circuits that you've been working with? ... Then air cannot carry current at all easily or it would spoil your experiments. And what would happen to your batteries? ... It looks as if air must be a non-conductor, a very good insulator like glass and paper and wood and cotton, and things like that. Yet we can persuade gases to carry currents. I will show you some experiments.'

Make sparks with a Van de Graaff or a Wimshurst machine (or, lacking that, with a large insulated metal object charged up by repeated chargings from an electrophorus – the point is not to have a wonderful machine to make the sparks, but just to show that a spark can go through air). Show that when a spark jumps from some supply to an insulated object connected to earth through a microammeter there is then a current through the meter. D30

Then show the shadow of a candle flame in an electric field. Place a candle (or a yellow gas flame fed by too little air) in the space between two metal plates on insulating stands. Connect those plates to a Van de Graaff or Wimshurst and look at a shadow of the flame cast on a screen by a compact light source. (If the tungsten-iodine lamp is not available, this is still worth doing with a lamp with a compact filament.) Two streams of particles will be seen in the shadow picture, moving opposite ways. The two streams will not look equal. There is no reason why they should do so, since one carries a stream of electrons, and the other carries a more complicated stream of ions. One is luminous, probably with carbon particles, and the other is not so luminous. D31

Show a neon lamp (fed in three different ways; d.c., a.c. and electrostatic supply), or even an ordinary fluorescent lamp, as an example of an electric current going through an excited gas. D32

These demonstrations are best done quickly at this stage. If the teacher has practised them beforehand and can run through them without much detailed explanation, they will make a good contribution here. We shall discuss currents in gases, and electron streams, more fully in Year IV. * * * * *

ELECTRON STREAMS

Then ask the final question: 'Can an electric current go through a vacuum?' Ask for comments and suggestions. Point out that the ordinary television tube has a vacuum inside. Pupils will say 'Yes; but something must carry the current'. T

> 'Yes, a TV tube has a thing that releases electrons at one end and we arrange to drive those electrons down the tube so fast that they go slam into the face of the tube inside and make it glow. If there is a little gas left in the tube, by mistake, the electrons go slam into one gas molecule after another and make them glow. We can show that to you. (The glow does not show the crash of the electron hitting the air molecule. It comes just after that, when the molecule recovers from the damage of the collision – but that is something you will learn about much later.)'

Then show the fine beam tube. D33

> 'This big bulb has an "electron gun" in it that releases electrons and drives them so that they come out from this small spout moving very fast indeed.‡ Then you can see the path they take because there is just a little gas – only a very little – left in this big globe, and that gas will glow when electrons hit it. (There is a pretty good vacuum in it, but a little hydrogen gas has been let in.) So you can see the path of the electrons that come shooting out from this electron gun by looking for a little bluish glow in the gas.'

‡ *Note to Teachers.* The final speed of electrons, that have been driven by a p.d. of 180 volts on the gun, is about 8,000,000 metres/second. In a TV tube with 7,000 volts it is about 48,000,000 metres/second. It is best not to tell pupils any such values at this stage when we cannot support the statements.

Let pupils gather round the tube, wait until their eyes are used to the half-dark, and then show them the electron gun with its orange-hot filament and say:

> 'Now I will turn on the supply to drive the electrons out of the muzzle of the gun very fast. They'll shoot straight up in this direction.'

Try a small gun voltage, then a bigger one, then a bigger one, until the children see the vertical pencil of glow. Cut the gun voltage down a little, and raise it a little, and let pupils watch what happens. Increase the gun voltage until the stream strikes the glass of the bulb. Then say:

> 'We can pull the electrons in that stream over to one side by giving this little plate above the gun a positive charge, and that plate a negative charge, by connecting them to a battery here. Watch. Now, reverse the battery. Now, add another battery. That looks rather like a man swinging a fire hose round to different directions.
>
> 'What do you think would happen if we connected those two little plates to an alternating supply? Sometime you shall see that.'

This is an experiment for real delight: for young people to 'see *
electrons' – though we must warn them that they are seeing them *
only indirectly – and enjoy the promise of understanding more *
atomic physics in the course of time. We should not labour the *
story with explanations about electric fields; though, of course, *
we can ask questions: *

> 'What do you think is happening when the stream goes only T
> so far in the very thin gas in the tube; and then, when we use a bigger driving push on the gun, the stream goes further? What do you think we're changing? Are we making a bigger electron, or a heavier one, or what?'

For this first look, and for every look in later terms, it is important *
to have pupils near enough to the tube to see it properly. This is *
too important an experiment for a vague look from a distance. *
Only four or five pupils at a time are really able to see clearly. *
With adult physicists, one can gather a crowd of ten around the *
tube and still have them see; but beginners need and deserve a *

closer look. So the teachers should plan to have sufficient time for pupils to look in groups of four or five; and each of those groups needs several minutes for a good look at this unfamiliar sight. * * *

(Some teachers report that their pupils see clearly from a considerable distance, so that the whole class can see the demonstration at once. Even so, we believe that this very important experiment deserves a much closer look than that.) * * * *

This is another experiment, whose importance and demand for time are difficult to foresee until one has actually tried showing it with a complete class. * * *

Fine beam tube with magnetic field: to be postponed. The effect of a magnetic field is a marvellous sight, but it is much better to avoid this now and keep it for the next look at the tube. That raises more mysteries than it does good, at this stage – and it would be skimming cream from a later Year's work. * * * * *

Cathode Ray Oscilloscope

If we turn the fine beam tube over till its electron beam is horizontal, pointed straight out to the class, we have a model of a television tube. (In the latter, the deflection is done by magnetic fields, but it is best not to mention that now.) We also have tubes like this which are not used for television but do all kinds of jobs in science. This is called a cathode-ray oscilloscope (C.R.O.). The teacher should turn the fine beam tube over, and show a C.R.O. beside it. T D34

> 'It is just a big tube with an electron-gun at one end, and a very good vacuum inside (because we do not need to show the beam by glowing gas). It has a screen in front to show where the electrons hit. It has a pair of plates inside just like the little plates outside the gun in the big globe, and these can be given electric charges to pull the stream up and down so that the glowing spot on the front face can be moved up or down. There is another pair of plates also just beyond the gun, arranged to pull the electron stream sideways, so that we can swing the glowing spot to and fro sideways. So there are two pairs of plates, one pair like this‡ and one pair like this.‡

‡ For each pair of plates, the teacher holds his hands parallel, palms facing, either vertical or horizontal, to show the plate arrangement.

'Here is the tube, and now we can start up the gun and make a green spot at the place where the electrons hit the front of the screen. If we connect this battery to this pair of plates, the spot moves up. If we connect this battery to this pair of plates, the spot moves across, like that. Then we can apply a battery to one pair of plates and another battery to the other pair of plates, so that we can move the beam across sideways and move it up or down, just as we like. In fact we can use this to plot graphs for us. You can see that the electrons obey orders and move the glowing spot to the new place far quicker than you can move any pencil when you're plotting a graph from point to point.

'But we also have a very clever arrangement that will swing the spot smoothly across from left to right like this.'

Then show the time base moving very slowly indeed.

'Then we can use this to draw time-graphs for us. The spot's up-and-down movement will show any electrical signal that we feed into it and plot that against time moving steadily along the horizontal axis. After each sweep across the bright spot is switched off (by an electronic trick), for the return journey – much as our own eyes and brain do when, reading, we move from one line to the beginning of the next.

'Watch while the time base swings the spot across again and again and again. I will turn the battery on and off, on and off, to pull the electron-beam up and down, up and down.

'Now let us stop the left to right movement and then connect this to the electric mains. We will use a transformer to transform down to a safe supply. Watch what happens. Why does the spot make a line like that? Has it moved up or down, or what? . . .§

'Yes, perhaps it is moving up and down very quickly, too quickly to see. Some of you may be able to see what is happening if you twist your head very quickly and watch out of the corner of your eye. But we can get at this much more easily by dragging the spot steadily across from left to right while this strange thing is going on. Then we shall be plotting a graph of what happens

§ 'This series of experiments has proved fascinating to both children and myself so far! I think that they are really beginning to feel like real scientists, particularly when they see such things as the C.R.O., with which many are familiar via science programmes on TV, etc.'

against time, from left to right like this: Monday, Tuesday, Wednesday, Thursday, Friday . . . not at that speed, but very fast indeed.

'Let's turn off the supply and turn on the time base. There it is. Now turn on the supply. What does that pattern tell us about the supply? What will happen if our time base moves the spot across faster than that? ... (Try that.) What would happen if we moved the time base much slower?'

This is probably *not* the time to let pupils have an oscilloscope to work with themselves. If there is time to spare, and the teacher feels prepared to be patient about it and give a considerable amount of help when pupils get lost with the controls, it would indeed be a delightful class experiment to offer an oscilloscope to each group of four or eight pupils and let them try what they can with it. There is not much that they can usefully do except try an alternating voltage on the vertical plates, perhaps an alternating voltage on the horizontal plates instead of a time sweep, and try a battery and switch on either or both. Unless there are at least two full periods for play with oscilloscopes, this class experiment is more likely to produce confusion than pleasurable growth of knowledge. However, we should look forward to giving children small oscilloscopes in class experiments in a later Year and asking them to use the oscilloscope as a simple graph-plotter to show what is happening in certain experiments. Far from regarding it as a delicate instrument to be locked away we should use it as often as possible as a handy tool. C34 * * * * * * * * * * * * * * * * *

Electric Charges

We can ask a very important question about the oscilloscope and the 'fine beam tube': 'What is it that moves the electron stream sideways; what does the battery provide?' T

'Connecting those little plates just outside the gun to a battery puts what we call "electric charges" on them which push and pull the electron stream and move it. I can put some electric charges on these two balloons just by rubbing them.' Repeat D10

(This is a poor transition from the electric field in the oscilloscope to electrostatics experiments, because we do not use a battery on the balloons, and we do not get opposite charges on them. We should need much bigger voltages than are available. The highest voltage power-pack that is likely to be available will give 5,000 * * * * *

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

U.

You have seen in the laboratory a clear glass apparatus with a very good vacuum inside it. By means of a special apparatus called an 'electron gun', electricity can be shot through the tube.

a. Imagine a similar 'thought experiment' that might be done with a rifle firing bullets and a powerful hose 'firing' water or molten metal. Describe your experiment in a few sentences and say what you think you would expect to see.

(Note 1. Better try it in a tunnel rather than a glass apparatus!)

(Note 2. A thought experiment is one which you do in your head! It is an experiment which you think could possibly be done, though it might be very difficult to make the apparatus. But you do not think it necessary to do it because just thinking about it helps you to sort out your ideas.)

b. Does the fact that we can use a kind of gun to shoot electricity into a vacuum mean that electricity must be made up (consist) of particles ('bullets')? Write a sentence or two in explanation.

V.

Following the last problem: Freddie Jones says that the electricity from the gun cannot consist of particles; it must be a stream of something like water, 'because', he says, 'if there were particles we should see a flicking effect, a series of 'blips', where the electron beam hits the glass. We don't, we see a continuous light, therefore the beam must be continuous.' What do you say to this?

W.

You have seen, first, a large clear glass bulb with an electron gun inside, and later a 'cathode ray oscilloscope' also containing an electron gun.

a. You could actually 'see' the beam inside the first of these, but not in the oscilloscope. Yet it is the same kind of electron beam in both. How do you explain the difference?

b. On the other hand, the spot on the oscilloscope where the beam ends is much brighter; why is this?

c. Which of the two tubes you have seen in the laboratory has the greater resemblance to a television tube?

d. It is dangerous to fiddle around inside a radio receiver which is still connected to the electric mains. Why is it even more dangerous to do this with a television receiver?

volts, and with that used to give opposite charges to two balloons – *
or to charge each balloon equally with respect to ground – the *
forces would be too small to be noticeable. For impressive forces we *
need a 20,000-volt supply. *

However, we should just be able to show such effects with very D35
light metallized polystyrene balls on long insulating threads, charged
by connecting them to the plus and minus of the 5 kilovolt supply.)

We can start pupils on class experiments with electrostatics by C36
explaining that while *we* know quite a lot about electric charges and what they will do, and how the battery can bend the electron stream by putting charges on the plates, it is the pupils' turn to find out about those things for themselves.

Then we give pupils small, light, conducting balls on monofilament nylon threads as insulating supports and strips of material to make charges by rubbing, one of cellulose acetate, another of polythene. We ask pupils to try rubbing the strips, and wiping 'charge' off on to the suspended balls. They should look for any unusual forces between the balls. They should try touching the charged balls with fingers, threads of nylon, cotton, wire, wet paper, etc. They should draw simple sketches in their notebooks and record what they see happening.

These class experiments are amusing and interesting, but we *
should make them go rather quickly. At this age they will not *
yield a large body of well understood knowledge; and if we let *
them take much time we shall be tempted to clear up the story by *
definite teaching of further knowledge. That is better left until *
later; and anyway adding that it would spoil the flavour of these *
'open' experiments.

We expect pupils to find that when things are given 'charges' *
– whatever that may mean – they exert small forces upon each *
other; forces that are bigger when things are closer; and forces that *
are sometimes pulls, and sometimes pushes. (Give the words *
attraction and repulsion presently, but stick to the direct simple *
words at first.) They should find that there are two sorts of 'charge',
and only two sorts. They should find that some materials seem *
to keep charges there very well – these we call 'insulators'. Others *
seem to carry charges away, or if we try to give them charges, those *
charges run away, unless those things are supported on insulators. *
These latter we call 'conductors'. *

At this point, the teacher should offer a clear statement of what 'charges' are. They are not, so far as we know at this stage, crowds of electrons, or remainder-crowds of atoms that have lost electrons – there is no evidence for those descriptions yet. We can say they are 'electricity', if we like, but that is only substituting one new word for another. To be honest, we must say that giving something a charge merely means doing something to it so that it pushes away other things that have been given the same kind of charge, picks up little bits of paper, and attracts things which have been given the other kind of charge. T

'Where have you met something like that before? Where have you met scientists describing something just by the things that it will do and saying "That is all we really know about it, in fact that is how we will have to measure it, by what it does" ... Yes, we had to say that about electric currents, and now we have to say that about electric charges. So far as these experiments go, we don't know anything about them except that "charge" means something extra that pushes or pulls.'

We hope that each school in our programme will have a Van de Graaff machine; (or, if the school already has a good Wimshurst, they could use that instead). Show the machine at work.

'We have a machine for doing the same kind of thing as this rubbing to make charges, almost like a charge factory. It was invented by a young man called Van de Graaff, who nowadays has a Company for making huge machines of this kind, some of them even 100 feet or more high. Here is our small Van de Graaff machine. That can pump up a huge charge on the big ball at the top. If we let it go on pumping, the charge on the big ball may be so great that it damages the air around it and sparks carry the charge away. We can let the big ball give some of its charge to a small metal ball hung on an insulating thread. We bring the small ball up to the big one on the machine and let it touch the big ball so that some charge runs on to it. Or we can let the big ball share some charge with a whole lot of bits of paper or light metal balls. D37

'Now watch what happens if we try to let the big ball share its charge with the great earth itself, by means of this wire. (We connect the other end of this wire to the water-pipes which run to the ground and give electric charges a very good chance to run out all over the earth.)'

Bring an earthed wire to the Van de Graaff, holding it, if you like, by an insulating handle.

> 'That is another thing which we can say an electric charge will do: if we give things a big enough charge we can make sparks. We can call that another part of the description of what we mean by electric charge.'

Let a suspended ball carry charge across in successive trips.

> 'Instead of connecting the big ball to the earth direct, carry the wire from it as far as this metal plate, then have a space in air and another plate connected to the ground. If we hang a metal ball by a long insulating-thread, like a pendulum, between these two plates, it can collect some charge and move across and ... Now watch it.'

Then change from the Van de Graaff to a power pack with the D38
ping-pong ball bouncing to and fro between the plates. Insert a sensitive galvanometer between one plate and the power pack on the earthed side, and show there is a current as the ball bounces to and fro. Explain that the ball is carrying positive charge across one way and negative charge across the other way. Now that we have a power pack with terminals labelled positive and negative driving this 'current' of charges, we can talk more confidently about labelling the two kinds of charges 'positive' and 'negative'. (The galvanometer for this must be a sensitive one – with as high a current-sensitivity as possible for this use, although one should usually select the highest voltage-sensitivity in buying a galvanometer for many sensitive measurements. A 'Scalamp' instrument is a very useful luxury; but smaller, cheaper galvanometers are available. For the present use, the shorter the period the better. For a large class, an instrument with a taut suspension and a mirror is very good here; and it will prove very useful for slow-motion a.c.)

Note to Teachers on Electrons Moving

At this point, some pupils may bring up the question of which *
moves, the positive charges moving one way or negative charges *
moving the opposite way, or both kinds moving in the two direc- *
tions. We must be careful to be honest, and say that nothing in *
these experiments pupils are doing, or in most of the experiments *
that we ourselves know about, makes any distinction between these *
three possibilities. We simply do not know, from these experiments, *
which is right. Therefore, on to strict principles, we should be wise *

to follow the general advice of modern physicists such as Einstein *
and Bohr, and not put unwarranted details into our descriptions. *
For that matter, Newton himself had some feeling in that direction *
when he wrote '*Hypotheses non fingo*' – 'I will not *feign* hypotheses' *
– though he also made many speculative guesses. *

Children find it irritating if we say it is unwise to put in extra *
details. They want us to be 'really truthful'. So if we put our ag- *
nostic view to them, we should put it gently; and yet we should *
insist on keeping an open mind and we should always be wary *
about decorating our descriptions of the microscopic world with *
unnecessary details. *

In that, we shall be following the practice of modern physicists, *
who make most progress in knowledge of atomic and nuclear *
structure by avoiding words and descriptions borrowed from the *
large-scale world. They try not to talk about the 'size' of an *
electron, because that may be meaningless in the microscopic *
world – it is certainly not a straightforward thing like the size of a *
billiard ball. They hesitate to say that a neutron 'contains' a proton *
and an electron in the way that we say an egg contains the yolk *
and the white – that might be even more misleading than a child's *
idea that a half-crown has a florin and a sixpence rattling round *
inside. In general, we are warned that extending our vocabulary *
from the man-sized world to the microscopic world may lead us *
into paradoxes and mistakes. *

Yet, here, pupils have heard of electrons and will themselves tell *
us it is the electrons that move. So we should in practice move with *
the times – and accept this and say it, if pupils do not say it for us. *
But we must point out that while we believe that the moving things *
are only negative electrons in metals, there are positive things that *
move as well in semi-conductors, and certainly both positive and *
negative moving ions in solutions and in gases. Our experiment *
with the ping-pong ball was a model of + and – ions, moving *
opposite ways.

'When we make charges by "friction", one material pulls a few *
electrons off the other, leaving the latter positively charged.' *
Such descriptions are helpful, and children welcome them, and we *
should use them; but, again, we should be careful not to sound *
too dogmatic. (See note in General Introduction at the beginning *
of Year I on 'Teaching Electrostatics with Electrons'.) *

Knowledge of Charges and Currents. Children should have T
found some things about the behaviour of charges in their own class experiments; and we shall have shown in demonstrations some connection between the things that drive electric currents (batteries or power packs) and those electric charges.

Postpone Electroscopes to Year III. At this stage a gold leaf *
electroscope would not be particularly helpful and would take too *
much time. A little acquaintance with charges and forces is enough *
now, and we shall return to electrostatics in Year III, to deal with *
electrostatic induction and the electroscope and fields. *

Chapter 4

MORE FORCES

Weight, Friction

Programme. *We now return to questions of force and work and energy. We should revise, clarify and continue the discussion of Year I. Already in this Year II pupils have met some forces including those between magnets and those between electric charges. We now remind them of the things that forces can do.* T

(In this and in the ensuing discussion of work and energy, we should go fairly fast when we are revising things done in Year I; but we must be careful to see that any late-entry-waifs get the teaching they need to bring them up to date. For all, we must be careful to cover any needed things that we omitted in Year I.) * * * * *

Even at this second attempt, we only aim at increasing a sense of knowing something about energy: its many forms and exchanges. We shall not expect a competent understanding of this great and powerful concept by the end of this Year. We may ask for descriptions in examinations but we shall not expect to receive good definitions or even consistent descriptions. * * * * * *

FORCES

Pulls and Pushes. Start with a demonstration of some forces: stretch a big spring, stretch a large rubber band, stretch some elastic cord and then pull a string taut and ask: D 39a

> 'How do you know there is a force in that string? Any suggestions?'

Use the spring to pull a truck along, and point out that when there is a pull it makes the truck move. Repeat that, pulling the truck with the spring, with a rubber band, and ask whether you need a bigger pull or smaller pull or the same, for the same motion. (Give pupils for a class experiment the simple spring of Year I if not done before and ask them to try loads on it very quickly to look for a simple relationship between force and stretch.) D 39b

Muscles. Ask each pupil to hold a load of a pound or two in his hand with his forearm out horizontally and feel his biceps muscle, also its tendons, as he raises the load. Then try the same without the load but with another child pushing down on that hand. This is just to emphasize our intuitive muscular sense of force. C 40a

A working model to imitate a muscle is well worth the trouble of making. Make two pieces of plywood to represent an upper arm bone and a forearm bone, jointed at the elbow. Fix the top of the upper arm to a retort stand, allowing it to hang vertically. Then arrange a 'muscle' to pull the forearm up to a horizontal position. D 40b

The 'muscle' is a piece (about 8 inches) of bicycle inner tube tied tightly with string or wire to close it near each end. A rubber tube connected to a bicycle pump enters through the lower tie, so that this 'muscle' can be inflated – which will make it contract. Pieces of cord, representing tendons, run from the upper and lower ties to appropriate places on the upper arm and forearm. When the muscle is inflated it contracts and pulls the forearm up. If the ties are slightly leaky the model imitates a characteristic of real muscles: the pumping has to be repeated to maintain tension.

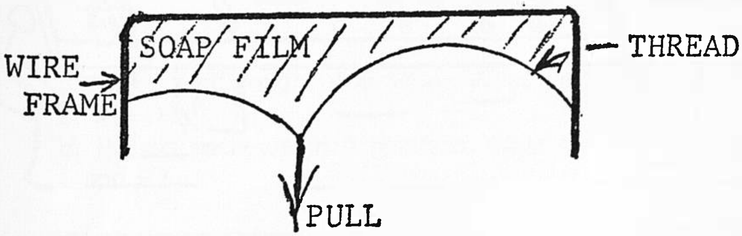
Extra Experiment: Springs. Those who have not tried it before might make a copper spring as well, by winding new copper wire on a pencil and trying loads on that. C41a

If any want an extra experiment, ask them to heat a copper spring in a Bunsen burner and then experiment on it when it is cool. Then show them how to work the spring by pushing it in and out – do not tell them that this will work-harden the copper, but see if they notice that. C41b

Elastic Forces. Continuing the class experiment ask pupils to try compressing things: latex foam; perhaps a weak, wide spring; plastic foam (which, compressed by squeezing, does not recover much). These are just things to do and look at, feeling the forces; no measurements, no record to be made. (If pupils did not play with the samples of rubber tube at the beginning of the Year, issue them now.) C42

This is not a stage for any detailed study of elasticity: these samples of materials and suggestions of distortions are simply offered as illustrations of forces and their effects, to be looked at quickly. * * * *

Soap Film. As an amusing demonstration of another kind of force, show a soap film in a little wire frame that forms three sides of a rectangle, with a loose thread to form the fourth side. Pull that loose thread by another thread attached to its mid-point and show C43



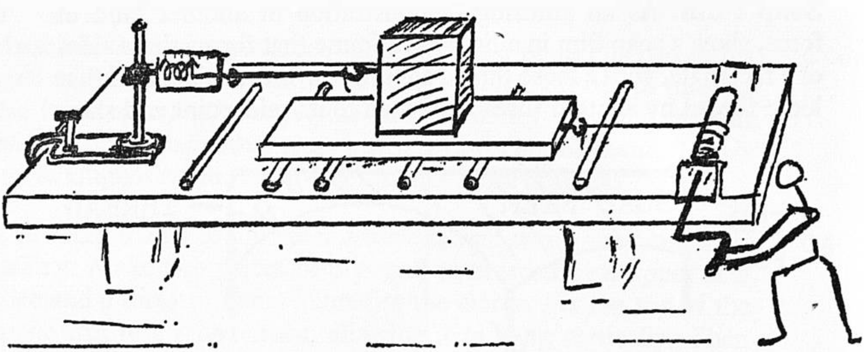
that the film behaves like a sheet in tension. It pulls the loose thread back against our pull on the centre thread. See *Experiment Guide*.

Friction

As another study of forces, give a quick demonstration on friction or encourage a class experiment to be done quickly. This is to provide familiarity. Any attempt to extract 'laws' – or worse still to give laws and ask pupils to verify them – would be a mistake here. Drag a block along a plank with a spring-balance and look at the force. Press the block against the plank with a finger to increase the force pushing block against plank, and again drag the block along with the spring-balance. D44a

If this is shown as a demonstration, the spring balance must be a large dial one. To show a whole class the essential reading on a little tubular balance would be a mockery of good teaching – it would be better to omit this experiment.

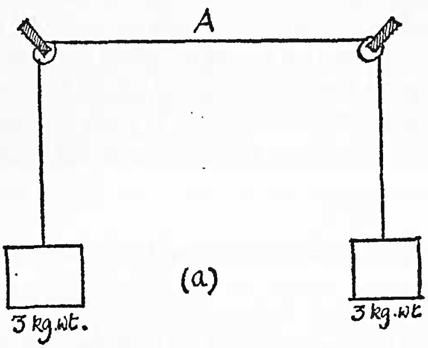
Special apparatus for smoother motion. It is difficult for pupils or for a teacher giving demonstrations to make consistent measurements, because the spring-balance jiggles while it is being carried along and gives uneven readings. It is not so much the friction that is uneven as the motion of the operator's hand. To avoid that trouble, place the plank on rollers and pull the plank along at constant speed by a string which is being wound by hand on a crank. Meanwhile hold the block at rest (while the plank moves along under it), by a horizontal string from the block to a spring-balance held at rest. That will give steadier reading. If this is done as a class experiment, ask definite questions and urge the class to look for answers roughly and quickly. D44b

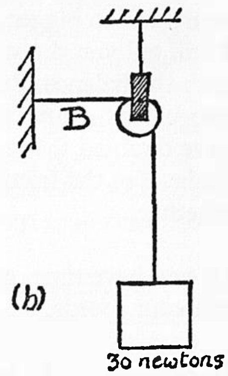


SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

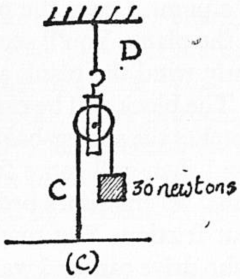
X. Pulley Questions

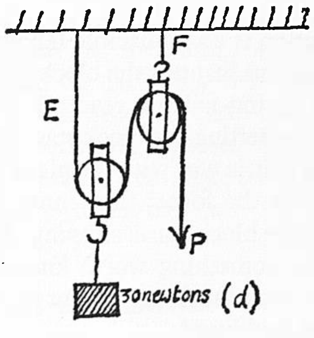
(NOTE: The following questions are not intended to encourage an expansion into the teaching of pulleys. Nor are they intended to involve the class in discussion that is too difficult or seems irrelevant. They are only offered as possible stimulants for thinking and discussion.)





a. Freddie Jones says the tension at A is 6 kg wt; what do you say? What curious thing would happen if Freddie were right?
b. You and Freddie agree that the tension at B is – What? By the way, Freddie drew the picture and of course it's wrong. What's wrong with it?





c. Pulley itself weighs 4 newtons. What are the tensions at C and at D?
d. Pulleys each weigh 4 newtons. What are the tensions at E and F?

Friction Discussion. These experiments should not be allowed to take long.

'Once the board is moving along smoothly under the block, does the friction force stay the same, or does it change a great deal from one run to the next? If it does, take two or three runs and average them. T

'Pile a load on top of the block to press the block against the board with a bigger force than just the weight of the block itself. I will tell you the weight of the block, or you can go and find it with the balance. Put an equal load on top of it; when you have two blocks'-worth pressing the block down on to the tables you have doubled the force pressing them together. Try the friction again. Try the friction with three times the force pressing them together.

'If you have time, go back to the plain block and try friction for different speeds.

'If your block can be turned over on one side, so that the area of its face on the table is smaller, try the effect of that change ...

'I must warn you that what really happens in all these things has been investigated with microscopes and other things that look into tiny details in the surfaces, and the full story has been found to be much more complicated. This is only a rough look at the general behaviour.

'Friction is an adjustable fellow, up to a point. Leave the plank at rest and just put the block loosely on the plank. You'll see that your spring-balance reads O. Now gently wind the plank along without letting the block start slipping. The block will be carried along a little way with the plank as it stretches the spring-balance. Look at the force; then more force; and then still more force, until the block starts slipping. Just try that several times because it tells something worth knowing about friction. You may see something that is important to people who drive cars and want to avoid skidding.'

All this should be done very quickly – it deserves one period at most, not two.

Fluid Friction

Fluid friction is interesting and forms a valuable beginning for *
Newton's Laws of Motion. Instead of announcing Newton's Laws *
as the right rules, as one might do in discussing things with a *
mature scientist, we shall be wiser to start looking at motion with *
friction, which is more common in the real world. Solid friction *
does not give such an interesting story as fluid friction, which has *
the important property of increasing its force with increasing speed. *
So a body whose motion is controlled by fluid friction will, if pulled *
by constant force, approach a constant speed (terminal velocity). *
This is what happens with parachutes, raindrops, clouds, divers in *
water. It is even what really happens with many an object thrown *
out of an aeroplane as in a physics problem and allowed to fall *
through a large distance. Such problems often ask for results calcu- *
lated from acceleration formulae for free fall when in fact, with the *
distances given, the object would be approaching terminal velocity. *

Discussion of Fluid Friction. When we teach anything about *
fluid friction, or when we encourage pupils to try class experiments *
on it, we must bear in mind at least two different types of fluid *
friction: the kind associated with very slow streamline motion (as *
for Stokes' Law), and the kind that leaves a wake of vortex motion *
and involves a resistance that varies as the square of the speed. *

Experts in fluid dynamics warn us that both our commonsense *
thinking as physicists and most textbooks are misleading about *
fluid friction. When we increase the speed the whole pattern of flow *
round the moving object may change, and if so the 'constant' in the *
formula for friction will change. And at even higher speeds the *
whole relationship may change completely, as mentioned above. *
So the simple laws that are often quoted do not apply well over *
a wide range of speed. What follows here is only a description of *
two simple, but rather extreme, cases of motion through real fluids. *
Incidentally, the experts agree that if we could try moving an object *
through an *ideal* fluid with no viscosity, we should find that it *
experienced no resistance or drag at all. *

For very slow motion through a viscous fluid, friction varies as *
speed, and (for a given shape) as the first power of a linear dimen- *
sion such as the radius of a sphere. $F = k\,r\,v$. In air, ordinary rain- *
drops fall far too fast for this to apply. It does hold for the tiniest *
drops in fog or clouds. *

For much faster motion, we may regard the resistance as due to the *
body leaving behind it a wake of fluid in confused motion with *

kinetic energy; and then the resistance varies as v^2 and varies as the density of fluid (d), varies as (linear dimensions)^2 and does not involve the viscosity coefficient. $F = k' d r^2 v^2$. * * *

We certainly should not tell pupils any of this detailed story; but we may find it useful ourselves in interpreting what happens. * *

Demonstration Experiment. Terminal Velocity. Let a ping-pong ball fall. Then attach a small parachute of paper or cloth (handkerchief), and ask pupils to watch the motion again. D45

Class Experiment to see Terminal Velocity. Give pupils a tall glass jar of water – a gas jar will do – with some small objects that will fall slowly in water (e.g. small balls of steel or glass beads: for slower motion, pieces of wood or wax weighted with wire, scraps of solid plastic or of chalk). If some heavy oil is available they may try that instead of water. Ask them to see what they can find out about the falling motion. C46

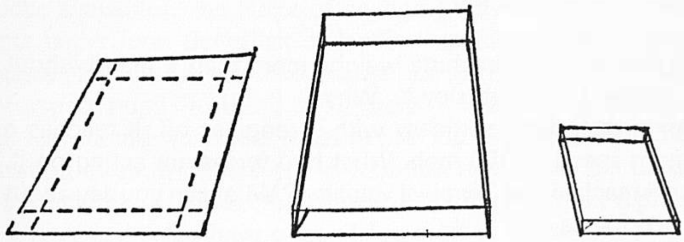
Pupils will ask for a clock; but a stopwatch or even an ordinary clock will prolong this quick look at fluid friction unduly; so we should just provide some device that ticks loudly about once a second. If possible, use the large crude pendulum suggested for Year I; a broomstick loaded with two bricks swinging on a nail. A projecting spike at the bottom of the broomstick hits a card each time it passes through the lowest point. The clicks made by that are clearly audible and pupils can use them for timing distances. The card should be arranged so that it is at right angles to the plane of swing of the pendulum, so that the spike gives it a sharp tap. The bigger the area of the card the better. If instead of holding it in a clamp at the bottom, we bend a portion of the lower edge at right angles and strap it to a sheet of paper or rubber across a large beaker, we shall get even more sound from it. Or the spike can be arranged to hit a bell like the gong of an electric bell. If the background noise in the classroom is so great that even these signals are not audible, then the teacher, or a pupil, may make loud taps or hand-claps instead each time the pendulum swings through the lowest point.

When the pendulum hits the card it loses some energy, so the amplitude will die down. But the time of swing of the pendulum is almost independent of its amplitude; so it will keep good time. The card delivers an opposing impulse to the pendulum at the mid-point of its swing, and that does not change the phase of the motion, so no part of a cycle is gained or lost at that impact, and therefore the timing is good. If the teacher likes, he can even keep the pendulum going by giving it an occasional impulse with his hand, always at the mid-point of the swing.

We offer sticky tape or a special pencil to mark the stages of fall on the jar. The behaviour of 'styrocell' beads is interesting for they will fall at various terminal velocities in water. If we boil them, they swell up so much that they will fall in air as 'slow motion raindrops'. The beads do not all swell to the same density, so a collection of them shows a strange variety of motions.

Pupils should find that the motion quickly approaches an almost constant speed. If not, it is because the bead is too dense and therefore needs a longer distance of fall before it is close to its (greater) terminal velocity. In that case, we should substitute heavy oil and let pupils crowd round and watch it. We should *not* give any discussion of gravity fall at this stage – that would make the motion of the bead seem *unnatural*! But we may ask naïvely, 'Why doesn't it move faster and faster?'

Class Experiment on Air Resistance. Show pupils how to streamline a sheet of paper by bending up the edges to make a little rectangular tea-tray. On an 8 inch × 10 inch sheet of paper, the bent-up sides should be about $\frac{3}{4}$ inch high, and smaller trays should have sides in about the same proportion. Point out that a plain sheet of paper flutters when allowed to fall, but the tray falls more steadily. Ask pupils to find out all they can about the way such a C47



tray falls. Tell them they have 20 minutes to find as much as they can and that, after that, when we hold a council-of-war to find out who has discovered what, they'll be sorry if they haven't managed to try quite a number of different things. Then give them more than 20 minutes – because, when young people start trying things they take some time to get going. It would be a great pity to give detailed instructions and simply have pupils observe what they're told to look for.

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

Y.

A small object, which is 'heavier' than water, is held at rest just under the water in a deep pond and then released.

1. Write one or two sentences describing its motion after you have let go (if you can, draw a rough graph of downward speed or velocity against the distance fallen).

2. Describe in your own words the meaning of 'terminal velocity'.

3. When a falling object reaches terminal velocity, what is the total of all upward and downward forces acting on it?

Z.

Try the following experiment: Get a penny. Cut a small disc of stiff paper the same size as the penny. Hold the penny flat between the thumb and fingers of one hand; hold the paper disc in the same way with the other hand. Let both drop at the same time.

1. Which reaches the floor first? How do you account for the difference?

2. Now put the paper disc on top of the penny and drop both together. What happens now?

3. Freddie Jones has done the same experiment, and he says it shows that, if air resistance is removed, paper falls as fast as pennies. The experiment certainly does not disagree with this conclusion, but would you go all the way with him in saying that 'it shows that . . . .'? If not, write a sentence or two saying why not. What would be a more satisfactory experiment to show the same thing?

AA.

1. A man with a parachute weighs more than a man without one, yet he falls more slowly. Why?

2. An aircraft dives vertically with its engines off. It reaches a constant speed of 350 mph. What two forces are acting on it, when it reaches that 'terminal velocity'? What can you say about the two forces?

3. The aircraft is still diving when the pilot switches on the engines (a 'power dive'). What happens now? Assume the plane does not hit the ground, or break in pieces – why is it likely to break in pieces under this treatment?

With some groups, this play with paper trays can be very interesting and fruitful.§ It strikes other groups as childish, and as an opportunity for undisciplined waste of time. In the latter case, we should either avoid the experiment or give it limited time near the end of a class period; and perhaps preface it with the following two demonstrations which give a hint of a serious use of experiments with paper in future years:

1. Hold two sheets of thin paper vertical, parallel, about one inch T
apart. Hold your mouth just above the sheets at the top and blow a strong current of breath down through the space between the sheets. Before doing it ask what the pupils expect will happen. Then either do the experiment yourself or let pupils try it.

2. Hold a sheet of paper by one edge, pulling that edge taut, horizontal, by holding the two corners with finger and thumb of two hands. Bring that edge up just under your lower lip so that the rest of the sheet projects away from your face curving down under gravity. Ask what will happen when you blow a strong current of breath over the top of the sheet. The previous experiment may offer a hint. Try it, or let pupils try it; and then point out that this may show the secret of the way in which the air supports an aeroplane.

With the paper trays there are several different things to find (but we should not suggest these): the effect of starting the tray upside down; the effect of starting it near the ground or high above; the behaviour of the air as the tray goes past (if someone has some smoke available); the effect of changing to a smaller tray of the same paper, and the effect of loading up the tray with multiple masses of the same paper to change the gravity force. We should not expect pupils to think of all these possible things to try, and still less should we expect them to provide clear answers. The last question of all, friction force vs terminal velocity, is too hard and should neither be asked nor answered at this point: but a physicist at a later stage can have a lot of fun with it and arrive at a very interesting, clear conclusion.

(If available for a quick demonstration, finish this discussion by D48
showing small steel balls falling in a tall jar of glycerine or heavy liquid paraffin.)

§ 'I set them a homework question on this. I was surprised how well they set to and tackled this problem. In the fast group, two boys approached me with a theory which included vortices, etc. They are trying experiments at home with small trays in a large smoke-filled jar.'

All we want from these experiments is just a feeling for the way in *
which fluid friction brings a moving body to a practically constant *
speed. If we could deal with friction in a single period – by some *
compression, some light-hearted skipping and some complete *
omissions – that would be better than spending three periods on it. *
At this point, we would like pupils to know about friction; but we *
want to hurry on to studies of work and energy. *

WEIGHT, THE PULL OF THE EARTH

Return to a reminder of one more kind of force: the common one T
that we call weight. We should speak of that from now on as 'Pull *
of the Earth'. *

(Children will not question that statement: they will not say, 'I *
have no evidence that my weight, which the weighing-machine *
and my shoes, etc., tell me is there, is a pull of the great round *
Earth on me'. At this stage it is wiser not to raise that question.) *

'Any falling thing moves towards the Earth, and popular report T
has it that a similar ball released in a laboratory in Australia, will fall in exactly the same way. They're moving towards the centre of the Earth. So we guess that the Earth is pulling on those balls and indeed pulling on all things that we see around us. We call that attractive force, the pull of the Earth on a thing, the weight of the thing. In physics that is all weight means, the pull of the Earth on the object in question.

'The Earth pulls every object towards it. Do big and little objects pull each other? Do *you* attract the pupil over there in the next desk? Does one cricket ball attract another cricket ball placed on the table near it? Have you ever seen them rolling towards each other, pulled by some attraction?'

That is not a question to leave unanswered because pupils easily develop, and keep, the idea that weight is a peculiarity of the Earth alone. We should say that scientists do believe that every object attracts every other object, but that the attractions are very small indeed unless one of the objects is an immensely big massive one.

'The Earth is so big that it pulls ordinary small things like this brick with enormous forces. Watch what that pull-of-the-Earth, the weight of this brick, makes it do when I let it go. It moves faster and faster and faster, so much that it arrives with a crash on the ground like that.'

Note to Teachers: Safeguarding Ideas of Mass and Weight. All through this Year, and right on through Years III, IV and V, we should say again and again, whenever '*weight*' arises or is used in any discussion, '*the-pull-of-the-Earth*'. This will help to avoid some of the confusion between mass and weight which is promoted by the unfortunate variety of uses of 'weight' and 'weigh' both in common practice and in science. Try it, and you will find that this change to 'the pull of the Earth' will work magic.‡ T

'We measure the pull of the Earth on things in several ways. We can measure it by letting it pull out a spring, as in this spring-balance. If I want to know the pull of the Earth on this brick, I hang it on a spring-balance and it stretches the spring until the spring pulls the brick up with its own tension forces just as strongly as the Earth pulls the brick down. Then I read the balance 1·6 kilograms. D49

'I want them to be quite sure that people know I am telling them how much the Earth pulls this brick when I say *1·6 kilograms*, so I do not say it like that, I say the weight of this brick, the pull of the Earth on this brick, is *1·6 kilograms-weight*. Then, with the word 'weight' tacked on at the end, they will have no doubt that I'm talking about the pull of the Earth on 1·6 kilograms. T

'When a scientist just says "I have 1·6 kilograms of brick", he is usually talking about how much stuff he has got there. He only adds the word "weight" and says kilograms-weight when he means the pull or force with which the Earth pulls the thing.'

Marking a Spring-balance for use (if not done in Year I)

'Here is a blank spring-balance with a good spring but no marks on it, no scale. I will give each of you one of these balances and some chunks of metal, all alike. Some of you can have chunks that are 100 grams each, a tenth of a kilogram. Others can have quarter-pound chunks. C50a

‡ In a later Year we shall talk of the Earth's gravitational field; and we shall make the Earth's gravitational field strength an important concept in calculating weights. g is the acceleration of a freely falling body; but it is also the strength of the Earth's gravitational field. A freely falling body has an acceleration of 9·8 metres/second per second; but a body at rest (or with any kind of motion) is pulled by the Earth with a strength of 9·8 newtons per kilogram. It would be absurd for anyone (except a General Relativity expert) to say that an object at rest has an acceleration of 9·8 metres/second per second; but it is quite sensible to say that such an object is pulled with an Earth-pull of 9·8 newtons on each kilogram of stuff in it. Adopting the latter view will make it easier in Year IV to handle absolute units for forces in calculations.

'Hang a chunk on your balance and make a mark at the place where the pointer is. If you work with a partner, make sure you both agree where the mark should be. Then try another of the lumps to see whether it is just the same as the first one. If it is not, please *complain to me*. Now hang both lumps on the balance and make another mark labelled "2". Why did you have to make sure that the second chunk pulled the spring to the same place as the first chunk before this? Then mark 3 and 4 and so on, as far as you can go.'

We certainly should not raise any question with children about the assumption behind this calibration process, yet the teacher should keep it in mind: we assume that four equal lumps hung together on a spring pull it down with four times as big a force as one lump. We have to make some assumption like this in constructing a scale-of-measurement for a *thing* like force. There are other systems of defining and measuring force, but the equivalent assumption will always be there, though it is sometimes more deeply concealed. In our teaching, we should take this assumption as obvious and necessary. It is not really a weakness in our construction of physics; but rather a definition of how we are trying to construct physics to express our understanding of nature. Yet there is some knowledge of nature in our statement that the Earth pulls four equal lumps together with just four times its pull on one lump; this agrees with the experimental fact that gravitational pulls do not interact with each other, but simply add up – the Earth's pull on the upper lump is not shielded by the presence of the lumps underneath it.

When children have made calibrated spring-balances, we may give them an object such as a lump of rock to weigh on their balance, saying: C50b

'Find out how much the Earth pulls on this piece of rock, in whatever units you have used for making your balance.'

This simple experiment, which may seem almost pointless to us, is an important example for beginners to show how scales of measurement are made and perhaps to reinforce the idea of weight as the pull of the Earth by doing something with it.

Hooke's Law and Spring Balance: Note to Teachers. We did not appeal to Hooke's Law in calibrating the balance. As we have used it here, the spring need not obey Hooke's Law as long as it is 'elastic', that is, as long as it does not become permanently distorted. People who make spring-balances are glad of that because

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS
BB.
Quotation: 'An earwig, a cat, a man, and an elephant all fall over a high cliff. The earwig walks away unharmed, the cat breaks a leg, the man is killed, and the elephant splashes.' Why is there this difference?
(*Note to teachers:* This raises questions of 'scaling'. Air resistance, for medium speeds, varies as the square of linear dimensions, while weight, and the forces involved in the rapid deceleration vary as mass, and therefore as cube of linear dimensions. This is interesting and important for physics teaching at later stages; but we should not diverge into much discussion of it here.
Another example: 'Why is a big block of flats cheaper to keep warm – per family – than a small house?' A similar matter of scaling appears in problems of critical size for nuclear reactors.)

such springs give an even spacing of marks on their scale. That is what scientists call a 'Linear Scale'. But here we do not need Hooke's Law, because we can make our marks on a balance anyway. * * *

'We can mark a spring-balance in pounds-weight. A pound-weight is the force with which the earth pulls one pound. Or we can mark the spring-balance in some other units which we call newtons. We shall use newtons a great deal later on.' T

We should show a spring-balance marked in newtons, or better still give such balances out for a quick class experiment. Pupils should pull and feel forces of a few newtons. They should weigh a kilogram in newtons. C51

Then we show a 'forces box' and keep it available for a week or two for pupils to try. D52

'You will find a string coming out of that box over there which will let you feel a pound-weight of force. And another string pulls with one newton of force. Go round to the back of the box and you'll see how it's all arranged. We'll keep the box there for some time so that you can feel what those forces are like.

'If you'd like to feel what a pound of *stuff* feels like without bothering to lift its weight – pull against the Earth's pull on it – you can just shove a pound along on the flat coasting-table over there. The tiny balls are there to act as rollers and make the friction almost nothing. Then you can feel what it costs you to get that pound of stuff moving without having to push hard against any friction. Even if there is no friction, you still have to push hard if you want to get a thing moving very fast; or else you have to go on pushing for a long time. That is a really important thing about all kinds of matter: to get it moving or make it move faster you have to push it.' D53

At this point when we are talking about the pull of the Earth, and saying that that is what we use the word 'weight' for, we should say clearly that it is 'bad manners' to measure a force in plain grams or kilograms or plain pounds. We ought to say very clearly 'grams-weight' or 'kilograms-weight' or 'pounds-weight'. T

'If my friend George is a 70-pound boy, that means he is made up of 70 pounds of stuff, 70 pounds of matter of various kinds. We use pounds for the amount of stuff there is in George.

> ‘When we want to talk about the pull of the Earth on that stuff, we talk about George’s weight and we say he has a *weight* of 70 pounds-weight. “70 pounds-weight” means “the pull of the Earth on 70 pounds of stuff”. If you are wise you will always put the word “-weight” at the end whenever you’re talking about a force.
>
> ‘Presently we shall measure all forces in newtons and then we shan’t have any trouble about adding the word “weight”, because newtons are only used for forces.’

(With a very fast group, one might give a very brief warning of *
what is to come, saying that we expect George’s *mass* – 70 pounds *
of stuff – to stay the same even if we send him in a rocket to the *
Moon or leave him drifting about in outer space. Yet we are sure *
his *weight* would be much less on the Moon. There the Earth’s *
attraction would not be noticeable, and the Moon’s attraction *
would be about six times smaller – George could jump with *
astounding success. If we still called the gravity pull of the Moon *
upon George 70 pounds-weight then 70 pounds-weight would *
mean a much smaller force so we should have to say ‘70 pounds- *
weight-on-the-Moon’.)§ *

Point out to children that weights can also be measured by a T
seesaw: we put the thing whose weight we want to measure on one side and then pile up standard chunks of metal the same distance out on the other side until the seesaw balances, and then we believe that the pull of the Earth is the same on both.

The Newton

With a fast group, we might discuss the advantage of newtons for force.

> ‘There is a story that very long ago the foot as a unit of length T
> was the length of the King’s foot; and in that case it must have been a unit that changed from time to time – not a good one for science. A pound-weight (or a kilogram-weight), a possible unit of force, does stay the same from day to day or year to year, but it does not stay quite the same if you travel about. You will find it is a slightly stronger force near the North Pole than near the equator; and, if you could get to the Moon, you would find this same pound of stuff being pulled by the Moon with a much weaker force. So scientists decided on a definite unit of force

§ ‘The differences in ability come out much more strongly in sections like this where some quite abstract ideas are involved.’

which would stay the same and be the same everywhere. ... They call it a newton.

'Here at the surface of the Earth, this pound of stuff is pulled with a force of 1 pound-weight which is a force of roughly $4\frac{1}{2}$ newtons. If you took this to the Moon, you'd still have the same chunk of metal, the same mass as we call it, the same amount of stuff, but the Moon would pull it with a smaller force: only about $\frac{3}{4}$ of a newton.'

With a very fast group, we might continue with a difficult question:

'Here is a difficult question to think out: Suppose the Earth does pull on things with every piece of the Earth helping to pull. Imagine you could dig a tunnel right down to the very centre of the Earth and have a small lab there in the middle. ... Hold *this* chunk of metal, this one pound there at the centre of the Earth. Which way would the Earth pull it? How much would the Earth pull it? Would it have any *weight*? Would the *mass* of stuff still be there?'

Leave those questions to brew. *

We point out that a newton is a little more than $\frac{1}{4}$ pound-weight, *
about the size of the force needed to push a light broom along the *
floor against friction. *

Chapter 5

ENERGY

Energy Changes; Power

YEAR I's INTRODUCTION TO ENERGY

In Year I there was a preparatory treatment of energy. If that amounted to general, qualitative descriptions with nothing defined, we must make a new start now. If that contained some definite quantitative discussion (as it should) to introduce work and talk about measuring *changes* of energy, those were such tough, new ideas for young people that in that case too we should start afresh now. So we take Year I's work as a useful introduction to the idea and to some names connected with it, and now we try to be more definite and to expect a clearer grasp.§

Fuel

In Year I, we introduced energy as something stored in fuel, something whose *move* from fuel can get useful jobs done. Even then, we did not say fuel produced the energy; we only said it 'released it'. We did not say we 'used' the energy – as if we consumed it – but we said the useful job is done as the energy is transferred from its stored form in fuel to some other form such as potential energy of a raised load or heat in bathwater.

Energy-Changes in doing useful Jobs

In teaching Year II, we should remember that energy-*changes* are often more important than energy itself. If we haul a load of bricks up to the top of a building using our own arms and a pulley system, we transfer a considerable amount of energy from an invisible store of chemical energy form in our body to gravitational potential energy, equally invisible, located somewhere in the gravitational field. The useful thing is that we have raised the bricks higher up. That was not done by any energy being manufactured or by any energy disappearing but only by some energy *changing* from one form to another. We have also moved the energy from one place to another, but while we are fairly sure that it resided in our body, when it was in chemical form, we can hardly tell quite where it is when it is in the form of potential energy, presumably in the gravitational field and therefore not very easy to locate.

Energy-Changes FROM . . . TO . . .

All through discussions of energy now and later we should carefully name the two forms between which the transfer occurs. We should say, for example, 'So much energy is transferred FROM chemical form stored in our muscles TO motion energy'. It makes things easier and clearer if we underline the FROM and the

§ 'I thought this was slow in Year I. But after maturing during long vacation many had grasped and remembered it.'

TO, and insist on pupils always telling us the two forms and *
including FROM and TO in their statements. *

Work

We use work, introduced in Year I, not as a form of energy itself *
but as a calculated number-statement, of the quantity of energy *
transferred from one form to another. Thus, if we have a 2-kg *
brick pulled by the Earth with a weight of 2 kg-wt and raise it *
3 metres, we calculate the work to show how much energy is trans- *
ferred. We state that in full 'the transfer of energy from chemical *
form to potential energy is 6 kilogram-weight.metres'. Use those *
units and ft.lbs-weight at first during this Year, but point out that *
a newton.metre is also a unit of work and useful because it is a *
universally constant unit – so useful that we give it a special name *
and call it 1 joule. (If pupils ask how we prove that a joule is a *
newton.metre, we explain that this is just a shorthand word for a *
newton.metre so there can be no proof. 'How would you *prove* that *
a knot is a sea mile per hour? It just is a name for that.') *

DISCUSSION OF ENERGY (Some of it revision from Year I)

In our present teaching of energy, which continues the building of acquaintance from Year I, we shall use informal names for several forms of energy whose official names would be puzzling and add difficulties. These are:

'*motion energy*' for *kinetic energy*. In our treatment below, we shall use this informal name when we are suggesting discussions with pupils. But we shall, of course, refer to it as kinetic energy or just K.E., when we are discussing policy or methods with teachers.

'*uphill energy*' instead of *gravitational potential energy*. Again, we shall use this informal name in our suggestions for teaching, but we shall of course call it P.E. in our own discussions as physicists.

'*springs energy*' instead of *strain energy* of a wound-up clock spring or a stretched wire, or a bent beam. This wording may sound uncouth, but we believe it will help in teaching at this stage, by conveying the feeling of springy material holding some stored-up energy. However, when strain energy is involved in some machinery which is transferring energy from, say steam in a cylinder to, say, spin energy of a fly-wheel, we shall evade some difficult distinctions by calling that '*mechanical energy*'.

(In fact, when ropes, pistons, levers, etc., transfer energy from one place to another or transform it from one kind to another, the energy does go through some form which we should call strain energy, essentially travelling in some form of waves. This raises considerable difficulties, even to ourselves, both in picturing the location and behaviour of that energy and in explaining its transport. Therefore this part of any discussion of energy-transfer should be avoided in elementary teaching.)

'light' energy instead of *'radiation energy'* or any other name for the energy of electromagnetic waves. At this early stage, the word 'radiation' will not make things clear to our pupils – particularly since our class experiments on radiation are yet to come – and we should be teaching in a mistaken order if we started referring to waves at this stage. It would be unfortunate if we misled pupils by choosing a name that usually refers to the visible spectrum alone. We must at once explain to pupils that we are thinking of light itself – all the colours red, orange, etc. – *and* some 'invisible light' which our eyes do not notice, such as ultra-violet light and some other kinds beyond the red. As a safeguard, we then put the word 'light' in inverted commas as long as we are using it for this purpose. After pupils have done the class experiments of the 'radiation circus' we might wisely change to *radiation energy*. At the moment, however, we want to keep the naming simple when we are trying to deal with this important and difficult concept.

Here is the kind of introductory discussion of energy that we suggest:

> 'Mankind uses forces in many ways. Can you think of examples of very big forces? ...'

Failing enough suggestions, the teacher may need to add some:

> 'Big forces are needed for riveting, for holding bridges together, for supporting tunnels under water, for pulling a train along, etc. And big forces are involved in the smash of a hammer or the starting blast of a rocket.
>
> 'In some cases, we can get a big force that we need very easily. We can use a lever, or seesaw as a force-multiplier. Think of the force you can get with a pair of nutcrackers, or the force you can get if you use a long crowbar to prise something up. You can get a very big force if you put something in a vice or a small clamp and tighten it up. You can get a very big force just by building

a tall pile of sand or lead blocks, or something like that. The pile will press down on the floor under it with a very big force.

'Some of those forces do their job for us by just staying there. When we clamp up some pieces of wood in a vice while the glue is setting, or when we build big supports under a bridge to hold it up against its weight, we do not have to go on paying day after day and week after week to keep such forces going. But there are some other jobs that forces do for us (besides supporting things and holding things together) that we do have to pay for, and go on paying for.

'If we pull a cart along a rough road we have to provide some kind of pulling agent – a man to pull or push the cart or a horse or a petrol engine, and in each of those cases we have to pay for some stuff to keep the agent going – food for the man, hay for the horse, petrol for the engine. Or, if we want to haul a big load up to the top of a high building, we have to provide fuel for an engine, or food for a man, or something of that kind to get that job done. There are a lot of jobs which need fuel. Those are not jobs in which a horse or an engine just stays still and goes on pushing or pulling without moving. They are jobs in which whoever applies the force *moves along*. We can think of the force moving along, shoving along for a considerable distance. And that, if you think of it, always costs fuel.

'The useful jobs which *do* need fuel, or food (or indirect fuel like the electric supply) and cannot just be done at no cost, all ask us for something to get them done – something that costs money but certainly isn't itself money. When we use fuel we draw upon a store of some kind of thing that will do useful jobs, and we call that thing energy.

'We don't manufacture energy and we don't believe we ever lose any, in the whole world; yet we do shift energy from one form to another. In that way, it is rather like cash. A wise country does not manufacture cash, but there are very important shifts of cash from one person to another, or from a person to a shop, and so on. To get jobs done by a workman, you have to transfer some cash FROM yourself TO him. To get these useful jobs of raising loads done, you have to transfer some energy FROM some store of energy in a fuel TO some other form such as the 'uphill-energy' of this raised-up weight.

'Or we can use the fuel to drive something and make it move faster and faster. You can't make a thing move faster without shoving it along, and then you have [shove] × [distance], some work done, some energy transferred, and this time we say it is transferred FROM the fuel store of energy TO energy of motion or "motion energy". Later on we shall call that energy of motion "kinetic energy, K.E." A moving thing has a store of motion energy, and that can be used because we can let the thing be brought to a stop, and in doing that it can haul up a load for us.

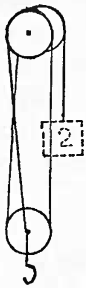
'Here is something you saw last Year. I want to raise up 2 pounds, 3 feet. I can simply lift it from the bench up to the top, or I can do it in stages. First I lift 1 pound, 1 foot. That costs me a little bit of "fuel". I have to draw upon some energy (that I get from my breakfast) stored in chemical form in my muscles. I change it, through my muscles, to some other form stored up in the springy pull of the Earth on this 1 pound. D54

'When I move my pull of 1 pound-weight up through this distance of 1 foot, I multiply force by distance and call that 1 foot.pound of work.‡ That is a way of saying how much it costs me. That work [force] × [distance], is not energy: it's just the way in which I calculate how much energy I have transferred from my chemical store ("breakfast energy") into something stored up by the load. Now I raise this another foot, costing me another foot.pound, and another foot.pound. The total cost is 6 foot.pounds and I find that if I move it all in one go 2 pounds × 3 feet, it still costs me just as much fuel, just as much food-energy, 6 foot.pounds. That has been tried with very careful measurements on human beings, though the argument behind the experiment is rather complicated.

'What happens if we take these two pounds at the top and let them fall down? We can attach them to a string like this and run that over a pulley to another load and then, as these go down, we can raise the other load up [almost 2 pounds] × [3 feet up], almost get our 6 foot.pounds lost by the first load and gained by the other. D55

‡ We are adopting a modern practice of using a dot to show multiplication of units as well as numbers. Five man-hours means five men multiplied by one hour, or one man multiplied by five hours or ... etc. In each case a quantity of men is multiplied by a quantity of hours and units should be men multiplied by hours. The old custom has been to write that 'man-hours'; but we shall now write it man.hours; and we do the same for units of work and energy such as:
foot.pound   foot.pound-weight   newton.metre

'But instead of that I could connect these 2 pounds up at the top to a pulley arrangement like this. If I had 2 pounds attached to the string here, how much do you think the hook under the lower pulley can hold? The pull is 2 pounds on this string, and it goes round the strings: 2 pounds, 2 pounds, 2 pounds, all the way. There are three strings pulling up the lower pulley; three pulls of 2 pounds; I think it could carry almost 6 pounds. Now we let the 2 pounds go down; we are losing the 6 foot.pounds of uphill energy that we had stored-up, but this 6 pound load is gaining 6 pounds multiplied by ... oh, but it's only 1 foot; so the load gains 6 foot.pounds. D56



'Now go back to the top and let the 2 pounds just fall down to the table. They go faster and faster and faster, and then stop with a crash. Just before the crash, they were moving very fast and yet they have lost their stored-up energy because of the height. Have they got the energy in some other form? D57

'[We cannot say they *must* have it because that would be just making rules about nature and trying to make nature obey our rules instead of finding out what nature does.]

'But, we can have a smooth curved slide like this for them near the bottom, so that instead of an arriving crash they rush on and along the table. Imagine what would happen if, when they are rushing along the table, we could attach a string to them and run it over a pulley over here and attach a load to that pulley. They would come to a stop, but they'd haul the load up some distance. D58

'I cannot show you that with the 2 pounds, but I can show it to you with this massive trolley on roller-skate wheels. I give it a shove and it runs right along the table, but if I attach this thread to it with a load on the other end of the thread and then give the trolley a shove, as soon as it pulls the thread tight it begins to raise the load and slow down itself. So we say that D59

when it's moving the trolley has motion energy. And when it is
brought to rest, it loses that motion energy and the load on the
end of the thread gains some stored-up energy, which we shall
call uphill energy for the present. Whenever we see an object T
moving along, we say it has motion energy. That is, more energy
than when it is at rest, because we know that we could make it
do a useful job for us by raising the load with a string or by
manufacturing heat, if we arranged to take its motion away.'

MEASURING ENERGY CHANGES BY 'WORK'

'Raising one pound one foot costs me some food-energy which is T
transferred to uphill energy stored up by gravity. I am going to
measure that transfer in foot.pounds; just as you measure
the transfer of cash in pennies or sixpences, I measure that
transfer and I call that the work. Work is not itself the energy:
the energy is first there in one form, and then moves to another.
Work *F.s* tells you how much you've taken out of one kind of
store and put into another.

'In that way, work is rather like a cheque that someone writes out from his bank account.‡ If I give somebody else a cheque for £5, that cheque isn't itself £5 in cash of any kind: it is an instruction to my bank that they are to pay £5 to the other fellow. That will make him £5 richer. His bank balance has a change of +5 but my bank balance has a change of −5. The cheque itself isn't + or −: it just tells us how much money is to be transferred from my bank to his bank. In the same way, we do not reckon work + or −, but we simply say, "The amount of work (calculated by multiplying the force by the distance moved) tells us how much energy is transferred FROM, say, chemical energy of fuel TO, say, gravitational potential energy".'

Note to Teachers on 'Work'. Teachers will note that this is a *
different treatment of 'work' from the usual one nowadays. This *
goes back to a more careful use of the term that was established by *
the great natural philosophers in the last century. We thus avoid *
the terms 'work done on' and 'work done by' with all the ensuing *
doubts about plus and minus signs, and simply say the work is so *
much, but always add to that statement 'this is the transfer of *
energy FROM (such and such form) TO (such and such other *
form). If we always insist upon that full statement, we shall find *
that energy-changes are much easier to keep straight. *

‡ Most pupils are not familiar enough with cheques for this to be a telling illustration. Perhaps a story about postal orders would be better. We hope teachers will look for some illustration still nearer to current life.

DEMONSTRATIONS OF ENERGY CHANGES

'Watch this brick that I have hung on a string. I swing it out to here and hold it. Has it gained any uphill energy? Have I pulled it up higher above the ground? ... Now I let it go. Look, there at the lowest point: is it lower? Has it any other form of energy? ... Now it's up there again. What has it there? The energy changes from a bit more uphill energy to motion energy to more uphill energy. D 60a

'Now hang the brick on this big spring. Watch it. It goes down, losing uphill energy. Here at the lowest point I'll catch it and stop it. Has it lost any uphill energy? Where has that gone to? The brick is not moving. It has no motion energy. What has happened to the energy? Yes, it is stored in the spring. The spring has what we call 'springs energy'. Presently we shall call that strain energy, or elastic energy. D 60b

'We can do that another way. I'll fix one end of the spring to the end of the table here and then pull the spring horizontally, stretching it till I have stretched it as I had before. Oh, but this time I see that I have to pull a bigger and bigger force till I have the spring stretched; so [force] × [distance] would be harder to calculate. But still, I could work it out: there is some work, some transfer of energy from my "breakfast energy" to some energy stored up in the spring. For the present we should call that stored-up energy "springs energy". Now, if I attach the end of the spring that I'm holding, stretched to a cord that runs over a pulley and up over another pulley, and holds a load, I can let the spring pull back and raise the load and you can see the spring is transferring energy from springs energy stored up in it to uphill energy of the load. D 60c

'Or, I can stretch the spring like this and let it pull this trolley. When I let go the stretched spring pulls and pulls and gives the trolley motion energy. D 60d

'Here is another change. I give this trolley a good shove, transferring some "breakfast energy" to motion energy, and then the trolley runs on to this rough patch of table and comes to a stop. What has happened to the energy there? What happens to your energy if you slide down a beautiful slide, going faster and faster, and then land sliding along a rough floor? You have gained a lot of motion energy from the uphill energy lost as you went down the slide and you now lose the motion energy. Where does it go to? Yes, there is heat there. Perhaps heat is some kind of energy if it is true that energy does not get lost.' D 60e

The teacher should show a large number of energy-changes, always mentioning the forms of energy involved in the transfer. Examples: D 61

1. Light a match (from Chemical E to heat).

2. Run a Bunsen burner (from Chemical E to heat).

3. Run a Bunsen burner under a model steam engine which has a winch to wind up a load (from Chemical E to heat, to Mechanical E in the machinery, to Uphill E in the load).§

Note that as the engine is running steadily there is *not* a continuing transfer of energy to spin energy or to K.E. of the rising load. * *

4. Run a Bunsen burner under a model steam engine without a load so that the engine goes faster and faster (from Chemical E heat, to Mechanical E to Spin Motion E). D 61 cont'd

That will raise the question of the kinetic energy of the moving parts of a flywheel. Say that we call that 'spin energy', though it is really nothing more than kinetic energy of a lot of parts of a wheel that is going round. * * * *

5. Bunsen burner drives toy steam engine, which drives small dynamo, which lights lamp (Chemical E to Heat, to Mechanical E to Electrical E to Heat and 'Light'). D 61 cont'd

6. Bunsen burner heats a piece of platinum white hot (Chemical E to heat; Heat to 'Light' Energy).

7. Battery runs electric lamp (Chemical E to Electrical E, to Heat and Light).

8. Grind a handle round against some form of friction brake which develops a lot of heat (from Chemical E provided by food to Heat).

9. Balloon blown up and released (Springs E of rubber to Motion E).

10. (For a fast group) Double pendulum (coupled system) to show transfer of Mechanical E from A to B to A and so on.

§ 'At this, I remarked on the obvious fact that the boys thought it was marvellous, but said that I didn't think the girls thought so. They very quickly informed me that they did!'

(This is a delightful demonstration but it is likely to confuse slower pupils when they are struggling with a wealth of different forms of this new scientific concept, energy, that seems strangely important to scientists. In our enthusiasm for showing interesting variations, we should be careful not to let the profusion overstep the margin of digestibility. This warning applies equally strongly to the 'Wilberforce Spring' (13) and to the variable flywheel (19).) * * * * * * *

11. Brick suddenly hung on a spring. (Uphill E to Motion E to Springs E – and then to and fro among the last two).

12. Torsion pendulum – (oscillating to and fro between Spin E and Springs E).

13. (For a very fast group) 'Wilberforce Spring' (oscillating between Spin E and Springs E changing to oscillating between plain Motion E and Springs E and changing back again).

14. Thermocouple and galvanometer (heat to Electrical E to heat (in wires) and Springs E (in hairspring)).

15. Fuel Cell (when available) (Chemical E to Electrical E).

16. 'Inertia operated' toys (Spin E to Motion E to Heat); and clockwork toys (Spring E to Motion E to Heat).

17. Hammer and nails (Chemical E (food) to Motion E to Heat).

18. Model pile-driver (... to Uphill E to Motion E to Heat?).

19. (For a faster group) Flywheel of variable moment of inertia. This is an axle with arms that carry two sliding loads. It is driven by string wound round axle and carrying falling weight. (Uphill E to Spin E and some Motion E). Use this to show the change of the proportion of Spin E to plain Motion E of the falling load when the flywheel's moment of inertia is changed.

20. Dynamo driven by falling weight. (Uphill E to Electric E to ...). (*Note:* when running, Motion E and Spin E.)

21. Dynamo driven by hand lights lamp. (Chemical E to Electrical E to Heat and 'Light' E.)

22. Battery runs electric motor (Chemical E to Mechanical E to Electrical E to Motion E etc. ... to Heat).

23. Spring gun fires a bullet (Springs E to Motion E ...).

24. Hammering lead (Motion E to Heat).

25. Energy changes with small water turbine.

26. Charge a capacitor then make spark (Chemical (?) E to Electrical E to Heat and 'Light' E).

27. Acid+alkali produce heat (Chemical E to Heat).

28. Photo exposure-meter: light produces electric current ('Light E' to Electrical E to Heat).

Energy Demonstrations for Year I. In addition, teachers may want to bring in other demonstrations from the list in Year I. However, we should be careful, when we are teaching pupils who have already done Nuffield Physics Year I, not to give the impression that we are going to show every major experiment all over again, year after year, just because we happen to have the equipment. That is particularly tempting where we have impressive apparatus that is not usually available, such as the steam-engine, the 3-dimensional gas model, the fine beam tube, or bromine diffusion. In the case of each of those examples, there is a good reason for repeating in several different Years; but in other cases we should be all the more careful not to repeat too much. T

'Light' Energy (Radiation). Some of these examples raise the question of radiation energy. We simply say light and ultra-violet light and wireless waves and some other things like that do carry energy, and carry it very fast. We get a great deal of energy from the Sun; and that comes by radiation. Some of it is light that we can see, but most of it something that is much the same except that our eyes do not respond to it. T

Energy Transmitted through a Vacuum? Ask if energy can travel through a vacuum. Tease pupils who say 'No' by asking whether a rifle bullet carries energy; and whether it can move through a vacuum. Then ask whether energy can move through a vacuum without any actual stuff (bullet, air, electrons) moving? What does move, that is not actual stuff rushing along with the full motion? Suggest waves. Ask what kinds of waves pupils know. T

Suggest sound waves. Try an experiment to see whether sound travels through a vacuum. Hang a small metal bell in a round glass flask and ring it by tilting or shaking the flask. Then pump air out with a vacuum pump and try the bell again. The bell must be hung from the stopper at the top of the flask by a length of rubber tubing – if wire is used to suspend it, too much sound will travel up the wire. This simple form of demonstration is just as good as the more modern one that uses an electric bell and it is less distracting. It is a somewhat misleading experiment because in fact the sound grows fainter as the air grows thinner, not because the few remaining molecules cannot carry sound but because the 'impedance match' between the bell and thinner air is so much poorer that the sound cannot get from the bell to the thin air. D 62a

Then show a flask in which there is a glowing filament of nichrome wire and pump the air out. Point out that we can still see the glow even though the air has all been pumped out. (As the air is removed the heat loss by convection is removed and the glow may grow brighter. Useful discussion.) D 62b

After that, ask 'How do you know all the air is pumped out?' Open the flask under water.

Energy Transfers in Car driving, etc. Discuss with pupils energy transfers in a lot of examples such as the following. At this stage it would be unwise to do this as a lecture in which we *tell* pupils what happens. However halting, the story should come from the pupils.§ We may have to make a ruling from time to time in order to avoid building up unsound knowledge (see note below on heat energy of gases), but in general, we should accept pupils' versions. We should certainly encourage them to continue the series of changes backwards or forwards. T

For example, if we discuss the change in a Bunsen burner that heats a lump of metal white hot, we may say 'from chemical to heat and "light" energy', but pupils may want to go on and trace the radiation on across space to an absorbing wall where it produces heat; and other pupils may want to trace the radiation back to the sunshine that helped the growth of trees, to make the coal from which we get the gas for the burner. Such straggling streams of red herrings, usually unwelcome in a well-organized class, can do nothing but good here.

§ 'This topic has proceeded well because some of it was done last year, and has made for better understanding.'

Here are specimens, for each of which we should ask pupils to describe the energy-changes:

a. Drive a car uphill. (From chemical energy of petrol+oxygen to gain of uphill energy+...? ... a possible thought about heat.)

b. Drive a car faster and faster along the level, accelerating from rest. (From chemical energy to motion energy+...?)

c. Let a moving car coast to a stop on a level road. (From motion energy to heat. Where? Some in the tyres and road, but some in the the air.)

d. Let a parachute descend slowly and steadily. (From uphill energy to heat in the air, via some temporary motion energy of moving whirlpools of air left in the wake. Some pupils will say from uphill energy to motion energy, but we must point out that once the parachute has reached a steady speed, it is gaining no more motion energy.)

Now return to the question of a car driving uphill or accelerating along the level, or even driving steadily along the level. Does the car turn any energy into heat by stirring up the air as it goes along? Obviously, yes: energy released from its fuel goes partly to other motions, wholly so in the case of steady speed along the level.

Note to Teachers on 'Heat Energy' of a Gas. When a confined *
gas is heated, it gains thermal energy in the form of increased *
molecular motion. Some of that is kinetic energy of random motion *
of molecules, but in all gases except monatomic ones there is also a *
gain of rotational energy and sometimes of energy vibrations as well. *
That is all the heat energy of the gas consists of: there is no store of *
potential energy except, of course, P.E. of the (P.E.+K.E.) of *
vibrational motion. Pupils sometimes think of a gas at high pressure *
as being like a compressed spring with strain energy. There is no *
such strain energy. *

If we compress a gas by pushing a piston quickly into a cylinder, *
the gas grows hotter, and all the transfer of energy from us to the *
gas goes into thermal energy of molecular motion. If we let the *
compressed gas cool back to the original temperature, it loses all *
the thermal energy that it gained, so all the energy that we trans- *
ferred to the gas now goes out to the outer world. The compressed *
gas, back at the room temperature, has no extra store of energy *
because it is compressed. Yet we can still make it transfer some *

energy to other things by letting it push a piston out with its high *
pressure. True, but the energy it then delivers will be supplied by *
the gas cooling down below room temperature. *

Heat the Final Form

Trace the energy-changes of a car that starts, goes faster, along T
the level, and uphill, then slower, then faster, and ends up at a stop again. What are the initial and final forms? Leave this question to brew in children's thoughts, but lead them in the course of time to the conclusion that all the energy of the fuel, petrol+oxygen, ends up in the form of heat in warmer air. (Unless, of course, the whole trip is from bottom to top of a mountain, in which case some of the energy does end up as stored potential energy.)

Then ask about a man who climbs a hill, and another who walks T
along the level. The latter transfers some food energy to heat in the air by stirring it up just as a car does, though on a very mild scale because he walks slowly. But he also turns a lot of food energy into heat in himself when he is walking. In fact, the human body is at best 25% efficient: for every chunk of energy transferred to some useful form there are three chunks of energy transferred to extra bodily heat that has to be wasted as heat to the air. So the walking man heats the air quite a lot – about four times as much as a walking robot of the same size driven by electricity. And the mountain climber, by the time he has come down the mountain again, has transferred a good deal of energy from his food store of chemical energy to other forms, all of it in the end to heat.

So far we have just been naming and discussing and demonstrating T
some forms of energy and changes between them. We should point out that in many of the chains of energy changes that are important in the world the final form of the energy is heat: so that the air gets warmer by a very small amount. From the energy point of view, the aeroplane that has made an enormous trip and comes back to its starting place has ended by transferring all the energy stored in fuel it uses into heat, somewhere in the world's atmosphere. Of course, there are exceptions: if I lift a brick from the floor up to a high shelf and leave it there, I have transferred some food energy into gravitational potential energy which will stay there as long as I leave the brick.

Note that in many cases it is the *changing* of the energy that matters *
to us: the *changing* from food energy to potential energy when we *
haul up a load of bricks; the *changing* from strain energy in the *

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS
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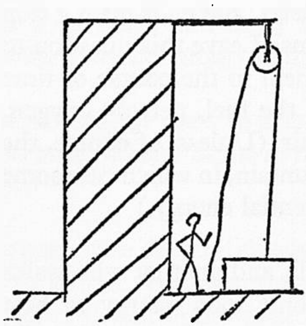
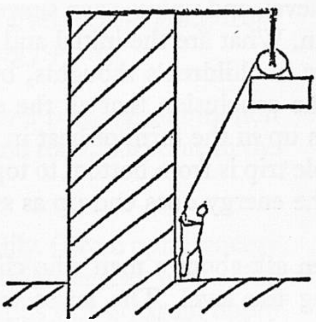
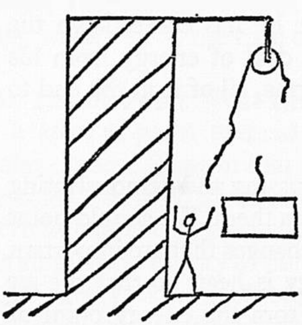

Chemical energy


to uphill energy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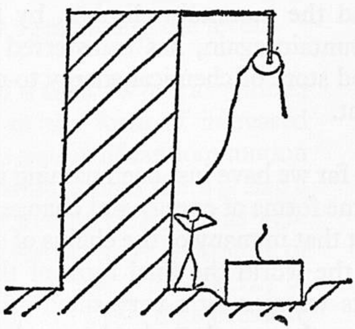

to heat

What has happened to the man and the rope and the weight is clear enough. You are asked to write *four* sentences explaining the energy changes that have taken place. §

§'A very good question – it revealed the ignorance of the class.'

wound up spring of a clock to other forms – ultimately heat – as the clock runs. In other cases, it is the *final form* of energy that is interesting to us; as in heating some bath water, or in winding up a clock. *

Transfer to Heat. When we use a coal fire to heat water for a hot bath, we transfer energy from 'chemical' form in the coal+oxygen to 'heat' in the water. There it is the actual energy in its final form, the heat in the hot water, that we feel is important. T

Work and Indirect Measurements of Energy-Transfer

Often (though not always) an energy-change involves a measurable force pushing something along through a measurable distance. In such cases we can multiply that force by that distance, and calculate the *work*, the energy-transfer in ft.lb (ft.lb-wt), or in kg.metres, or in newton.metres (which we call joules). T

Later on, we shall be able to calculate energy-changes into kinetic energy, which will be very useful to us in atomic physics. However, there are other cases, like the heating of bath water, where no tangible force shoves through a measured distance; so we cannot calculate the work, but then have to go at things more indirectly. We have to say, for example:

> 'If we made the heat for the bath water by shoving a rough block of wood along a rough table, instead of using fuel, how big a force would we have to shove with, for how long a distance, to get enough heat for that bath water?'

We could do an experiment to find out, but it would require an enormous amount of shoving rough blocks along a table to heat even the smallest lot of bath water – like the child who thinks he can easily light fires by rubbing two sticks together. However, that has been done (by Joule himself). And when we try to keep track of the energy-changes in those indirect methods we find that the cost of energy-change of heating the bath water seems to come to the same amount whatever way we go about it. So we think it is all right to measure energy-changes indirectly when we have to, though we are really taking it for granted then that energy never gets created or lost. If so there is never any danger in going by a roundabout process.

Climbing Stairs. Every pupil should climb a flight of stairs (not with a clock to time the climb – that comes later, when we measure power) and calculate his transfer from food energy to potential C63 energy for that climb, just making a rough estimate. That is a gain of useful potential energy because up at the top of the stairs he could be tied by rope and pulleys to some load that had to be raised or to the axle of a dynamo to be driven, or he could do some other useful job that requires energy transfer. However, we should tell pupils now, and remind them later, that when muscles draw upon chemical energy supplies they only transfer about one-quarter of the total to useful forms such as P.E.: the other three-quarters is transferred to heat – extra waste heat. They should calculate how much they transfer altogether in that stair-climb to other forms, including waste heat.

Newton.metres: Joules. Explain that we measure energy in T
more professional physics, not in foot.pounds but in newton.metres. To our pupils, a newton is still an unknown, universal, unit of force, but it can be felt by any pupil who likes to go and pull the string of the 'forces box'.

If we measure work, that is energy-change, in newton.metres we have universal units that are so useful that we give them a name, joules. (James Prescott Joule's name was pronounced 'Jool' by his friends; it was his rivals who spoke of his brewery as Dr Jowl's brewery.) A joule is roughly $\frac{3}{4}$ foot.pound. The 'forces box' should be arranged so that the string which carries a 1-pound load can be pulled out 1 foot, enabling the pupil who pulls to transfer 1 ft.pound-wt of energy from chemical form in muscles to P.E. The string carrying 1 kilogram and the string with a load that makes 1 newton tension should each be arranged so that it can be pulled out a distance of one metre, for energy transfers of 1 kg-wt.metre and one newton.metre (=1 joule).

Note to Teachers on Measuring Energy from Electrical Supplies

We raise the question: what changes occur when a lamp is run by a *
battery or by the mains. When there is such a transfer, which *
involves an electrical form of energy at one stage, we have, in our *
teaching, a choice among several ways of measuring the electrical *
energy supplied (transferred). *

1. Clock only (with source and resistance assumed *
constant). We turn the switch on for an agreed time, say one *
minute, and say we have taken 'one minute's-worth' from the *
supply. (We assume that the supply delivers energy at a constant *
rate – that the voltage is constant and the resistance is constant.) *
This may sound too brash; yet we make assumptions like that *

again and again in elementary teaching, when we measure off lengths with a metre rule or trust the simple harmonic motion of a clock. If we choose this method, it is for the sake of simplicity, because we think our pupils are not ready for a deeper discussion and therefore we should not mention the missing voltmeter and ammeter.

2. **Clock and Ammeter (with voltage assumed constant).** We turn the switch on for a measured time, and show that the current is constant while we are using the supply. This gives support to the assumption that one minute's-worth of the supply is the same from one minute to the next. And if we connect the supply to a heating coil that heats first water and then say a block of metal, and then perhaps oil, the ammeter will support our claim that there is the same demand on the supply for different things being heated by the heater. And we might extend that to other devices, such as a motor taking the same current.

3. **Clock, Ammeter, and Voltmeter.** We turn the switch on for a measured time and record readings of voltmeter and ammeter at regular intervals; or we keep one of those readings constant by adjusting a device such as a rheostat. Those readings would enable *us*, as physicists, to calculate the energy supplied, in joules instead of in arbitrary units which contain the current and/or potential difference as unknown factors. But:

a. most of our pupils do not understand voltmeters. Even if they can connect a voltmeter correctly in a circuit, they have no clear knowledge of its function as a meter of *energy-transfer per unit charge.*

b. If we trust voltmeter and ammeter to measure power we are assuming conservation of energy unthinkingly.

4. **Joulemeter.** This is a new teaching instrument, designed by a Nuffield Physics group to provide direct measurements of energy-transfers in joules. It is an a.c. electric-light meter with its gears changed so that instead of reading kilowatt.hours, it reads joules. Thus a joulemeter replaces the combination of voltmeter, ammeter and clock. A joulemeter could be used here, but many teachers would feel that it would make the teaching jump ahead unwisely in taking conservation of energy for granted; and it would add to the cost of equipment. We have decided not to use joulemeters for this in our teaching programme.

At this stage of our teaching, all we want to do is to illustrate energy changes FROM electrical form TO, say, heat. Our own belief that such changes are part of a great energy conservation system is to be discussed two years later. So we suggest that our duty in teaching now is only to provide *illustrations* in a simple form. * * * *

We suggest adopting method (1) or method (2) of those described. In each of the experiments below, the ammeter is optional – a meter to vouch for a steady supply. The teacher should decide whether, for his pupils, the insertion of an ammeter will make things clearer or not. * * * * *

Electrical Energy Supplies. We ask what change occurs when a battery runs a lamp (chemical energy to electrical energy, to ...); and again what happens when the mains run a lamp. As a demonstration, we run a lamp from a battery, and then a lamp from the mains (with an ammeter) for a measured time such as 15 seconds. In each case we describe the energy-transfer as one from electrical energy to heat and radiation from the lamp. D 64

Chapter 6

HEAT

Measurement and Effects, Temperature, Molecular Models

Class Experiment: Measuring Heat

Without explaining fully what we mean by heat, we ask pupils to find out what five minutes' heating with an electric heater (running on 12 volts a.c. supply) will give to water. We simply say that we know we have to run the electric heater and pay for the electric supply (or pay for something equivalent) to make the water hotter. And we think, by common sense, that the more water to be heated and the hotter we want it, the more we shall have to pay. We give the name 'heat' to the thing we give to the water, the thing that makes it hotter, the thing we *pay for*. Scientists decided long ago, to measure that thing, heat, by giving it to water, weighing the water and measuring the temperature rise and multiplying the results. We announce that measuring scheme, and suggest the question: C65a

> 'How much heat does your electric heater supply in five minutes?'

We ask them to heat 1 kilogram of water in an aluminium saucepan. They should take the temperature of the water before starting, run the supply for 5 minutes, stirring constantly, then turn the supply off and continue stirring and take the highest temperature.

Measuring the amount of water by *volume* would probably cause confusion in any later experiments involving specific heat. Even though we ask pupils to use so many grams of water, we risk confusion if we then provide measuring cylinders. It is much wiser to spend extra time on quick weighing with lever balances. (Unfortunately, the lever balance has a limit of 1 kilogram, so pupils cannot just weigh an empty saucepan and then add water until an extra kilogram has been added. Instead they should weigh a beaker, add water until they have $\frac{1}{2}$ kilogram of water in the beaker, by weighing, and put that in the saucepan. They then add another $\frac{1}{2}$ kilogram to the saucepan. Alternatively, they may place a smaller mass of water in the saucepan; but this will lead to more trouble over arithmetic in the end.)

Explain that for over 150 years scientists have been measuring heat given to water by multiplying the mass of water by the temperature rise. Notice that we have been talking about heat for some time without ever defining it, but just taking it for granted that the word means 'the thing that's given to bath water to heat it up'. And obviously the amount of that thing depends on how much bath water there is as well as on the temperature rise.

Naming our Unit for Heat. Say that we call the heat energy needed to warm up 1 kg of water one degree on the centigrade scale, 1 kilocalorie. Explain only very briefly that little calories are 1,000 times smaller and that some people call kilocalories 'large calories' or 'Calories'. And we install the rule for measuring heat: let the heat heat water and multiply mass of water (in kilograms, by weighing) by temperature rise (in centigrade or Celsius degrees, by thermometer). C65a

Ask pupils to find out how many kilocalories are delivered by the electric heater (running on the same supply) in 5 minutes to half as much water, 0·5 kg. C65b

Ask pupils what would happen if they did the experiment starting with quite hot water. Would that be an accurate and reliable experiment? In the light of the answer to that, was their original heating experiment likely to be completely reliable and accurate? (We should give pupils a sense of concern about heat losses from the very beginning.) T

Discussion of 'Heat Delivered'. Collect answers to the questions: 'How many kilocalories did your heater deliver to one kilogram of water in 5 minutes? How many kilocalories to half a kilogram?' T

In most cases, the answer to the second question will be roughly similar to the answer to the first, suggesting that our multiplying rule does give a suitable measure.

Of course the two results will not be equal, because we have not allowed for the aluminium saucepan; and in any case heat measurements like this are beset with serious troubles of heat losses. (That is why we suggested raising the thought-experiment of starting with much hotter water.)

Careful allowances for the saucepan, and elaborate precautions to reduce heat losses might make the experiment more accurate, but they would not make it clearer. In this case, it is better to warn pupils straight away that there are heat losses and that therefore the experiment is only a very rough one. Yet we should point out that it could be made, and has been made, very much more precise – though that would need some information which we do not yet have concerning the behaviour of aluminium.

(It is possible to conduct the experiment like this with water in a container of negligible thermal capacity: a polythene bag. The risk of the bag breaking, and the popular hope that that will occur, are so great that we do not recommend its use.)
Assuring pupils that the differences we have found are due to difficulties of measurement, we arrive at a rough estimate of the heat, in kilocalories, delivered by 5 minutes'-worth of running the electric heater.

Bunsen Burner If time and interest permit, we may ask pupils to find the heat delivered by a Bunsen burner running for one minute under a saucepan of one kilogram of water. Unfortunately, we cannot compare costs of heating – electric supply *v.* gas – because we have neither a voltmeter at this stage nor a gas meter. C65c

Alcohol Flame. If time and interest permit, pupils may try heating 1 kilogram of water with a small spirit flame, using 1 cubic centimetre of alcohol in a small cup pressed out of aluminium foil, or in a tiny beaker. The same saucepan with a kilogram of water must be supported one or two inches above the small alcohol flame. For that, a strip of tin sheet about 3 inches wide, bent into a vee or a circular arc will serve as support for the saucepan and a wind-shield for the flame. A cubic centimetre delivers, when burned like this, about 4·5 kilocalories to a saucepan of water. In this case it would be possible to arrive at an estimate of the cost per kilocalorie. C65d

All the experiments above are aimed at giving a general feeling for heat and its measurement. They should not be extended to take up much time, nor should the obvious inaccuracies be discussed at length. In modern teaching of Chemistry, considerable attention is paid to calorimetry; and we shall want pupils to regard heat as something that they can, in principle, measure in kilocalories when we discuss conservation of energy fully in Year IV; but that requires a general idea rather than a knowledge of techniques. T

However, some pupils will themselves have raised the question of heating up the aluminium saucepan as well as the water, and we should now tackle that question and make a simple introduction to specific heat in a class experiment.

Specific Heat: Introduction and Estimate

Ask pupils to feed energy from the electric supply to the form of thermal energy or heat in a block of aluminium.

They should heat the block of metal for 5 minutes with their electric heater, just as they did with the kilogram of water. We should tell them that they may take it for granted§ that neither the heater nor the electric supply authorities can tell whether it is water or aluminium, or even air that is being heated; so they may take it for granted that the heater delivers the same amount of 'heat' in each five minutes. That is a large unsupported assumption, which we should offer in an apologetic tone. C66

If we could provide voltmeters and ammeters and if pupils understood their use, we could make that assumption *seem* well supported; and if we provided joulemeters instead, we could give an even simpler and stronger sense of assurance. Yet we should be taking conservation of energy for granted, implicitly, just as much as in the present suggested treatment. The measuring instruments would only tell us that the heater is running at the same level, in each case, so far as the electric supply is concerned. So we suggest that teachers should be content with a simple experiment, resting on a temporary assurance that the heater delivers the same heat in 5 minutes whatever it is heating. * * * * * * * * * * *

Pupils should weigh the block of aluminium, and measure its temperature before and after running the heater in it for 5 minutes. C66

The block of aluminium must have holes drilled in it to receive the thermometer (at some 'average position' in the block), and to receive the heater. Pupils must put oil in both these holes to provide good thermal contact, or the experiment will be slow and uncertain.

If pupils follow the method used for water, of multiplying mass by temperature-rise to calculate the heat gained in kilocalories, they will find that this disagrees seriously with the result they had for water. They should *assume* the water experiment's result applies to the heater in this case too and find the 'extra factor' that must be used to make the new answer agree with the old one. (The assumption there is the weak point of this whole experiment; and it would

§ 'They did not take it for granted, but concocted four plausible theories to explain why the aluminium got hotter than the water.

1. Heat travels more quickly through Aluminium than water
2. Heat comes out of the heater more quickly in Aluminium
3. More electrical energy is used in the case of Aluminium
4. Aluminium takes less heat to warm up

They devised tests for each.'

be just as weak – though it would not seem so painful – if pupils had instruments to assure them that the heater is running at the same rate.)

Calculating [mass] × [temperature-rise], pupils find that a block of aluminium seems to take much fewer joules, much less heat, to heat it up through the same temperature-rise, so we give aluminium a special number, to show its 'appetite for heat'. Instead of multiplying mass by temperature rise as for water, we multiply mass by temperature rise and *then* multiply by that special number to find how many kilocalories are needed. Working backwards from that idea, we ask pupils to calculate the special number for aluminium. We explain that we call this the 'specific heat' of T
aluminium and consider it a useful number to know. They will not obtain an accurate value such as 0·2. This is an 'experiment of principle' to enable pupils to meet the idea of specific heat and learn how it *could* be measured. (We may also tell pupils the result of more careful measurements, about 0·2.)

Remember, we actually heated an aluminium saucepan as well as the water in the first experiment, and now we can go back and find how many kilocalories went to the saucepan, by multiplying its mass by the temperature rise (much the same as for the water) and multiplying by the extra factor 0·2 as well.

In asking pupils to do this experiment the teacher should remember *
that this is an *exploration of energy measurements* and not an attempt *
to measure specific heat with any great precision. We give the *
'official' value to pupils; yet they should not be encouraged to *
think of their own experiment as inferior and 'giving the wrong *
value', like a black market exchange, to be obliterated by the right *
value. *

Motor. If possible, run a commercial electric motor with an ammeter in series as a class experiment or demonstration. If the motor has a band-brake to work against that will be interesting but too difficult to explain in detail or to use for measurements. However, if pupils see a band-brake in use now, that will be valuable preparation for Year IV. If the motor has no band-brake, it should be made to haul up a load. D 67

In any case, pupils should see the ammeter reading more when the motor is doing a useful job of work. Even when the motor is running light, there is a continual supply of energy to it. Ask where that goes.

If an electric fan is available, run that with an ammeter in series. Ask where the energy goes. Or, try an electric mixer from the kitchen, stirring various loads, with an ammeter in the line.

Machines. We now discuss machines as energy transmitters. Refer back briefly to the lever and pulleys that were tried in Year I. Show them quickly as a demonstration. Emphasize their use to increase the forces, as 'force-multipliers'. D 68a

Then discuss the energy-changes briefly, once again, using a big seesaw as an example.

> 'Suppose I balance the seesaw with a big load here on the left against a small load out there on the right. If I let that load on the right go down, the Earth pulls it down with the weight of that load. Suppose it goes down 10 inches. Then we can calculate the work [force] × [10 inches]. That is the transfer from the Earth's gravitational field, from 'uphill energy' (P.E.) to mechanical energy (Strain E) that travels across the seesaw and turns into a gain of 'uphill energy' (P.E.) in raising the big load on the left side.
>
> 'If the big load is just ten times the little load and they balance, then its distance from the pivot must be just one-tenth of the small load's distance. If you draw this picture, showing the little load going down and this big load being raised, you can see that the big load at one-tenth of the distance out only rises one-tenth as far as the little load falls. It rises 1 inch; so we can calculate the work of transfer to uphill energy for the big load: [ten times as big a load] times [only one-tenth as big a rise]. So it is the same amount of work.
>
> 'What you put in with the small force being pulled down a big distance comes out as a big force pushed up a small distance. This machine does *multiply force* for you, but it *does not multiply energy*. You get out just as much energy as you put in.
>
> 'You'll find that with the pulleys, too. The man pulls down three times as much rope as the rise of the big load, but the big load is three times as big. So the energy-transfer from the man is just equal to the energy-transfer to uphill energy.' D 68b

In real pulleys and levers and other machines, the output-energy is not quite equal to the input, but is a little less. T

Discuss the answer to the question: 'Where does the small bit that seems to be lost go to?' Point out that if we wish to make things worse we can give the pulleys poor bearings and then we should actually feel heat being developed with friction there.

Heat as a Form of Energy

Now return to a discussion of a rock falling from the top of a cliff. T
If it topples over the top the rock starts with considerably more uphill energy (P.E.) than it will have lower down, but as it loses uphill energy (P.E.) it gains motion energy (K.E.) more and more until it has most motion energy (K.E.) just before it reaches the ground. But there it stops. What happens at the ground?

Pupils will obediently say that the rock makes heat, but they have never seen a rock landing at the bottom of a cliff and turning red hot, or even felt it becoming appreciably warm. Give them a ham- C69
mer and a small thin piece of lead and some kind of anvil and ask them to swing the hammer as fast as they can and let the hammer stop with a bang and give its motion energy to the lead. They should feel the lead after several strong hammer-blows. Explain that the reason why we use lead is because it stops the hammer and does not just make the hammer bounce back with some kinetic energy.‡

To pupils who are likely to be interested, we might point out that a diesel engine fires the mixture of oil and air in its cylinder by a sudden high compression, which raises the temperature above the flash point, almost like the hammer blow on lead.

We shall not make further measurements of specific heat. Pupils *
could have an interesting time making careful measurements of *
different specific heats with electrical heating but we shall not need *
specific heats in this course; so that is a part of physics which we *
shall omit in order to save time. Specific heats are of use in Applied *
Physics, though they are not used as often as one might expect. *

‡ It is often said that lead shows a big temperature-rise (and therefore should be chosen for this experiment) because it has a very small specific heat. However, lead also has a large specific gravity, so that the thermal capacity per unit volume is only a little smaller for lead than for other metals. The important characteristic is that lead is inelastic: all the energy of the hammer is turned into heat by pushing lead atoms beyond the elastic arrangement of the crystal lattice.

Specific heats are of considerable use in Chemistry and we have *
agreed to hand over both the teaching of specific heat measurements *
and some apparatus for it to the Nuffield Chemistry programme. *
In modern physics specific heats are not of much interest until one *
reaches a study of their changes with temperature, which suggest *
quantum effects. Then they are indeed illuminating. So we shall *
postpone specific heat studies to A-Level Physics. *

CONSERVATION

In all these discussions we have been tacitly assuming that energy *
is conserved. This is not the time to question that and make pupils *
feel that they – or we – are not quite sure what we are doing with *
the energy. The whole discussion of energy is new and complicated *
and we had better blandly assume conservation at this stage. *

Yet, the teacher should always keep in mind this warning, that we *
are at present – just for present teaching – assuming the complete *
conservation of energy. At a later stage, we shall go back and show *
pupils that that is not just a dogmatic belief but is in considerable *
measure based upon experiment. *

It is good for children to know about the conservation of energy *
and to have growing understanding of it. And here we are giving *
that by taking conservation for granted at first – just as both scien- *
tists and children have long taken the conservation of mass for *
granted – but we should keep a warning flag there in our own minds *
as teachers and issue an occasional comment to children to warn *
them that we must show why we believe conservation is supported *
by experiment. The pupils should know that the flag is there. *

We should be particularly careful not to offer the remark 'You *
can't get something for nothing' as support, still less proof, for *
conservation of energy. That remark does apply to some things *
such as momentum and cash, but not to others, such as force, *
pain. It is only *after* we are convinced by experiments, etc.,‡ that *
energy *is* conserved that we can safely apply that remark to it. *

GASES: 'HEAT A MODE OF MOTION'

Now that we think of heat as a form of energy, we can ask 'What T
happens when heat is given to a gas, which we already think of as

‡ The 'etc.' here refers to our extended treatment of energy in the conceptual scheme we build for physics – see Note on Conservation of Energy in the General Introduction at the beginning of Year I.

made of rapidly moving molecules?' They make gas pressure by bouncing against the walls of their container. 'If we keep a gas in a closed container and heat it up, what happens?' Children will guess that the pressure grows bigger, and therefore the bouncing effect grows bigger.

> 'How can a number of gas molecules bouncing about in a closed box bounce harder? What *must* have happened to them when we heated them up?'

Elicit the answer 'moving faster'.

For a short class experiment give pupils the gas model of marbles in a tray and ask them to try 'changing the temperature'. If, in a hotter gas the molecules are moving faster. 'What kind of energy do they have more of?' Elicit the answer 'motion energy'. C70

At this stage, we might mention to a fast group the possibilities that molecules acquire other forms of energy – spin energy and vibration energy – but for most pupils it would be better to keep those out of the picture at this stage, so that we may for the moment think of heat going into a gas to make the molecules move faster, increasing their individual kinetic energies of random motion. Temperature which we have not tackled clearly so far, but have merely taken as the thing given by a thermometer, may well be connected with the kinetic energy of gas molecules. Some such remark to foreshadow what is coming next Year might be a help.

Temperature

We treat the effects of heat quickly and simply; so we shall not discuss temperature, 'measured hotness', in detail. We say it is the thing that the thermometer measures and point out that some thermometers use the expansion of mercury 'to show how hot the thermometer itself is'. Others use different things which change with warming, such as resistance of a wire, or voltage generated by two different metals joined together. Ask whether one can be sure these different types of thermometer will agree with each other. Warn pupils that we cannot expect that, but must just choose one standard type. In fact, we agree on mercury in glass for ordinary purposes because it is convenient, agrees well, by good luck, with our standard gas thermometer which in turn agrees well with the absolute thermodynamic scale. T

Mercury Thermometers. Mercury has some practical advantages over some other liquids, such as visibility, and a wide range, and lack of surface-tension troubles. Its relatively small coefficient of expansion is an advantage, because it makes exposed-stem errors less important.

We should never say, 'Mercury expands uniformly' in listing its advantages, since that is automatically true if the expansion is compared with temperature by a mercury thermometer; so, as pupils interpret it, the remark is a silly one. The only sensible form would be to say that the expansion of mercury happens to agree more closely with that of gases than does the expansion of most other liquids.

These 'advantages' of mercury do not need to be discussed with pupils; we should rather adopt an attitude that we can choose any reasonable system we like for measuring temperature; and we happen to choose a mercury thermometer for convenience, and shall probably change to a better standard later on.

Effects of Heat

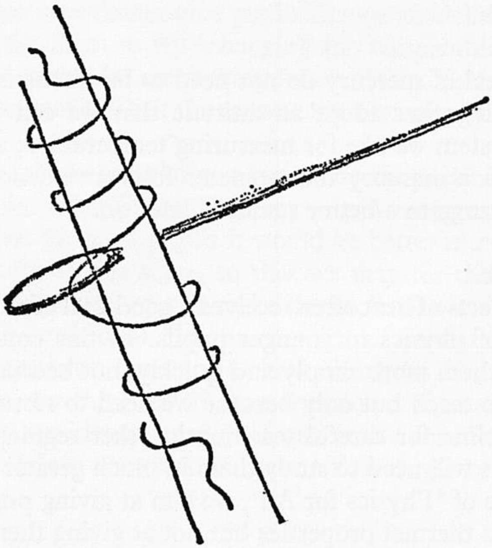
In the past the effects of heat often received a good deal of attention in the teaching of physics to younger pupils. In this course we propose to treat them more simply and quickly, not because they are poor things to teach but only because we need to restrict our material to give time for careful teaching in other regions. Professional scientists will need to study them in much greater detail. But in this course of 'Physics for All', we aim at giving pupils an acquaintance with thermal properties but not at giving them considerable details of either theory or practice. Acquaintance will suffice in this course, particularly if pupils make it by their own experimenting. So the following experiments are meant to be done briefly, as far as possible as class experiments.

Expansion of Solids. This should be treated qualitatively without precise measurements or calculations. T

Give pupils a long thick rod of iron or brass to heat with a Bunsen burner. Support it on a brick near each end and place one end against a firm stop such as a kilogram weight sitting on a brick. At the other end ask pupils to put a needle under the rod to act as a little roller, and fix a straw on the needle to act as a pointer. C71

If the straw slips on the needle, run a short piece of copper wire through the eye of the needle and wrap it round the straw. If the rod slips on the roller, hold it down more firmly on the roller by hanging a kilogram weight on it, near the end which rests on the roller.

(This experiment has sometimes been suggested as one which might emerge from a discussion with pupils in which the teacher poses the problem and asks for suggestions by giving them enough hints. It is possible to get pupils to suggest this apparatus for showing or even measuring expansion but that seems to be a long business and not a genuine matter of invention. So we propose to offer it ready to put together.)



Ask pupils to heat the rod and see what happens. This may seem to teachers who are familiar with careful measurements of expansion a mere piece of play. If one tries it with young pupils, one finds that this simple experiment, not obscured by worries over a micrometer gauge and its techniques, is something that pupils enjoy and learn from. This is not the time to argue whether one revolution of the straw means an expansion of one circumference or twice that; but one should ask pupils to estimate roughly how much the rod expands, and one should ask them how they can tell whether they have heated it as hot as boiling water or hotter. (Do not tell them that the answer is to try a drop of water on the rod. Research in science does not consist of being told the answers, and now and again we should leave a question like that unanswered so that the pupil who does think of an answer can have a full reward in his own mind.)

(Compensated pendulums and balance wheels are interesting; but we can omit them in an age when radio time signals make cheap clocks suffice even for navigation.)

Expansion of Liquids. Give pupils a thermometer and ask them to dip it suddenly in hot water and watch it. Ask what they can squeeze, like a detective, out of the clues that they observe.‡ C72a

Then give them a small soft-glass test-tube corked up with a glass tube through the cork that is either a capillary tube (bore about 1 mm) or an ordinary tube drawn out to a coarse capillary outside the cork. Ask them to fill this 'giant thermometer' with water (which may be coloured) and then plunge it into a saucepan of hot water, watching what happens. They should sketch this in their notebooks and write a note of what they see. Some will only see the general expansion of the cold water in the test-tube, but some will also notice the initial dip downward. Ask what information, knowledge, and ideas can be squeezed out of that. Do not give the answer but encourage thinking and leave this unanswered. If necessary, give the answer next week. C72b

Then offer the same device made with a pyrex test-tube, telling pupils that this is made of a different glass. Again, ask pupils what they can extract from what they see.

If the initial dip down is not clearly visible, either the test-tube has not been properly filled and has air bubbles or a finer capillary is needed. If the soft-glass tube does not give a much greater dip than the pyrex tube, that tube is not made of ordinary soda-glass but has probably been supplied in some 'semi-pyrex' – which will lead to fewer complaints of breakage but will not do well in this experiment.

Cracking Glass. As a demonstration, heat a piece of window glass with a Bunsen burner until it cracks and ask why it cracks.‡ D73

‡ We suggest this description as a useful way of giving young pupils a picture of the work of scientists, but each teacher will need to modify the wording to fit the interests or sense of dignity of his group of pupils. This suggestion came to us from a very able lawyer, who is himself concerned with conveying an understanding of scientific work to laymen; and we hope teachers will put it to a good test.

‡ This is very unlikely to be dangerous. As a precaution in a first trial use the shielding sheets of perspex recommended for such demonstrations.

Give pupils small pieces of soft-glass tubing to heat in a flame and plunge in water. Then give pieces of pyrex. If possible have a demonstration piece of transparent pure silica tubing. Ask them how they can 'explain' the different behaviour of the pyrex. This is a matter to leave until next week when the experiment with the two test-tubes is discussed. C74

(The different behaviour of pyrex might be due to: lower expansion, ability to stand a greater strain – strain is the important quality here, not stress – or greater thermal conductivity. The first one is the real reason, vouched for by the experiment with the two test-tubes. The second one can be ruled out by bending glass tubes till they break: put two tubes of equal size as a bridge across between two stools. The tubes should be 3 or 4 feet long, one tube of pyrex, the other soft glass. Push the centre of both down until they break. Usually they break at about the same bending. The question of conductivity can be investigated later when pupils try tubes of both kinds of glass in a flame and run their fingers – or an unlit match – along to make comparison of conductivities.)

Melting. (In the following list of suggestions, experiments already done in Year I should not be repeated now.)

Pupils should do experiments on melting: heat a test-tube with some naphthalene till it melts and then let it cool. For most classes making a series of measurements of temperature for a cooling curve will take more time than we ought to spend at this stage. And the pupils are not ready for it. This should be just a qualitative looking at things; but in a fast group a thermometer should be stuck in the melted naphthalene and watched while it cools down through the melting point. C75a

Pupils should try the following in a Bunsen flame (if not done in Year I) a few grams of lead, a few inches of solder, a piece of iron wire, a piece of copper wire. C75b

If snow is available, pupils should try heating snow in a tin can, stirring it carefully and looking at the temperature changes. This experiment sounds promising but is in reality a messy one which gives uncertain results unless we use very fine snow and at regular intervals turn off the heating supply and stir for some time. (Chipped ice will not work, because it leads to icebergs.) C75c

If possible give pupils a little carbon dioxide snow to warm up and watch. C75d

Boiling. Pupils should bring a small beaker of water to the boil, watching its behaviour carefully. They will see the vapour bubbles forming at an air bubble: but we cannot go into details of mechanism at this stage. C76

Changes of Volume

Water to Steam. If available, give a demonstration to show the change of volume when 1 gram of water turns to steam. This is difficult. Teachers may well prefer to postpone it to Year III. It can be shown with a large, hypodermic syringe which must be of glass. A small measured quantity of water is introduced into the syringe from a much smaller hypodermic syringe. Then the large syringe, with the small sample of water, is placed in a large beaker of boiling brine. The sample of water turns to steam and pushes the piston out to a volume which can be estimated. As an easier but more artificial alternative saw out a centimetre cube of carbon dioxide (solid, not snow) and hold it in warm water under an inverted jar or box to measure the gas produced. D77

Ice to Water, and Ice Water warmed up. Pupils may be told about the strange volume-changes as water warms from 0°C to 10°C; but we do not suggest a demonstration such as Hope's experiment. That takes too much time and is not always very convincing. The change of density is strange and important, but is so small that a simple demonstration is hardly possible. D75e

The volume change from ice to water is also one that should be known. We suggest that the teacher should simply tell pupils that a kilogram of water occupies practically 1,000 cubic cm (or 0·001 cubic metres) but when it freezes to form ice it swells up to a volume about 10% bigger. T

Force in freezing Expansion. If a demonstration of cracking an iron flask full of water by freezing it is available, that is one that pupils should see – rather than hear. The little cast iron bottle should be filled with water that has been boiled to remove dissolved air. The stopper should be screwed in with the bottle quite full, without air bubbles. The bottle is placed in a freezing mixture of ice and salt in a bucket and covered with a large cloth, because fragments may fly when it bursts. The bursting will be quite audible; and fragments may be shown. D78 OPT.

Expansion of Gases: Qualitative Study

Volume Change of Gases. Pupils should try a simple *qualitative* demonstration of expansion of gases. For example, a small flask with a cork which carries a long tube in which one can place a C79 bead of oil. Plunge the flask into cold water, then warm water. In a later Year, pupils will meet a more formal experiment in which measurements of temperature and volume are made and the question of absolute temperature is discussed.

Pressure Change of Gases. The pressure change of a gas heated at constant volume should be shown. For this we need a flask connected to a direct-reading pressure gauge, preferably a Bourdon type of gauge, graduated to show absolute pressure, including 0, so that it can also be used with a vacuum pump. Plunge the flask in cold water and then hot water. C80

Summary of Thermal Expansions. Pupils should emerge from these simple, directed, class experiments knowing that metals expand a very little when heated, that liquids expand a little when heated, that gases expand a great deal when heated, if they are allowed to do so, but will increase in pressure if they are not allowed to expand. These experiments are for the sake of acquaintance, for what the pupil feels in his bones he knows about nature, after having tried the experiments. Records in notebooks should be very brief indeed and measurements should wait for a later occasion. T * * * * * * * *

ATOMIC AND MOLECULAR PICTURE OF MATTER

Solids, Liquids and Gases

We now have an opportunity for a very important description, our 'atomic' picture of solids, liquids and gases. (See D 81, C 82, D 83 for models.) T

Solids. In discussion with pupils, look back at the discussion of solids and crystals in Year I. Point out that we picture solids as made up of atoms in regular piling like oranges on a fruit stall – different patterns of piling for different types of crystal, the pattern being probably controlled by the external electrical properties of atoms which control their chemistry.

In solids, then, the atoms, or groups of atoms, are arranged in a regular lattice. But what happens when we heat a solid? It stays solid; so the atoms stay in their regular arrangement and yet we have tried to give them some motion. So we picture the atoms as moving to and fro, vibrating around their standard position. Thus we have a picture of a solid as an array of atoms linked by spring forces like a vast three-dimensional bedspring. The atoms are in constant vibration which grows more violent when we make the solid hotter. T

As we heat a solid and its atoms vibrate more and more, we can think of them in their more violent vibrations stretching some of the springs which connect atom to atom. These springs are in fact the springs of electrical forces, the kind of forces that make two pith balls with unlike charges attract, and two with like charges repel each other. However, the vibrations can only take on extra energy in definite chunks – and there we are meeting quantum behaviour. * * * * * * * *

If pupils ask how far you can cool a solid, we might be tempted to say simply that we could cool it all the way down to absolute zero, and that then the vibrations would have stopped. But, we now have good reason to believe that even at absolute zero the atoms of a solid would be left with a small residual vibration. That is one of the curious things which the whole body of knowledge summed up in quantum mechanics makes us hold as highly probable. * * * * * * *

Melting. Heating a solid still hotter brings it to the point where the springy forces connecting atoms are, so to speak, stretched beyond their strength and the solid pattern comes to pieces. First a few atoms break loose and then all of them, moving about close to neighbours but with random motions. This process of melting, involving the tearing apart and breaking, in a sense, of inter-atomic springs, takes some energy, which afterwards lies concealed in the 'stretched springs' (force fields) that are left attached to the separated atoms or molecules. So we should not be surprised to find that melting takes in quite a lot of heat and keeps it in concealed storage. In return, when a liquid solidifies, quite a lot of heat is given out. We mention the warm air after snow forms; and the long time of heating needed to melt some ice. T

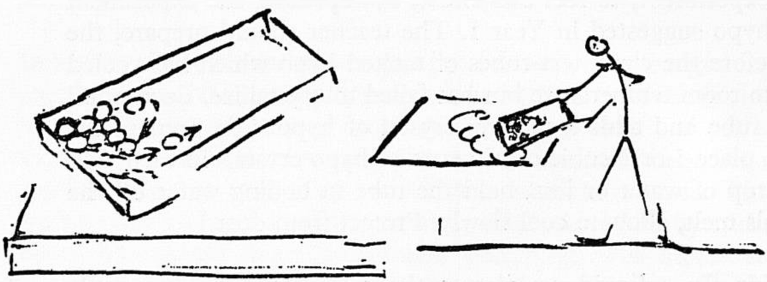
Mention the storage of heat in melted crystals in some modern schemes for heating houses by stored sunlight. Pupils may do a class experiment, to feel this effect, by repeating the experiment with hypo suggested in Year I. The teacher should prepare, the day before the class, test-tubes of melted hypo which has cooled back to room temperature but has failed to crystallize. Each pupil has a tube and adds a seeding crystal of hypo. (To prepare the tubes, place 1 or 2 cubic centimetres of hypo crystals in each, add one drop of water or less, hold the tube in boiling water till the crystals melt, allow to cool slowly. Protect from dust.)

Liquids. In a liquid we picture the molecules as only a little farther apart than in a solid; the essential difference is that they T move fast enough to keep moving in and out among neighbours so that the crowd stays fluid. Picture the atoms in liquid as moving fast and bouncing against each other, very often moving only a very short distance between one collision and the next. When one atom bounces up to a neighbour, it bounces quickly away again and does not spend a long enough time in close approach to get locked into a crystal array. Heating the liquid increases molecular speeds.

Even when viewed in the light of much fuller knowledge of physics, liquids are harder to picture and understand than gases – whose molecules are far apart and independent – and solids – with such orderly arrangement. Liquids with their patches of short-range order, subject to a complex of cooperative vibrations, *are* difficult to deal with. So if pupils find the picture of them less clear we can only agree.

Gases. In gases, the atoms or molecules are much farther apart so that much of their time is spent in moving fast far away from any other molecules, out of the influence of any other molecule. There are violent collisions but these occupy a very short time when strong repulsive forces come into play at very close approach. Heating a gas increases the speed of random motion. T

Models: Demonstrations and Class Experiment. These pictures of solid, liquid and gas can be illustrated: a 'solid' array of balls connected together by springs, arranged so that the balls can vibrate with various motions with some independence between one ball and its neighbours; a two-dimensional 'liquid' of many marbles crowded into a rectangular tray kept in a state of agitation; a two-dimensional 'gas' of much fewer marbles in a tray kept in motion by agitating the tray. D81 C82



There should also be a demonstration of a three-dimensional model of gas molecules in motion. This may be a handful of plastic beads or metal balls kept in motion by a vibrating piston at the bottom of a tall wide tube of glass or Perspex. D83

These models which may seem to us merely pretty toys, serve the very important purpose with young pupils of showing them our pictures of molecules which we already have clearly in our heads but which to them are quite new things that need models for teaching.

Note to Teachers, on Models. We should show models, preferably in several forms, but we should also murmur gentle warnings that a model is not the real thing, in many cases not even meant to show what we think the real thing is like. This kind of reservation is discouraging when young people first meet it; but they can learn to enjoy devising models and thinking in terms of them with much greater freedom and skill and imagination once they realize the greater scope of scientific models as we use them.

We have models of gas molecules – as real balls, or in imagination – to help our thinking about gases, to suggest a line of investigation, or to illustrate a technical term such as mean free path. We might contrast such molecular models with mock-up models such as a tiny wooden model of a fission reactor or a huge wax model of a flower. The latter models are used to aid people in visualizing; the former are used for constructive thinking.

All our theoretical physics uses models as essential parts of the framework of knowledge – but with great care to remember where the words, phrases, descriptions, are only parts of models. Without imaginative thinking in terms of models, scientific knowledge would be merely a pile of facts, codified here and there in laws – little more than a handbook of data.

We cannot put this to our young pupils at this stage; and we should not even be wise to try; but we should think about our own picture of science and the part played by models in it when we use demonstration models as part of our teaching skill.

The two-dimensional tray model referred to above is easily made. The tray may be shallow metal baking tray of bright 'tin', say 12 inches by 8 inches which can be obtained from ironmongers for less than two shillings. It is *essential* for the sides of the tray to be vertical – most such trays have sides that slant outwards and the

marbles do not rebound well from those. The more massive the *
side walls the better, of course. The marbles should be the smaller *
of the two common sizes available in toyshops, sixpence for the two *
dozen needed for the gas model. With these coloured marbles, we *
can arrange to give pupils one marble of a different colour from all *
the rest so that they can watch its progress. *

Pupils keep the tray on the table and move it about with a rapid *
irregular motion to keep the marbles agitated. With a rectangular *
tray, a circular motion is adequate but a more irregular motion is *
better. This model enables pupils to look at a model of the random *
motion of molecules, chart a molecule's free path, simulate *
temperature changes, diffusion, Brownian motion (by adding a *
much larger marble among the rest), and even to gather statistics *
of velocities by taking a photograph with not-too-short an exposure. *
*

The noise can be reduced by placing a carpet of thin cork sheet in *
the tray, though that is not essential. With the cork sheet, pupils *
will hear collisions between marbles and the impacts of marbles *
on sides of the 'container'; and they can distinguish between them. *

We make use of this tray and marbles in Years I, II, III and IV, *
one for every two or four pupils. *

Expansion: 'Atomic and Molecular Story'. Thinking in T
terms of these models, we can talk about expansion of materials; we can picture the atoms in a solid metal, elbowing each other a little further apart as they vibrate more and more. A more honest picture would go into details of the competition between fairly short-range attractive forces between atoms and very short-range repulsive forces between atoms. These must maintain a system in equilibrium, changing their values when atomic vibrations increase, because those vibrations carry individual atoms to different distances where they experience different forces. Then, as a result of those changes of forces, the whole array takes up a different length and strength, again in equilibrium – but that is too complicated a story to explore convincingly.

In liquids the picture of expansion is easier: we should expect expansion when heating raises the speeds of the molecules which are in constant colliding turmoil. The more violent motion enables molecules to succeed in pushing each other further apart, on the average, against those fairly long-range attractive forces which still hold the liquid together. We picture that as rather like a crowd that is jostling about: then what happens if all the members of the crowd start hitting each other, with violent fisticuffs? We may expect the crowd to expand slightly.

In the case of gases the picture of expansion is clearer still. We know that heating gas in a closed container makes its pressure increase. The molecules must move faster.

If the gas is in a container that allows expansion, heating will produce a bigger pressure which will drive the walls of the container outwards until the pressure is same as before, but the gas has bigger volume. Then the molecules are farther apart, and, having longer to travel, they bombard the walls less frequently though each impact is more violent.

These are not interpretations to be taught with care and installed as written notes. They are rather matters in which the teacher should talk as a senior physicist to his pupils as younger physicists.

Chapter 7

HEAT TRANSFER

Experiments on Conduction, Convection and Radiation

Heat Flow. We have talked about the 'flow of electric currents' as being rather like the flow of water. When we find the similarities in our experiments we start using the name 'current' in electricity. We also find that heat seems to 'flow' along a bar of solid and in other media, when it is *conducted.* T

Heat can also be carried by wholesale movement: warmer fluid moves, displacing colder fluid thus conveying heat in convection currents. Since pupils have been interpreting heat as molecular motion, this may be a suitable moment for some simple class experiments on heat flow (or heat transfer); and then on radiation.

Conduction and Convection, Radiation

Professional scientists use the words *conduction* and *convection* with confidence and pleasure in discussing design of experiments and in commenting on events in the household or in the world at large. The other words for ways of losing heat – *radiation* and *evaporation* – serve as equally useful, important pieces of language. Yet when we teach young pupils about heat transfer, the names are apt to seem more important than the real process. Freud once said: 'Words and magic were, in the beginning, one and the same thing.' Even when pupils understand very well what is happening they still regard these matters as rather a remote part of science. The danger is illustrated by a pupil's remark about a problem on a car smash: 'Oh, the force comes out at about 20 tons-weight; but of course that isn't real force, that's just an answer.' T

Good demonstrations, though they are as delightful to pupils as to us, do not seem to remove the difficulty completely: the phenomena, or rather the descriptions of them, remain artificial. That can be cured if pupils do experiments themselves. We know that is necessary in the case of electric circuits which we still think of as artificial; and we should realize that to young people heat transfer may seem equally artificial. So we offer a series of class experiments. The instructions for these will be fairly complete and clear; but that will not make the experiments completely 'cookery book' ones, because we shall ask pupils to try to argue out some scientific knowledge from the clues they obtain.

We start by telling pupils we want them to look at various ways in which heat travels from one place to another; and we describe some possible mechanisms and give our names for them – rather like Ohm having the name for resistance before he went to look for it in electric circuits.

We describe conduction as some process of handing heat on from one bit of stuff to the next, like a message being handed along a line of pupils from neighbour to neighbour. And we describe convection as a wholesale motion, chunks of material moving and carrying heat with them, like a group of pupils carrying a petition with them through a crowd. It may be best to leave radiation until after some experiments on convection and conduction; but, from the first mention of radiation, we should always say clearly:

> 'This is quite different; it is not a matter of something hot carrying heat itself, or of atoms handing heat on from one to the next. This seems to act in quite a different way. T
>
> 'Hot things can and do give out radiation, they produce something at the expense of heat, so they cool down unless we keep on supplying heat to them. But the heat that disappears does not travel out as such: it seems to change and travel in an entirely different way. You will find that it travels extremely fast, and usually in straight lines. That is why people call it radiation: that means something that travels out like the spokes of a wheel, radii. When radiation hits something and stops, it usually turns its energy back into heat.
>
> 'I write a message on a piece of paper. I want to get it to someone over there. That message can be *conducted* from pupil to pupil, or *conveyed* by a gang of pupils running with it. Now if we want to think about the message being 'radiated' we must take it to a wireless station where it can be changed to a wireless message which radiates out. On the other side of the Channel or elsewhere far away it can be turned back into another message on a piece of paper – but none of you would expect to see a piece of paper whizzing along with its message in a wireless wave.'

We should insist – in the early stages chiefly by avoiding misleading remarks – on regarding radiation as a quite different form of energy in motion.

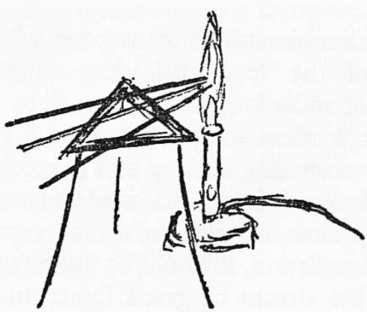
Perhaps some of the difficulties which many people feel about this come from the use of the very misleading expression 'heat radiation'. *Any* form of radiation, be it green light or infra-red radiation or X-rays or wireless waves, will yield 1 kilocalorie of heat per second to any absorbing surface that is receiving a 4,200 watt stream of that radiation. It is true that while it is easy to make a gas fire or an electric heater, or even an ordinary coal fire emit 4 kilowatts of infra-red radiation, it would be difficult to build any of those to emit a 4 kw stream of green light: and hopelessly difficult, and dangerous, to build a heater to emit 4 kw of X-rays. All the ordinary incandescent sources we know, including the sun, emit infra-red radiation in a much more powerful stream than visible light. The reason why a thermopile or thermistor exploring through the spectrum is heated so much more in the infra-red is not that infra-red consists of 'heat radiation' but simply because there is more of it! * * * * * * *

The old nursery riddle 'Why do white sheep give more wool than black sheep?' is useful here. One watt of green light gives just as much heating, when absorbed, as 1 watt of infra-red 'light'. (We might make a small reservation in the case of X-rays since they excite some of the absorber's atoms, so that a little of the energy goes into electric fields instead of thermal motion.) * * * * * *

Radiation so easily develops a confused reputation that it seems wiser to be dogmatic and insist that there is no special kind of 'heat radiation' or 'heat rays'. Another peculiarity of radiation that we should establish early – and this can be done by experiment – is that it *produces heat only when absorbed*: it provides no heat as it travels through a transparent medium and it produces no heat at a perfectly reflecting mirror. It would be easy enough for us to say, 'Oh well, of course when it goes through it continues with its energy, and when it is reflected it carries its energy away with it'; but in a way that argument assumes what we are trying to explain, by imputing to radiation, just the right energy-carrying nature to support our story. T

Class Experiments on Conduction and Convection

1. Give pupils a Bunsen burner and a tripod stand (and an asbestos sheet to protect the table) and a collection of rods and wires of copper, brass, iron, glass, and other materials if possible. Ask them to make a very rough comparison of conducting powers, by placing several different rods on the tripod as support, so that each rod has one end in the Bunsen flame. C84



'Then run your finger along the rod from the outer end until you find the place where the rod is too hot to touch. See how far from the flame that place is. How does that tell you which rod is best at conducting heat?

'What is really happening is that heat is flowing along in the rod rather like water in a pipe but it is also escaping from the surface of the rod so after a time the rod reaches a steady state, very hot in the flame, hot some way out, fairly hot still farther out, and quite cool perhaps at the end. Can you judge with your finger which is the best conductor and which is the poorest?

'You might think it would be best to time the speed at which the heat seems to run along the rod, with a clock. But we know from further work on conduction the speed at which the heated region spreads along the rod after you put it in the flame does not just depend on the conductivity; it also depends on how greedy that particular metal is for heat, how much heat it has to receive and mop up before it grows much hotter. So the metal's "specific heat", as we call it, affects the speed as well. Therefore you should go on heating the rods till they reach a steady state.

'If you don't like using your finger, try using a match head instead. If you like, we may be able to lend you an electrical thermometer (thermocouple) to explore with more carefully.

'Also see what the thinner rods do compared with the thicker ones.'

When pupils find that thinner rods do not get hot so far along T
from the flame, ask:

'Can you think of a commonsense reason for that? Remember people say conduction of heat along a rod is rather like water flowing along a pipe.'

Note: we should not push this story very far: the close analogue *
would be a pipe that has leaks all over it! *

This is a chance for young pupils to enjoy finding out about conduction. Some of them will do other things: e.g. they will melt the glass rods and try to stick copper wires in them; but that is all part of playing with thermal properties. This is not the time for any attempt at measurements, let along difficult arguments about a cross section and surface losses. It is just a time to see and feel things, and enjoy gaining knowledge oneself.

Optional Demonstration. If the school has it, we may show the old 'Ingen-Hausz' experiment of a set of vertical rods of different materials, coated with paraffin wax and hung from a steam pipe at the top. A heavy collar that can slide on the rod is prevented from falling down the rod by the wax: so when a steady rate is reached, the collar will have slid down to the place on the rod where the temperature is the melting point of wax. The distances *for steady state*‡ indicate conductivities. D 85

The conductivities are not proportional to the lengths of melted wax, but more nearly to the squares of those lengths. We should *not* tell pupils this as, at this stage, it would be an unsupported, dogmatic, piece of information. * * * *

This form of the experiment has long been a favourite demonstration. It works well and we as physicists appreciate its ingenuity; but to young pupils it conveys much less lasting knowledge than do their own rougher experiments. So we do not advise schools to buy this apparatus or even construct it. But if they have it already they may profitably show it. D 85 (cont.)

2. Provide beakers and test-tubes and material to mark currents in water – some crystals of potassium permanganate and some sawdust. Ask pupils to heat a beaker of water and watch the currents shown by the 'dye' from the crystals. They should try the same thing with a test-tube of water. C 86

Some will want to go on heating until the water boils. We should certainly not discourage that. We might well encourage pupils to start afresh with water without the dye. We who know all about dissolved air and the process of boiling might think this a useless

‡ Young experimenters naturally want to take the *speed* at which the initial heating travels along the rod as a measure of its 'conductivity'. Unfortunately, that does not agree with our professional definition of conductivity in terms of heat flow and temperature gradient. The speed at which a particular temperature (such as the melting point of wax) travels along a bar when we start heating one end is, essentially, the speed of 'temperature waves', which involves specific heat and density as well as conductivity. Thus, a rod of lead makes a quick start in the race although it is a poor conductor, but the wax-melting will not have travelled far when a steady state is attained.

The simple experiments suggested here involve heat losses from the surface of the rod. If, for steady state, the distance from heated end to melting-point of wax is twice as great for rod A as for rod B, then rod A has only half the temperature gradient but has twice the surface area for losing heat (in regions with that temperature range). So we argue that A must have four times the conductivity of B.

experiment; but a young pupil watching it carefully can get both delight and information from it. In fact, if this is done carefully enough, and the formation of steam bubbles is watched, the teacher too may get considerable enjoyment and even arrive at some puzzling thoughts. In making this comment, we are offering teachers a general reminder: we should be wise to let young pupils pursue what seems to them interesting developments. What we know to be sidelines, with obvious or unprofitable outcomes may seem just as wonderful to pupils as our main objective. And, since science itself has grown like that, we should allow such explorations. We should not direct the work straight back to the essential outcomes that we hope for. Of course a wise teacher will bring it back in time; though a very wise one may leave some pupils to pursue a sideline for a very long time.

Notebooks. Experiments (1) and (2) above, should be mostly experimenting. The notes to be taken should consist of a rough sketch – a very careful drawing would not contain much more information – and a few words saying what happened, just like a research man's record. This work should be doing, not writing. In the next experiment we give very detailed instructions (which certainly need not be copied into notebooks) but we ask pupils to record in their notebooks what they see happen and then to try to write down something that they conclude, some things that they can squeeze out of their experimental observations. * * * * * * * * * *

'Your experiment will give you some clues. You should then try to say "From that, my dear Watson ...".'

Class Experiments (continued)

3. 'Heat some cold water in a pyrex test-tube. To mark any currents in the water, drop a crystal of "dye" into the water and let it fall to the bottom without stirring. (Or you can use some water with sawdust already in it.) The dye will leave little colour as it falls; but if there are any circulating currents, it will colour the stream of water and show them. C87

'Try two experiments, in each case holding the test-tube *with your bare fingers* at one end and heating the test-tube with a Bunsen flame at the other end.

'Experiment (a). Hold the test-tube near the top of the water but not above the water level. Heat with the Bunsen flame at the bottom of the tube as long as you can hold it with your bare fingers. C87a

'You can hold it comfortably with your bare fingers. Then use a test-tube holder or a piece of folded paper to hold it. Watch the "dye".

'Experiment (b). Cool the tube carefully after Experiment (a) and fill it again with cold water. When the water is at rest, add a crystal of "dye" without stirring. Hold the tube at the bottom with your bare fingers, and heat with a Bunsen flame up near the top of the tube, just below the water surface. Go on heating and watch. C87b

'In your notebook, write down in your own words what you see happening in each case and draw a small clear sketch of each of the two experiments (a) and (b). Then write down what conclusions you can possibly squeeze out of the things you saw. Can you tell anything about convection, can you tell anything about any other matter of heat-transfer, judging from your experiments?'

4. For a demonstration experiment, use a small source of light such as an arc or a compact filament bulb (iodine and tungsten) to cast a shadow of a Bunsen flame. Pupils should look at the shadow and discuss it with the teacher; but to take notes on this and make use of them would be difficult. Also try other flames such as a yellow, smoky flame, a lighted match, perhaps a hot wire.§ D88

Mention convection in oceans, in hot water heating systems, in saucepans, and in ventilation. Ask whether convection in a saucepan is merely slower than stirring or quite different. Ask whether winds are convection currents.

Point out that convection currents occur in gases as well as liquids: smoke will show them. Clouds show them on a grand scale in the sky: winds are convection currents.

For conduction, mention silver spoons, insulating handles, advantage of mercury being a metal, use of copper rod to carry heat to inaccessible places (and to carry heat from them as in the dry-ice cooled cloud chamber). Ask about conduction through the bottom of an aluminium saucepan on a gas stove. (There is a thin, stationary layer of gas with a huge temperature difference.) Ask about clothes and air as bad conductors. T

§ One form asked 'What happens at the ceiling?'
They suggested using a false ceiling. It worked well.

When these experiments are done, we should give pupils some questions for homework and ensuing discussion in class. It might even be good to issue them before the class experiments on radiation. If so, give a very short description of radiation and then give the homework question – which will promote some thinking about radiation. T

Class Experiments on Radiation

For these experiments, we do not use special detecting instruments such as a thermopile, but ask pupils to use their own skin's sense of warming: 'Use your cheek or the back of your hand as a detector.' For source we use a glowing electric heater‡ (the heating element of a bowl fire), for some experiments. For others we use as source a large sheet of copper about 10 inches × 10 inches × $\frac{1}{16}$ inch which has been heated by several Bunsen burners. One face of the sheet is painted matt black with soot in methylated spirit (*not* ordinary black paint or shiny enamel). T

For a class of 16 pairs of pupils, there should be at least 4 electric heaters placed around the edges of the room, and there should be 1 or 2 big sheets of copper. In front of each electric heater, there should be a sheet of asbestos, preferably covered with an aluminium sheet on the side facing the heater, with a 1 inch hole so that radiation from the heater comes straight out through the hole. It is better if the wire of the heater is shortened by about 20%, so it runs at a higher temperature.

Some teachers in trials have suggested that more heaters and other equipment should be provided to avoid long queues. But we feel that the heaters deserve some supervision by the teacher, so we do not recommend having more of them. If teachers have arranged the class in the form we suggest, a 'circus' in which pupils go to different pieces of apparatus in various orders, this amount of equipment will do well for a class of thirty to thirty-six pupils.

5. 'We are now going to look for some things that this strange thing called radiation will do. I will tell you that radiation comes out more freely from very hot things than from cold ones. It is radiation that you get from the Sun – that is another name for sunshine. Use that glowing electric heater as a source. Look at C89

‡ If the glowing electric heaters are not available, substitute a Bunsen burner with a 'tree' from a gas fire hung in the flame of the burner by means of a handle of stout iron wire. The tree, when fully heated, will radiate very well indeed.

that hole with your eyes and see if you see any red-light radiation coming out through the hole. Put the back of your hand near the hole and note what you feel. Use your cheek as a detector: place your face some way away, 10 inches or more from the hole; can you feel any warming? Now hold a book between the hole and your cheek. Take the book out and feel what happens. Put the book back. Make notes of what you find out.

'Move your face as far away from the hole as you can while still feeling some warming of your cheek as you face sideways. Ask your partner to put a book in the way just near your face and then take it away. Then ask him to put the book in the way just outside the hole and then take it quickly away. How quickly did the warming start and stop when he moved the book? Did you notice any delay between the book being taken out of the way and your, where you are, feeling some warming? was that just the same when the book was clipped to the heater? Do you notice any difference in the time taken between the book being taken out of the way and your noticing some warming? Suppose whatever the thing is that warms you travels very slowly. Would there be any difference then? ... Make notes.

6. 'Hold your cheek 10 inches or more from the hole in front of the electric heater, and hold a thick sheet of glass between the hole in the shield and your cheek. Take the glass out. Put it back. What do you feel? What does that suggest to you ...? C90

'Now try a different version of that. Hold the sheet of glass beside your cheek and move up closer and closer to the hole by the electric heater, keeping the glass between you and it. Then take the glass away, *only for an instant.* C91

'Can you think out what that tells you about the things glass will do with this thing that we are going to call radiation?'

(If a slab of rocksalt is available, pupils should be able to borrow it and try it instead of glass.) C92

When pupils have tried interposing glass between cheek and red-hot electric heater, some will say that the glass cuts off all the radiation. Then we should say 'I think ordinary light that you can see is part of the radiation. Are you sure that that slab of glass cuts out *all* the radiation from the glowing heater?' That raises an interesting question, but it is not a very strong objection to the statement that no radiation gets through, because in the radiation T from an arc or a tungsten filament red light carries a very small fraction of the total. A better reply is to ask the pupil to move up, with the glass there, closer and closer to the hole and heater. He will feel *some* radiation getting through. Offer him several sheets of glass to try different thicknesses.

7. 'This strange thing that we are going to call 'radiation' seems to come from hot surfaces. Is there any difference between how much comes from a bright surface and how much comes from a dull one or a black one? Try to find out by holding your cheek near each side in turn of a very hot sheet of copper. One side of the sheet is brightly polished and I have painted the other side black with some soot. I will heat up the copper sheet beforehand, by holding it horizontal over several Bunsen flames until it is very hot, then I will take the flame away and hold the sheet vertical in a stand. Then, one after another, quickly hold your cheek first near the black side then near the bright side. Make a note of what you feel; and see what you can extract from that like a detective using that as a clue. C93

'Is there any danger of one side of this copper sheet being much hotter than the other? Is copper a good conductor of heat? Did you do an experiment that tells you that? ... I think we can very safely take it for granted that hot copper sheet will be equally hot all through and on both faces.'

(If pupils express doubt about the two faces being equally hot, it may be wise to 'lean over backwards' by applying the Bunsen flames to the bright side.) * * *

A large copper box heated by having a lot of steam blown into it will suffice as a poor substitute instead. A small 'Leslie cube' with boiling water in it does not give pupils a fair chance to feel the effect. Teachers who try the very hot copper plate themselves will certainly want pupils to use it. * * * * *

Pupils may also compare, using their cheeks, radiation from a clear Bunsen flame and from a yellow flame. C94

8. 'This time let's go back to "radiation" – whatever that may mean – coming out of the hole in the screen by the glowing electric heater. Use your hand as a detector and find out about receiving radiation with various surfaces. We can change the surface of your hand from a bare skin to a "silver" surface and then a black surface. C95

First, go to the heater.

'Hold your hand close to the hole in the screen, with the back of your hand towards the red hot heater. Notice what you feel. Do not hold your hand very long, in case you scorch it. You should only do this for a short time to decide what you feel; – one ... two ... three ... four ... five ... – about that long. If you want to hold your hand there longer than that you may do so; but remember that unless you have a very horny skin it may scorch and feel sore later.‡

'Next, come back and have the back of your hand covered with a very thin sheet of aluminium leaf.'

The teacher applies the leaf to each pupil in turn. (See below for technique.)

'Go back to the hole near the heater and hold the back of your hand there and count up to 5. Keep it there longer if you like.

‡ This experiment is a simple and safe one; but teachers need to keep two warnings in mind:

1. If a teacher does not insist on pupils washing off the black paint and aluminium leaf by holding the hands under a gushing tap, but let them try to clean their hands by rubbing, the soot will get rubbed in and there will be complaints and much waste of time.

2. Some pupils may scorch their hands without realizing the danger until too late unless the teacher warns them not to hold their hand in front of the glowing heater too long. There are two forms of this danger:
a. Some pupils may be unnecessarily brave. Told to 'hold your hand in front of the heater as long as you can stand it' they endure considerable pain out of bravado or obedience. This may be allowable provided they know they may develop sore skin, and realize that we do not expect them to hold their hands there too long.
b. Some pupils have extra-sensitive skin which is irritated by strong infra-red radiation and develops inflammation later. With the arrangement suggested for this experiment the average pupil holding his or her hand in front of the hole in the screen for about 20 seconds would be quite likely to develop a red patch of inflamed skin afterwards; with a 10 second exposure most pupils would show little effect, but would have plenty of time to feel the warming; and with a 5 second exposure we believe no pupils would experience unpleasant effects.
Therefore, we suggest that teachers should tell pupils to hold their hands there for only 5 seconds.
In practice teachers running this experiment with classes find that after the first few trials they relax this stringent safety requirement in the direction of 'use commonsense'. The danger is not a very great one and we have only stressed the precaution here because the experiment is new to many teachers.

'Keep the leaf on your hand but come back and have the black paint painted over it.'

(See below for technique.)

'Wait until the black paint is quite dry and then hold your hand again in front of the hole and count up to 5 again. Make notes of what happens. What *information* concerning radiation and black and bright surfaces can you squeeze out of these clues? Write down whatever you decide in your notebook.'

Note on Techniques for Experiment (8). The teacher should have a booklet of sheets of aluminium leaf (*not* aluminium kitchen foil, but leaf, like gold leaf). When the pupil is ready to have his hand coated, the teacher should say: 'Clench your fist tight, lick the back of your hand until it is quite wet all over. Then hold it out to me.' The teacher then lays a sheet of aluminium leaf gently on top of the wet skin. He blows on it to push it on to the skin, saying, 'Relax your hand just a little to avoid cracking the aluminium leaf'. (The pupil must *not* open out his hand, or the leaf will crumple. He simply relaxes it a little.) T

For black paint, to be used over the aluminium leaf, a mixture of soot and alcohol, of the consistency of thick soup, is prepared beforehand. It is applied with a large soft paint-brush an inch wide. When the pupil comes back for this, the teacher applies black paint gently, saying 'Wait till this paint is dry, then try your hand in the front of the hole'. Pupils must be instructed to WASH THE BLACK PAINT OFF UNDER A RUNNING TAP and not to try to rub it off. Rubbing will smear the soot into the skin, but a fast stream of water from the tap sweeps the soot first and then the leaf, and hands will be fairly clean. This is a messy experiment for the teacher to administer: but it *is* so impressive and fruitful that those who have tried it continue to use it.

It is clear to us as physicists, even if only by habit of teaching, that a black surface absorbs radiation completely. That is not obvious to children. Even the word 'absorbs' needs to be translated into 'stops, and doesn't send it back'. We need to discuss this carefully, asking questions such as,

'Suppose some white light from a lamp falls on a sheet of paper and the paper fibres reflect it, make it shine back towards you, will you see the paper bright or dark? Suppose some green light from a special signal lamp ... Suppose you painted the paper black instead ...?'

It is certainly not obvious to children that if radiation is absorbed by a black surface (or anything else) it must produce heat. In fact it is this experiment which should tell them that, and not any statement in a book or assertion by us.

(Only some moving things produce heat when they are stopped: light waves, sound waves, hammers hitting lead, electrons hitting a target, X-rays stopping in dense material. Even the last two do not always turn all their energy into thermal form: an electron may produce an X-ray photon instead, and an X-ray photon may whip out a photo-electron and give it with kinetic energy. We may even imagine a train of purely geometrical waves which carry no energy but are just a moving pattern that will make no heat on being stopped. Or we may make a joke and point out that a stream of kindness warms the heart of someone who receives it but not with thermal energy.)

Extra Experiments to try

9. *Demonstration of Reflection of Radiation* D96a

If a pair of metal-surfaced, parabolic mirrors are available, a demonstration should be set up to show that (infra-red) radiation can be reflected and focused like light. Glass mirrors fail, unless their *front* surface is coated with metal, because glass is black, a good absorber, for most infra-red radiation. Unfortunately large parabolic mirrors are very expensive and we do not think the cost is justified. However, the parabolic bowls that were used until recently for electric fires with a compact heating element in the centre are available and are suitable. Two should be obtained, one of them with the heating element that is needed as source.

The two mirrors are set up at opposite sides of the room, facing each other. A glowing electric heater is set up at the focus of one mirror and pupils are asked to try placing their hands at the focus of the other. This can even be developed into a demonstration that radiation travels very fast. A pupil holds a large sheet of wood or cardboard in front of the 'source' mirror, while another pupil holds his hand or cheek at the focus of the other mirror. The obstructing wood is removed suddenly and the observer is asked to note how long it is before the warming effect reaches him. At best, this only shows that radiation travels very fast.

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

(Some of these are intended to promote discussion rather than ask for a clear 'right answer').

DD

By what means does energy travel to you when you are warmed by:

(*a*) the Sun (*b*) a hot bath (*c*) an electric bowl fire (*d*) a gas fire (*e*) a hot water central-heating radiator nearby (*f*) a hot water bottle warming your feet (in contact) (*g*) hot food burning your mouth.

EE

A cake is baked in an oven. How does the heat which arrives at the surface of the cake travel to it? Answer this for several different kinds of stove. How does the heat that cooks the inner regions of the cake get to them?

FF

In the experiment that you did with aluminium leaf on the back of your hand, you felt very little warming when your hand was coated with bright leaf and held near the glowing heater. The explanation of that *might be* that aluminium leaf is a very poor conductor of heat, so that the heating never got through to your skin underneath. What evidence can you quote, from your own observations, for or against that? What does aluminium leaf do to green light or red light, or any kind of light? What do you think it probably did to the radiation that came to it from the glowing heater?

GG

In your experiment with a very hot copper sheet, which surface gave out more radiation to your hand, the bright one or the black one? Which teapot would you expect to cool faster – a well-polished silver one or one that had been allowed to tarnish and grow grey?

10. Keep a copper box hot by boiling water or steam and, after comparing the radiation from a bright face with that from a black face, try a face covered with white paper put on with paste. D/C96b

11. 'Try putting white paper on your hand instead of aluminium leaf. (You might expect a surprising result since your pale hand did not appear to be very different from black in receiving infra-red radiation.)' C96c

12. Put a thermometer in a metal beaker of hot water and time the water cooling, first with a well-polished metal beaker, second with the same beaker after it has been given an 'overcoat' of soot (by painting soot and alcohol on it). C96d

13. 'Some electric light bulbs have a vacuum in them; others have inert gas. Investigate a light bulb when it is running by feeling it, with your fingers. Can you decide whether there is a vacuum or gas inside? This is an example of good scientific detective work.' C96e

14. 'Put your cheek near an electric light bulb. Switch the lamp on and off and see whether you can feel the radiation from the lamp arriving very promptly on your face.' C96f

General Comment on Radiation Experiments. In a way, we beg the question all the way through these experiments by saying they are experiments on 'radiation'. Yet by the time pupils have done them, they are in a position to know something about the properties of this process or phenomenon that we call radiation, because we have collected for them experiments that illustrate some properties. Young people seldom raise the objection that they have been treated in an illogical way; and in this case we may rejoice in the knowledge they have acquired and in the experience they have gained, with a lot of help from the teacher, in extracting the concept of radiation properties from these experiments.

Spectrum Demonstration. It would be a pity to leave this collection of observations and attempts at conclusions at this stage, with radiation remaining an unidentified, invisible creature. So, now, at the end of these experiments, although pupils know nothing of optics, they should share Newton's own delight on first making a spectrum. * * * * * *

Set up a demonstration spectrum with the brightest available white light source, a fairly wide slit, a lens to form an image of that D97

SUGGESTED QUESTIONS FOR HOMEWORK OR CLASS

HH

Suppose you lived in a room without any fireplace and without any radiator or hot pipes to warm you except a steam pipe that ran through your room from a boiler somewhere else to some other part of the building to provide steam there. And suppose that the steam pipe was properly protected by a wrapping of asbestos with a cover of bright chromium-plated metal outside that. All you have is a bright chromium-plated pipe going through your room. What could you do, without cutting a hole in the steam-pipe, to get more warmth into your room? Suggest several things if you can.

II

Two families A and B each build a house with a flat roof. A covers the flat roof with black paint. B covers the flat roof with a very bright, smooth, chromium-plated metal sheet. Except for the different roofs, the two houses are just alike. Suppose at the beginning of a cold, clear night both houses are at the same temperature inside. Which house will cool faster during the night? What experiment have you done or seen that illustrates that? Now, suppose that the two houses are at the same temperature at the beginning of a very hot, sunny day. Which house will warm up faster? What experiment have you done or seen that illustrates that?

JJ

You have seen in experiments that a surface which is good at taking radiation and turning it to heat, such as a black, sooty surface, is also good at giving out radiation; and a surface that does not take in radiation but reflects it, as a bright aluminium surface does, is also bad at giving out radiation. 'Good absorbers are good radiators, and bad absorbers are bad radiators'. (*a*) If radiation from a glowing electric fire arrives at a sheet of glass, what does the glass do with most of the radiation? (*b*) Would you expect glass to be a good radiator or a poor one, when it is very hot? (*c*) What happens when some green light (which is one particular form of radiation, which happens to be in the region of the spectrum where your eyes can detect it) falls on a sheet of glass? (*d*) Is the glass a good absorber (stopper) of that particular kind of radiation, or a poor one? (*e*) How do you know? (*f*) Would you expect a sheet of glass, heated very hot, to be a good radiator of green light, or a bad one?

slit far away, a prism (of as high dispersion as possible) just after the lens, and then a remote screen at such a position and distance that the lens forms an image of the slit in it in colour after colour after colour as a spectrum.

The slit may be left out and the lamp itself used instead, if the lamp has either a small compact filament (the tungsten+iodine bulb) or a line filament (a 12 volt, 48 watt lamp, over-run as much as possible).

The teacher can tell pupils what the apparatus is, in as short a T
description as the sentence just above. This is not the time to explain what the lens does or what the prism does beyond pointing out that the prism somehow splits up the white light into all these colours.

If the plane of the demonstration can be turned from horizontal to vertical, throwing the spectrum up to the ceiling, smoke or chalk dust will make the rays and the dispersion into different colours visible to a watching class. Then we should turn the arrangement back so that the spectrum is again formed on a screen on the bench or distant wall.

Ask pupils whether there are any colours beyond the ends of the spectrum. 'Well, of course not visible ones; but are there any things arriving like these patches of coloured light beyond the end of the spectrum?'

> 'We have been talking about radiation. We know that it comes from glowing things, that it seems to travel in straight lines, that it seems to travel very fast; and we know that light does these things. Perhaps light is just a special form of radiation which our eyes happen to be able to detect. And perhaps there is radiation, to which our eyes are blind, outside the visible spectrum. Absorb (stop) the radiation and look for some heating. What should we stop it with? ... Yes, you found that a black surface was best for that, so we take a small, very sensitive "thermometer", paint it black, and move it along the spectrum like this.'

There are now solid-state devices to replace the traditional thermopile. They are more sensitive and easy to use; but we must choose the type of device carefully. If we want to give an honest demonstration of the energy-flow in various regions of the spectrum we must use a *temperature* – sensitive device such as a thermistor, which will indicate the heating of its blackened surface by *any* radiation. If we wanted to distort the picture and emphasize the effect of a particular region, we should use a *photo*-sensitive device that responds selectively to quanta in that region – but that would be most unfortunate when we are trying to insist there is no special 'heat radiation'.

This is not the time to describe the working of the device and its T
meter. We should just take them for granted and go as quickly as possible to the actual exploration of the spectrum.

A sensitive device will show practically no heating in the blue or green, a little heating in the orange and more in the red, and still more in the infra-red; and much more farther out in the infra-red; and then, still farther out, very abruptly the reading drops down to nothing again.

Since there is a glass lens and a glass prism in the optical path, we must expect a cut-off in the infra-red where glass becomes opaque to longer wavelengths. This rather spoils the demonstration; and it does not help matters much when we explain to pupils that the glass has cut off the more extreme infra-red. With a fast group, we should try to appeal to the knowledge they have already gained from holding the slab of glass between their cheek and the glowing heater. But we should *not* use a diffraction grating for this experiment, because the overlapping of orders, when one includes the long, infra-red region, spoils it.

Perhaps the best thing is to arrange the optical system from lantern to prism all on an optical bench or on a board, which can be slewed round to bring one part of the spectrum after another on to the stationary device. The latter should be surrounded by a sheet of white cardboard to catch the rest of the spectrum: that forms a framework of reference for the part of the spectrum being measured.

How clearly the variations of power-flow across the spectrum can be demonstrated depends upon the device. It should be one with very small thermal capacity so that it responds quickly; and the meter should be chosen for the right kind of sensitivity, and should have a short period. (A galvanometer with a *taut suspension* has a short period and makes this demonstration clear, where the traditional experiment with a thermopile of large thermal capacity and a galvanometer of long period is confusing for beginners.)

This is, of course, a demonstration to rehearse very carefully beforehand. If there are hot water pipes or a radiator across the room in front of the device, it will truthfully record their presence in a disconcerting way. And even after a successful rehearsal, the radiation from pupils' hot faces in the audience can spoil things.

Discussions of ultra-violet light and its properties, colours and colour mixing, the extended electromagnetic spectrum, are best postponed to a later Year.

This demonstration is simply meant to be an exploration of the radiation-richness of various parts of the spectrum from, say, white-hot tungsten – a first look at a white-light spectrum for delight.

SUBJECT INDEX

NUFFIELD FOUNDATION SCIENCE TEACHING PROJECT PHYSICS SECTION

The physics programme was inaugurated in May 1962 under the leadership of Donald McGill. It suffered a severe setback with his tragic death on 22 March 1963, but those who were appointed to continue the work have done so in the spirit in which he initiated it, and in the direction he foreshadowed.

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Other Nuffield Physics publications

Teachers' guide I
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