REVISED

NUFFIELD PHYSICS

Teachers' Guide
Year 3

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Nuffield Physics
TEACHERS' GUIDE
YEAR 3

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NUFFIELD PHYSICS TEACHERS' GUIDE YEAR 3

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Foreword

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

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

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

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

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

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

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

General Editors' Preface

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

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

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

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

Many teachers have followed some general suggestions:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Eric M. Rogers
E. J. Wenham
General Editors

Preface to Year 3

This should be a year of capable play in physics, for pupils with a wide variety of abilities and interests. We want pupils to enjoy being scientists, *doing* experiments and—sometimes—*thinking* about them.

What *outcomes* do we hope for? Knowledge of laws? Skills in framing hypotheses and solving problems scientifically? No; these demands are much too sophisticated for our young pupils. At best the teaching would promote cold, remote, mechanical learning—the only pleasure would be in getting the answer right or in receiving praise for dutiful work. At worst they would be dull incomprehensible disciplines.

What we hope for is some success for everyone, in being a scientist. Success comes when some experiment gives a young pupil a sense of pride in expertise: 'This is *my* experiment. *I* did it.'; or '*Knowing what I now know*, I can make it go well.' And, 'That result is *my* knowledge; I have thought it out *myself*.' Never mind which experiments a pupil spends extra time over and which ones he or she misses: quality of enjoyment and success matters here, rather than quantity of coverage.

Yet we should worry to some extent about quantity: if the programme is too slow or thin there will be boredom. But we need to think about the *kind* of success each pupil deserves rather than the *amount* of material. Learning by rote in science may yield a lot of 'success' that is measurable but of short life and little educational value. When we encourage learning for understanding and enjoyment we must often be content with rarer yields: one experiment in several catches a pupil's fancy; one new idea is fascinating but others are not. But of course different experiments and different ideas spell success for different pupils. Which *kind* of success should we seek for our pupils?

But what about the bogey of 'examination preparation'? Only some of our pupils will ultimately take an O-Level examination or the equivalent; and the defining boundaries of examinations are still far away. Whatever a pupil does now will make a useful contribution to a humane examination if he or she carries it forward with understanding. But to worry about an examination syllabus and hurry any or all of the pupils through everything mentioned would be a grave mistake. Time to finish an experiment and leisure to think about a question are more important than coverage: they are essential for each pupil's sense of success; and, thereby, for the good name of Science.

Two major topics of this year's programme, waves in a ripple tank and optics of images and instruments, are not treated again in later years except that some aspects are drawn on in Year 5. However the *circus of revision demonstrations by pupils* which we suggest in Year 5 should insure against a feeling that those two topics must bear an unwelcome burden of exam preparation now. The other three major topics of this year's programme continue in Year 4 and some of their later parts are marked *OPTIONAL NOW* to suggest they may be postponed to Years 4 and 5.

So we hope teachers will make sure that pupils enjoy the year by giving extra time for some topics, and treat some topics very lightly, postponing some until Year 4 if necessary.

From the beginning, members of the Nuffield Physics Project devised and designed apparatus for the suggested teaching. Some forms are novel, and a few pieces are new inventions, but most of the apparatus was already known and in some use. We re-designed it and arranged for its production in robust form and in quantities that would enable pupils to do their own experimenting. It is now available from suppliers, much of it in 'kits' of 16 sets so that pupils of a whole class can work in pairs.

The provision of such equipment is essential to the suggested teaching method. Since teachers may find some of it unfamiliar, we give below some notes on Nuffield apparatus for Year 3.

The New Apparatus

In Years 1 and 2 we gave pupils instruments to use as scientists: magnifying glasses, microscopes, balances, centimetre rules, Bourdon gauges and U-tubes for pressure, thermometers, stop-watches or clocks, simple current-balances, ammeters, simple cloud chambers. In Year 3 we offer more devices for pupils' own experimenting.

Waves in ripple tanks To let pupils learn some aspects of wave motion by personal experience we provide simple trays of water—at least one for every four pupils—and ask pupils to go through a series of experiments with ripples. These tanks are much simpler than the usual demonstration form, but they are robust and the ripples are easily seen by shadowing. The essential purpose is *not* to prepare for later work on refraction, interference, and theories of light, but to let pupils enjoy experimenting and, we hope, develop pride in their skill and knowledge.

Optics by laws and constructions The usual teaching of optics starts with the reflection and refraction of rays, given as laws which are tested by marking rays with thin pins—and the aligning of the pins often obscures the optical reality. Then formulae for mirrors and lenses are derived from the laws.

Pupils test those object-and-image relationships by experiment. To many a pupil, however, these experiments are simply measurements of 'the focal length'. The general action of a lens becomes lost in worship of a particular image point, the focus.

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

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

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

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

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

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

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

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

Optics by images and instruments In our approach to optics in Year 3 we start instead with empirical knowledge of rays and images—which pupils see in their own experiments. We feel that approach is less 'fundamental' but more realistic. We offer our young pupils a start that is equally based on experiment and pupils are able to deal with optical instruments earlier and in a way which seems more direct.

The only great loss is that we do not have the Laws of Reflection and Refraction so early or make them so prominent in our collection of great general laws; and that is a loss, because we want pupils to see the part played by general laws in the structure of science. Nevertheless, we follow a treatment in terms of *images* which has been tried before and gives pupils more confidence and skill with optical instruments.

Pupils *start* by making simple cameras and 'image' begins to take on a meaning. Then after brief play with lenses they make their own telescope.

They see how a lens in a box of smoke bends rays to an image. They then work in pairs on a series of class experiments with lamps and lenses to see rays forming images.

A small lamp shoots streaks of light through the slits of a comb. These 'rays' run across a sheet of paper on the table. Pupils see them meeting a lens and being bent to pass through an image. Pupils see in detail how lenses and mirrors treat rays. These are *not* the usual ray-box demonstrations, but a series of simplified *class experiments* with large glass cylindrical lenses made for the purpose.

With a pair of lamps as image pupils make beautiful clear ray-streak models of telescopes etc. The following properties of rays emerge from those experiments:

a. Rays travel straight out from an object-point.
b. All rays from an object-point pass through the image point.
c. Rays from a remote object-point that pass through a positive lens proceed *straight to* a real image-point after the lens, and continue *straight* on through that image-point.
d. Rays from an object-point that pass through a lens which forms a virtual image emerge along lines that appear to come *straight from* the image-point.
e. Every ray aimed at a central point in a lens (called the optical centre) passes straight through.

(Pupils *see* that statements *(b)* and *(e)* need some modification in practice.)

Then pupils make more instruments: a telescope again, this time with measurements of magnification; a magnifying glass, a microscope; and they discuss eyes and spectacles.

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

Spectrum and colour A further chapter on optics carries pupils through class experiments and demonstrations with a spectrum and some simple experimenting with colour filters. Most of the things in this chapter are *OPTIONAL NOW.*

Measurements of force and motion We offer trolleys and ticker-tape timers for a few introductory experiments. The trolleys are small carts on roller-skate wheels; the timers vibrate at 50 Hz, making dots every $\frac{1}{50}$ second on paper tape drawn by the trolley. Each pair of pupils should have a timer for various experiments; but, pupils may have to work in quartets for a look at forces accelerating trolleys on a runway.

The first experiments are interesting novelties, such as pupils' timing their own running speed. They also serve to introduce techniques that will be used for a study of Newton's Laws in Year 4;* but this year's work should be short and lighthearted, amusing experimenting for all.

Gases Pupils see the three-dimensional teaching model of gas molecules again. They use their own two-dimensional model of marbles in a tray to illustrate changes in a gas and evaporation of a liquid.

* Pupils who continue to Year 4 will use trolleys and timers and elastic pulling-threads to make measurements of force and acceleration, and acceleration and mass—an investigation to give confidence in Newton's Laws. Then they will measure momentum in collisions, looking for conservation. The same trolley equipment will be used to make tests of energy-changes involving kinetic energy.

Meanwhile pupils will be shown how to develop algebraic formulae relating distance, time, acceleration, etc.; and an expression for kinetic energy.

Teachers will also offer demonstrations: velocities measured by millisecond pulses counted by a scaler; and 'multiflash' pictures of moving bodies photographed through a spinning strobe disk.

All that should give acquaintance and some knowledge; yet, even in Year 4, studies of Newtonian dynamics should be short—if they are long they will be boring and seem pointless. We should remember that Newton himself did not state his Laws to enable people to solve artificial problems in mechanics. He gave them as his starting-points for a great theory of the Solar system, as we hope pupils will see in Year 5.

Therefore, any preparation with trolleys in Year 3 should be brief and informal.

In a class experiment they use Bourdon gauges to measure pressure-changes with heating. (As this is followed by a theoretical discussion leading to the idea of absolute zero it is much better to have the experimental part in pupils' hands rather than make it a demonstration.)

For the expansion of air with temperature-changes pupils see a new demonstration with a sample of air kept at atmospheric pressure by a piston of oil connected to an open reservoir. This replaces the awkward class experiment with a capillary tube.

Electromagnetism Pupils continue from the Worcester circuit board experiments with a new series. The Westminster kit provides magnets, wires, etc. for pupils to work alone or in pairs to make magnetic fields, arrange working models of meters, motors, bells, buzzers and loudspeakers; and then to make a 'discovery' move to dynamos.

To start *all* pupils on something fresh, the series begins with magnetic fields of *currents* and deals with permanent magnets later. (If we started with permanent magnets, some pupils would say they already know all that.) The *Pupils' Text 3* gives simple general instructions for all this; but pupils are left largely on their own to assemble apparatus and try things.

There is also a model transmission-line experiment which shows very clearly the advantage, in efficiency, of high voltage for power transmission.

Magnetism theory A short, crude version gives pupils a chance to put theory to use. Each pupil is given a ring of steel, which shows no poles. Can the ring nevertheless be magnetized? Pupils make theory suggest an answer; then they test the answer, with a very pleasing result. Theory talks good sense.

FLOW CHART FOR YEAR 3

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

PAST: Nuffield Years 1 & 2 or Combined Science

GENERAL ACTIVITIES & OUTCOMES

Acquaintance

Experimenting: enjoyment of doing one's own experiment

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

GUESSING ESTIMATES

BEHAVIOUR of lever, springs; (laws ?)

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

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

ENERGY from fuel, forms, interchanges, (work)
cloud chamber, spark counter

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

PRESENT: Nuffield Year 3

GENERAL ACTIVITIES & OUTCOMES

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

Thinking about models: idea of laws

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

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

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

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

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

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

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

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

(8) ELECTROSTATICS
charges
(fields)

(9) THEORY OF MAGNETISM
as an example

.... KNOWLEDGE .... INTELLECTUAL SATISFACTION

FUTURE: Nuffield Year 4 and 5 for pupils who continue

GENERAL OUTCOMES

Connected knowledge

Ideas of use of theories and models

Pictures of atom models

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

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

KINETIC THEORY yielding speed, spacing, size of molecules

ENERGY CONSERVATION

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

ELECTROSTATICS
electroscope
charges and forces, fields;
Millikan experiment

OPTICS
interference & diffraction
comparison of theories
electromagnetic spectrum

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

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

RADIOACTIVITY
atomic and nuclear information

ATOMIC MODELS
simple model
Rutherford atom
wave model

PUPIL'S DEMONSTRATIONS FOR REVISION

USES OF THEORY

CHANGES OF EXPERIMENT NUMBERS IN YEAR 3

New	*Old*	*New*	*Old*	*New*	*Old*	*New*	*Old*	*New*	*Old*
0a	1c	7c	7c	31b	14r	60	52	92	†80o
0b	67	7d	7d	31c	†14s	61	50	93	—
0c	—	7e	7f	31d	17	H62	H51	94	—
0d	71a	7f	7e	32	26	63	53a	94X	—
0e	90c	7X	—	33	27a	64	53b	95a	—
1a	—	8	8	33X	27b	64X	53b	95b	82
1b	—	9	9	34a	28a	65a	54a	96a	83a
1c	—	10	—	34b	28b	65b	54b	96b	83b
1d	—	11	10a–c	34c	28c	65cX	54c	97	84
1e	—	12	—	35	28d	66	—	98	—
1f	—	13	12	36a	29a	67	56	99	85
1g, h	(Y.II)	14	11	36b	29a	68	57	100	86
2	1a	15	—	36c	29a	69a	†58a	H100	H86
3a	1b	16	10e	37	29b	69b	58a	101	—
3aX	1c	16X	—	37a	29b	69c	58b	102	87a
3b	2	17	10f	37b	29c	70	48	103	87b
3c	3	18	8	§38	—	71	64	104	88g
4a	4a	19a	14a	39	—	72	65	105	88a
4b	4b	19b	14b	40	29d	73	70	106	88b
4c	4c	19c	14c + 14n	41	†30	74	66a	107	—
4d	4d	19d	14e	42	31	75	67	108a	88d
4e	4e	19e	14f	42X	32	76	68a	108b	88e
4f	4f	19f	14h	43	4t	77	69a	109	88g
5	5	19g	14i + 14k	44a	4r, s	78	71a	110a	89a
4g	4g	19h	14l	44b, c	34, 4p, q	79	71b	110b	89b
4h	4h	19i	14g	44c	4q	80	72	110c	89c
4i	4i	19j	14j	45a	33b	81a	74	111	90c
4j	4j	19k	14o	45b	§§36, (33a)	81b	74	112	†91, 92b
4k	4k	19l	14p	46	35a	82	76	113	92a
4l	4l	H19l	H14p	47	35b	83	75	114a	94a
4m	4n	20	—	48	38	84	77	114b	94b
4n	4m	21	16	49	39a	85	†78	115	93
4o	4o	22	15	H49	H39a	86	79	116	93
4p	4p	X	—	49X	39c	87a	80a	117	100
4q	4r, s	Y	25	49XX	39b	87b	80b	118	†(98, 99)
4r	(4s)	23a	18	50a	40	87c	80e	119a	95a
4s	4q	23b	18	50b	40	87d	80c	119b	95b
4t	4t	23c	13, 18	H50	H40	87e	80d	120	—
4u	4u	24	22b	51	41	87f	80f	121	—
6	—	24X	22c	52	42	87g	—	122	100
6a	6a	24XX	23	53	—	87h	—	123	101
6b	6b	25	24	54a	43	88	—	124	102a
6c	6c	26	21a	54b	43	89a, b	80h, i, j	124X	102b
6d	6d	27a	21b	55	43	89c	80g + 1	125	†103
6e	6e	27b	21b, 22b	56	44	89d	80k + 1	126	104
6f	6f	28	19	57	45	90a	80n		
7	7	29	20	58X	46	90b	80m		
7a	7a	30	new	58	47	91	†80o		
7b	7b	31a	14q, m	59	49	91X	—		

Key to changes of Experiment numbers in Year 3

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

Old numbers: 10d, 14d, 22a, 55, 60a and b, 62, 68b, 69b, 81, 88f.

Experiments in original *Guide to Experiments III* postponed to Year 4 or Year 5 in revised programme:

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

† means changed to new apparatus or new format
§ indicates new experiments, some from Year V
§§ means measurements omitted
X (example: *Demonstration 3X*) means not in Pupils' Text

Note: To aid teachers requiring quick reference, the experiment numbers are printed at the foot of the page concerned.

Experiment List

This list contains an index of experiments for *Pupils' Text Year 3* and *Teachers' Guide Year 3* (with additions for *Teachers' Guide* in italics).

THE FIRST CLASS

Optional introductory Demonstrations 0

0a A Machine that shows a Wave travelling along
0b 'Frozen Pearls' of Water
0c The Current taken by big Electric Motor
0d A Teaching-model of Air Molecules in Motion
0e An a.c. Transformer lights a lamp

CHAPTER 1 WAVES

Questions and Experiments 1 Why worry about waves?

1a Sound: Echo and Speed
1b Sound: Beats
1c Sea Waves
1d Radio
1e Light
1f Radiation, visible and invisible: Energy
1g Radiation: Red-hot heater and curved Mirrors (*optional*)
1h Radiation: Energy among Colours (Spectrum) (*optional now*)

Class Experiment 2
Transverse waves on a rope

Demonstrations 3

3a Examples of Wave Motion: Slinky (or rubber tubing)

CHAPTER 5 GASES

CHAPTER 6 ELECTROMAGNETISM

Class Experiment 115
Using a Voltmeter (*advanced extension; optional now*)

Class Experiment 116
Using a Voltmeter to measure power (*optional now*)

CHAPTER 8 ELECTROSTATICS

Demonstration 117
The 'Naked Oscilloscope': Fine-Beam Tube

Demonstrations 118 Electric Charges and Forces
118a A Current, driven by power supply
118b Charges at Rest, provided by power supply
118c Charges of the same kind, provided by power supply
118d Charges made by 'Friction'
118e Charging Balloons by 'Friction'
118f Unlike Charges
118g Different Methods of Charging: the hybrid experiment
118h Van de Graaff Machine used to charge objects

Demonstrations 119
119a The Electric Compass Needle (*optional now*)
119b Electric Field Patterns (*optional now*)

Demonstration 120
Van de Graaff Machine and Electric Sparks (*optional now*)

Demonstration 121
Clearing Smoke (*optional*)

Demonstration 122
Fine-Beam Tube: Second Look

CHAPTER 9 A FRUITFUL THEORY

Class Experiment 123
Breaking a Magnet

Class Experiment 124
Giant Model of a Magnet

Demonstration 125
Magnetization of Soft Iron—Magnetization Curve and Saturation (*optional*)

Class Experiment 126
Is the Ring Magnetized?

CHAPTER E ENERGY AND POWER

(These experiments and demonstrations are mentioned in *Pupils' Text 3* only. E = Energy; P = Power.)

Demonstration E1
Hauling up a Load: a 'Useful Job'

Experiments E2
E2a Losing Uphill Energy
E2b Hammering Lead

Experiments E3
'Circus' of Energy transfers

Experiment E4 Force in newtons; energy in newton · metres
E4a See the size of a newton
E4b Feel a newton
E4c Move a force of 1 newton
E4d Make an energy-transfer of 1 newton · metre

Experiment E5
Climbing stairs

Experiment P1
Climbing stairs

Experiment P2
Power for an Electric Lamp (*optional now*)

CHAPTER 1

WAVES

Wave behaviour; experiments with ripple tanks

This Year begins with a study of waves, using ripple tanks for class experiments. A study of optics—chiefly optical instruments—makes another long series of class experiments.

After that we deal with motion. There is general experimenting and informal discussion concerning distance, time, speed, acceleration, motion of projectiles and satellites—preparing for a more formal study of Newton's Laws in Year 4.

Then the study of motion extends into a discussion of kinetic theory of gases, renewed from Year 1.

Since momentum and kinetic energy are not yet established in quantitative forms, our general treatment of kinetic theory must wait till Year 4 but we can suggest a dynamical concept of temperature. We look at gas behaviour, with demonstrations of Boyle's Law and the effects of temperature-change on pressure and volume of a gas, leading to a suggestion of a gas thermometer and the idea of an absolute scale of temperature.

Then pupils use the electromagnetic kit for class experiments with magnetic fields, model ammeter and motor, and electromagnetic induction.

The First Class

For the first class of the year, some teachers may hesitate to start on wave demonstrations and class experiments which lead soon to ripple tanks in a half-dark lab. It may be more convenient to start with a single period of demonstrations of *things that lie ahead*—like giving tourists a pamphlet of travel pictures before they visit a foreign country. Here are suggestions.

Introductory Demonstrations O *(OPTIONAL)*

Teachers might choose some of the following demonstrations or any others which they would like to show as samples. These should be given quickly *without explanation* at this stage.

Those here are mentioned in *Pupils' Text 3* with some commentary and questions; but pupils are reminded that they will see them in due course if they miss them now.

Oa A Machine that Shows a Wave Travelling Along

Show any demonstration wave model that the school already possesses. (See Demonstration 3aX.)

Ob 'Frozen Pearls' of Water

(See Demonstration 75.) This takes time and trouble to set up and adjust, but it is a delight to see. And it starts a question in pupils' minds about stroboscopic illumination.

Oc The Current taken by a Big Electric Motor

Run a large motor in series with an ammeter. Hold the axle with a gloved hand. (A dramatic energy demonstration that can start some thinking even without discussion.)

Od A Teaching-Model of Air Molecules in Motion

(See Demonstration 77.) Pupils have probably seen this in an earlier year; but here *Pupils' Text 3* uses it to begin a discussion of models and their uses.

Oe An a.c. Transformer lights a Lamp

(See Demonstration 111.)

Wave Motion

'Why do we explore waves?' Pupils need a good reason for that beginning. Our own reasons are clear, but they could hardly appeal to pupils now.

In our teaching plans we suggest waves with two aims in mind: chiefly to provide a descriptive field for pupils to enjoy their own experimenting with ripple tanks and build some pride in 'doing Physics'; and to provide those who will continue to later years with *qualitative* acquaintance, to be used in Year 5 for studies of diffraction and interference which will be needed for atomic models.

Pupils would see the point in starting with the physics of diesel engines, or of water-colour painting. They would consider nuclear fusion topical; and even a general discussion of energy would be physics of today. But 'Why waves?' Teachers will need to answer that unspoken question.

Therefore we offer a quick series of experiments that suggest three things about waves:

Waves usually travel fast; they can convey a message quickly.
Waves sometimes make strange patterns, which we should not expect of a stream of particles.
Waves (usually) carry energy.

At this stage, emphasis on waves carrying energy will bring them into importance so that pupils' experiments with ripple tanks seem relevant.

The series should be quick—with little or no explanation now—and should draw on several fields: sound waves, ocean waves, radio waves, light visible and invisible. (In the case of light, we should be tentative at this beginning and say that there are 'rival' views—since we want to contrast particle and wave explanations later this Year or in Year 5.)

Some of this series are just bits of common knowledge to be mentioned to pupils—and *Pupils' Text 3* does that, then asks informal questions. Others are simple demonstrations; but we list them all below.

The suggestions of comments to pupils are, of course, only offered as possible samples.

Questions and Experiments 1—Why worry about Waves?

1a Sound: Echo and Speed

'When you talk, sound waves carry your message through the air to other people. *Clap your hands and listen for the echo.* How do sounds travel so fast? Can sound waves in air travel faster than the winds?'

Explain that sound waves push our ear drums in-and-out; and ask what they must carry to be able to do that.*

1b Sound: Beats

Play two sources of sound of slightly different frequencies. Whistles or small organ pipes do best at this stage; but monochords or tuning forks will suffice. (A pair of oscillators with loud speakers would be red herrings.)

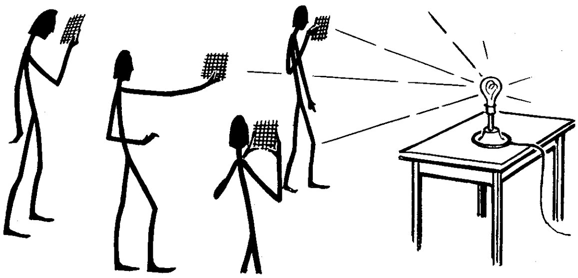
Say that the throbbing sound is called 'beats', but give no explanation now. Just ask how do two sounds manufacture beats and leave the question to brew.

1c Sea Waves

Mention ocean waves and ask how they travel all the way from a remote storm. Ask what they must carry to be able to roll a stone up the beach or even knock a bather down.*

1d Radio

'The signals of radio and television come to us as waves—not waves in water or air, but waves in electric and magnetic fields. Listen to time signals or watch a clock on TV. Do the signals arrive noticeably later if you are far away from the broadcasting station?

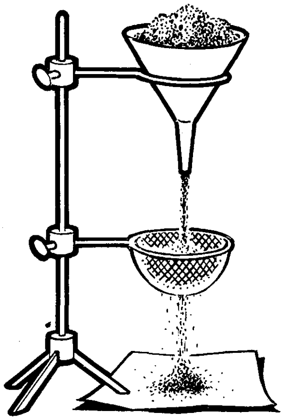


* We hope for the answer 'energy'—a concept that is undefined as yet but already interesting and useful. If pupils do not give it, just announce it!

Those signals bring in a tiny stream of energy which triggers a lot more energy from the mains or batteries.'

1e Light

(i) Set up a small bright lamp in a fairly dark room. Give each pupil a small piece of closely-woven umbrella cloth—*not* a diffraction grating at this early stage. Ask pupils to look at the lamp through it. Also suggest looking at a distant street lamp at night through an umbrella.



Ask: 'Why do you see an *extra pattern* of bright spots?' (Leave the question unanswered now: any successful answer would take far too long now.)

(ii) For comparison, set up a funnel over the table and put fine dry sand in it. Hold a fine-mesh strainer in the stream of sand. Ask whether the sand then makes an extra pattern of heaps or just one large mountain on the table.

'What makes the difference between light and sand patterns?' (Again unanswered now.)

1f Radiation, Visible and Invisible: Energy

'We call all the colours of visible light, and infra red and ultra violet, etc., "radiation". They all carry energy. (Think of energy here as something that does the useful job of warming things.) Hold your hand near a glowing fire or an electric heater. What do you feel?'

The more formal Demonstrations 1g and 1h will help this introductory suggestion of energy-transmission by waves. If they are shown now, detailed explanations would be out of place—they are just part of the hors d'œuvres; and they are suggested again for full discussion at later stages.

1g Radiation: Red-hot Heater and Curved Mirrors *(OPTIONAL)*

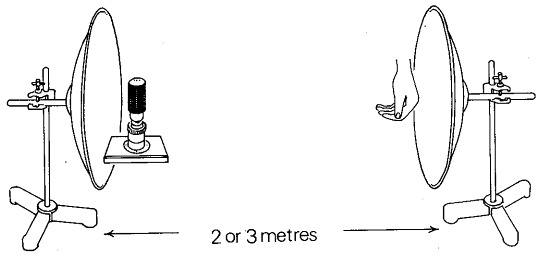
(This is a demonstration near the end of Year 2. Since some pupils may have missed it there, it might be done now.)

Apparatus

1 pair *metal-surfaced* parabolic mirrors (or two electric bowl fires; one with heating element, one without)	item 301
1 radiant heater (500 watt)	58C

Procedure

Set up the mirrors facing each other 2 or 3 metres apart. Place the heater at the focus of one of them—using the visible red radiation as a guide.



Find the image of the heater formed by the second mirror. Let pupils place a hand at the focus. Avoid telling them what to expect but suggest placing the hand *with palm towards the other mirror*.

Warning. Beware of burns: tell pupils to stop as soon as they feel anything.

Point out: 'Some energy seems to go across from one mirror to the other.'

Hold a large sheet of cardboard or plywood as an obstruction just beyond the heater. Ask pupils to try again with a hand at the focus of the second mirror. Whip the board away quickly. 'What do you feel? Does the supply of energy start again almost at once or only long after—as it would if air currents carried the energy?'

'How could energy get across there, so far away?' (Again unanswered now.)

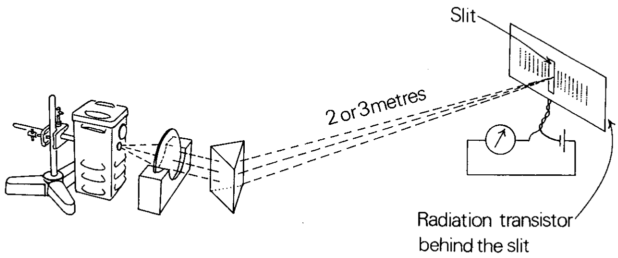
1h Radiation: Energy among Colours (Spectrum) *(OPTIONAL NOW)*

(This is a demonstration near the end of Year 2. Since some pupils may have missed it there it might be done now.)

Apparatus

1 compact light source	item 21
1 L.T. variable voltage supply	59
1 large positive lens	93B
1 high-dispersion prism	69
1 white screen	102
1 radiation-transistor (B.P.X. 25)*	229
1 cell	52B
1 demonstration meter	70
1 d.c. dial: 2.5–0–2.5 mA	71/4

* We suggest this device as a compromise—only partially honest in name and action. It measures *photons* and has a cut-off in the near infra-red beyond which each photon has too little energy to excite response. In Year 2 we tried to get rid of the myth of infra-red as peculiar super-calorific 'heat radiation'; and it seems a pity now to distort the story in another direction. The proper device would be a small black object whose temperature-rise is measured when it is in equilibrium with the energy-flow—in *any* part of the spectrum. A thermopile can do that but most of them are very slow: a quick, sensitive one is expensive and temperamental.



Procedure

Set up the compact light source (which takes 8 amps at 12 volts). No slit is needed: the lamp filament is small enough.

Place the lens about 20 cm from the lamp. (If the lens is plano-convex its plane face should be towards the lamp.) Move it to make an image of the filament on a white screen 2 or 3 metres away.

Then place the prism just beyond the lens and move the screen round to catch the spectrum *at the same distance from the lens as before* but in the new direction.

The spectrum will be pure enough for this demonstration if the prism is turned to minimum deviation. To make the spectrum longer, twist the screen to catch it obliquely.

Connect the radiation-transistor* (and cell) to the demonstration milliammeter. The transistor must be shielded so that it cannot receive radiation by a direct route from the lamp and its very hot housing. Move it through the visible spectrum and out beyond to show—quickly—that energy is arriving. At this stage give no explanation—the experiment and its explanation have a proper place later.

NOTE. There will be a fairly sharp cut-off in the near infra red, due to the glass of the prism and lens; or the photon sensitivity of the transistor may impose an even earlier cut-off.

Seeing Waves

Start by giving pupils a look at real waves, preferably in several media. This is *not* the stage for diagrams in time and space or formal definitions, or a talk on wave properties. This is the time for acquaintance with reality.

Waves on a rope Let pupils send a transverse wave along a rope. Show them how to start a pulse. Do not ask them to look for reflection—just hope that they will see it.

Some pupils will make 'stationary waves'. If so, we should point out that the pattern is not travelling. Though it is a nuisance here, this phenomenon will be important later. So we should not be discouraging.

* The proper, honest, device for receiving the radiation would be one that measures the flow of energy in each part of the spectrum—by measuring a rise of temperature as the sample of radiation is absorbed. A thermopile can do that but it is itself slow or very expensive; and, for a meter to exhibit readings quickly, a d.c. amplifier is needed. A bolometer is expensive but available now.

So, instead, we suggest the use of a *photo*-transistor. That does not measure the energy flow. A modern one which responds to photons all through the visible spectrum and a short way into the infra-red which will show increasing response from green to red and still greater in the infra-red. Then there is a sudden cut-off in the rear infra-red. The cut-off is more likely to be the photon-limit of the transistor than the cut-off due to glass absorption which is always met with a thermopile.

The photo-transistor suggested gives a quick reading on a milliammeter and although it would be dishonest to call it a truthful energy-measurer, it tells a valuable qualitative story.

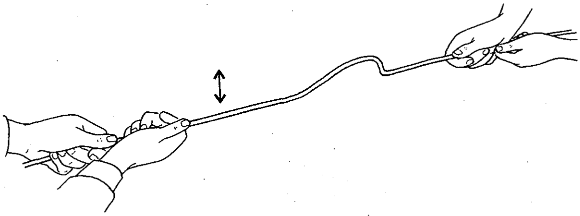
(There is a trick to produce stationary waves easily: stretch the rope and hold both ends fixed. Put marks on the rope at, say, $\frac{1}{5}$ length from the end, $\frac{2}{5}$, $\frac{3}{5}$, $\frac{4}{5}$. Hold the rope *loosely, at one of these nodal marks,* and shake it at the right frequency. This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

Class Expt 2 Transverse waves on a rope

Apparatus

16 lengths of flexible rope (each 3 metres or more).

The longer the rope the better, depending on the space available. It must be flexible and fairly massive. Clothes line is too stiff; string is far too thin.



Procedure

Pupils work in pairs. Each holds one end of the rope. A flick at one end starts a pulse which travels down and back. (This is easily done by jerking the end of the rope up and quickly down to stop on the wrist of the other hand.)

The pulse will be reflected back and forth several times if the rope is held firmly in mid air; but it may be better to start with the rope on the bench or on the floor.

Wave demonstrations Demonstrations of pulses and continuous waves are useful here, if they do not take much time. A rubber tube and a 'slinky' spring are useful media.

Unfortunately, longitudinal waves travel very fast on a slinky. An excellent model with very slow waves can be made with a line of trolleys; but this should wait until Year 4 when trolleys are familiar apparatus.

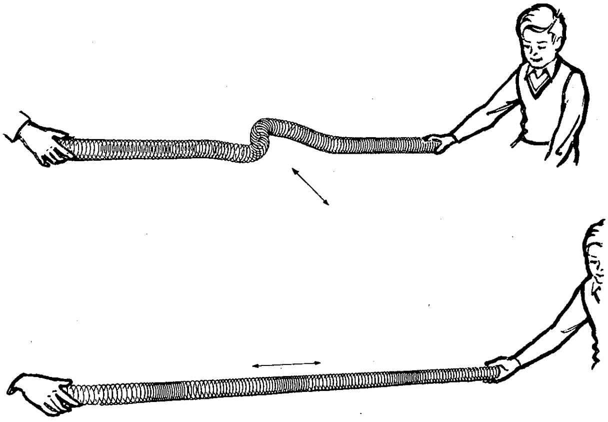
Demonstration 3a Examples of Wave Motion: Slinky (or Rubber Tubing)

Apparatus

1 'slinky' item 101
1 length of rubber tubing

The tubing should be at least 5 metres long and 8 mm or more in diameter.

The slinky should be at least 10 cm long when closed up.



Procedure

(i) 'Slinky': Pulses. Hold the 'slinky' on the floor with slight tension. Give one end a sharp flick horizontally.

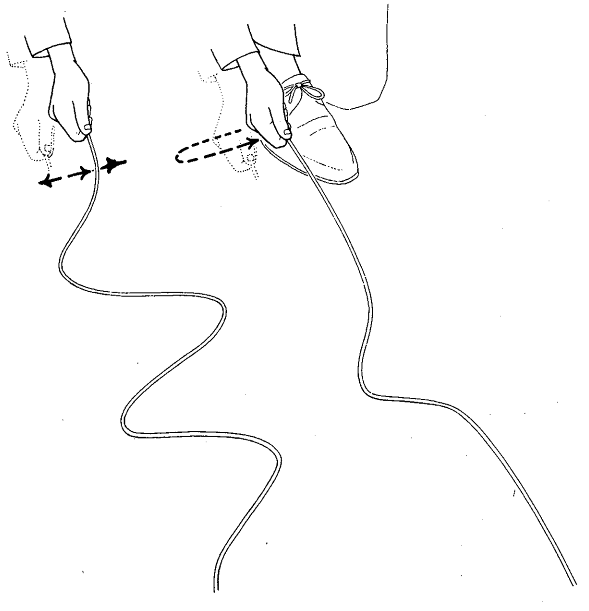
(While it is great fun to produce *standing waves* with the 'slinky'—and to make it walk downstairs—such experiments detract from the main object of seeing how a pulse travels, so they should be avoided.)

Continuous waves. Lay the 'slinky' on the floor or on a table. Make one end oscillate *transversely* by hand, with a small amplitude and a frequency of about 5 hertz (cycles per second), while keeping the other end fixed. The regular chain of impulses produces a continuous travelling wave. This is usually clearer with the rubber tubing.

With a 'slinky' it is also possible to show travelling *longitudinal* waves by pushing and pulling one end; but it may be better to omit longitudinal waves at this early stage.

(ii) Rubber tube. If possible, also show transverse pulses and waves on a rubber tube held with some tension on the floor or on a long table. Give one end of the tube a sharp flick horizontally. This is most easily done by holding one end against one's ankle and then jerking it sideways, out and back to the foot again.

Try different tensions; and pulses with slower motions. Then make a continuous travelling wave. This needs a long rubber tube so that the wave-train can be seen to travel before the return wave reflected from the far end complicates the picture.



If the school already possesses a wave model (e.g. a machine for demonstrating the motion of particles in various types of wave; or an apparatus of rods and springs to show torsional waves) it might be shown at this point; but we do not advise teachers to take long to construct or discuss elaborate models. As well as being too expensive in trouble and money, they are too 'special'. We do not advise any school to buy a wave model for Nuffield physics.

Waves along a line of pupils may sound too childish or undignified to be suitable. In practice, they are fruitful. For some pupils, the other demonstrations have just been things to look at, but these are real.

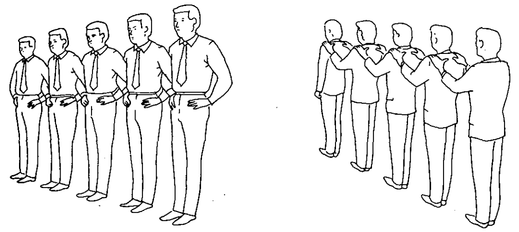
Demonstration 3aX Wave model *(OPTIONAL)*

If the school *already* owns a wave model that is ready for use, that may be shown as a quick demonstration, *in addition* to experiments 2 and 3a. (It may already have been shown in Demonstration 0a.)

Demonstration 3b Waves in a Human Army —a Line of Pupils *(OPTIONAL)*

Procedure

Transverse waves. Pupils link arms in a line. Move the shoulder of the end pupil forward and back to send transverse waves and pulses down the line.



Longitudinal waves. Pupils stand in line, one behind another, each with his hands on the shoulders of the one in front, and with elbows kept bent.

It is more vivid if the pupils face away from the teacher. A good shove from the teacher on the back of the end pupil will send a strong pulse down the line. When the pupils have picked themselves up, discuss the difference between that pulse and all the others so far. The 'particles' did not, in that case, return to their original places. This occurs in any medium with waves which strain the medium beyond its elastic limit.

Repeat the experiment with a gentle push while the pupils cooperate to carry a longitudinal wave without disaster.

Energy. Point out the transmission of energy in the wave.

This introduction to waves should be given just enough time to suggest the idea of a pattern-of-disturbance that travels. The teaching should proceed to the ripple tank practically at once. There is no need for a definition or a formula—pupils' experimenting will provide all they need. And we should not explain, yet, that waves carry momentum and energy. (For that matter, some waves do not transport any energy.)

The ripple tank will show the patterns of waves as the pupil looks down on a water surface. Before pupils embark on that as an open class experiment, show them water waves *in section* in a long tank.

{When waves travel on the surface of deep water, individual particles near the surface move in a vertical circle, and particles deeper down move in ellipses. One might be able to observe this by watching the motion of sawdust in water in a wave tank; but for most observers the motion is too fast.}

We can make much slower waves in the interface between two liquids if we fill the tank one-third full of water and one-third full of paraffin—preferably coloured paraffin. When the liquids have settled with a clear smooth interface between them, generate waves by moving a block of wood up and down near one end. Cleaning the tank after this oil-and-water experiment is troublesome; but this shows slow waves clearly, and teachers who have tried it consider it worth the trouble.

Demonstration 3c Watching Water Waves, in Section

Apparatus

1 large rectangular transparent tank with wooden block or paddle — item 100/2

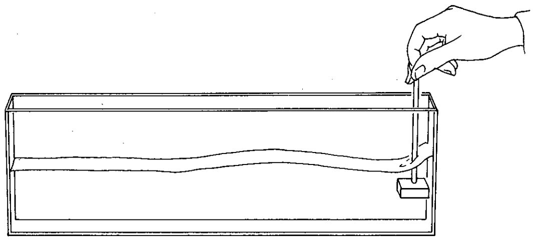
The tank, of glass or perspex, need not be wide from front to back—7 cm will suffice. It should be at least 15 cm high and as long as possible—30 cm is probably too short, 1 metre would be good but expensive. A very long tank is preferable to a short one, because the initial outgoing waves will be seen without the complication of the waves reflected from the far end.

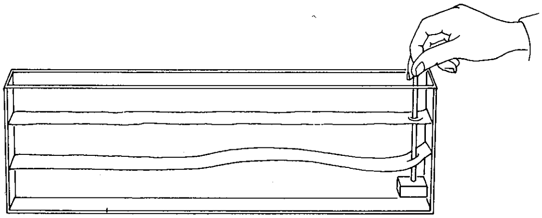
Procedure

a. Fill the tank half-full with water and place it so that the pupils can see the water line face-on and any waves passing along it.

Generate waves at one end by moving a hand or a block of wood up and down in the water—or, better, by sweeping with a wooden paddle. Pupils watch.

If some sawdust is mixed in the water, those watching at very close range may see the path of





individual particles in the medium when the water waves travel along. However, that motion is too fast to see easily and method *(b)* is advocated.

b. Fill the tank one-third full of water. Add paraffin (preferably coloured) above that until the tank is two-thirds full. Generate transverse waves *at the interface*, keeping the block or paddle immersed.

RIPPLE TANKS

'It's your experiment.' We suggest water ripples as a topic for pupils' own experimenting which will yield a sense of skill and interesting knowledge.

Class Expt 4 Ripple Tank (A Series of Experiments)

Pupils start with open experimenting, then pursue a series of suggested experiments on their own without needing cookery-book instructions.

AIM. We hope for delight, and pride in growing skill—outcomes which can have long-term value with good chances of general transfer, however insensitive they may be to attempts at short-term assessment. Thus, the essence of our suggested aim is that *pupils enjoy doing their own experimenting*.

These ripple tank experiments would be unimportant and unfruitful—better omitted—if done with detailed instructions and expected to yield definite results such as a clear law of reflection. At this stage, no definite results need be sought, except enjoyment and pride.

To promote the latter, we urge teachers to give the ripple tank plenty of time, *to let them spread over 4 weeks*. Compressed into two weeks they will be drill and will lose their value. Spread over 5 weeks or more they will be spoiled by boredom.

We hope that teachers will not regard these experiments as direct preparation now for examinations far ahead. In Year 5 pupils will need a little acquaintance with refraction of waves and diffraction, and simple knowledge of interference. But it would be a great mistake to treat the present ripple-tank work as aimed at those sophisticated outcomes. Able pupils will have time to enjoy looking at those phenomena now but any knowledge needed for examinations can be provided far better by a short revision with ripple tanks in Year 5.

Providing instructions for pupils: 'sailing orders' Our essential aim, almost the sole aim now, is for pupils to enjoy their own experimenting. For that, they need simple general instructions—*where to look, but not what to look for*.

We suggest these should be like the 'sailing orders' to a ship's Captain, that tell him the general plan of his voyage but do not insult him by giving details of victualling or instructions for navigating through a storm. The 'sailing orders' we offer in *Pupils' Text 3* represent the maximum we suggest should be given without spoiling the spirit of the investigation.

Running the ripple-tank series Running these experiments may well be easier for teachers who have never used a demonstration ripple tank. Those who have used carefully constructed tanks for advanced teaching remember them as providing an important demonstration which requires careful adjustment beforehand but can then be done quickly.

The ripple tanks that we suggest for this programme are larger and simpler and *intended for a different use.* A simple ripple tank offers each pupil a chance to find out a lot about a natural phenomenon—wave behaviour—by his own experimenting.

{Young pupils experimenting take a long time to 'get going'; and when they are experimenting in a new strange field—as this is, for them—they take still longer. To a teacher experienced in using demonstration ripple tanks with older pupils, the delay and the lack of definite results will seem worrying and disappointing the first time he tries this with a class of young pupils. This is the time for patience, verging on an attitude of mute agnosticism coupled with encouraging hope.}

{One can prepare oneself for that by playing with the simple ripple tank oneself, trying out everything one can think of, some time before using it in class.}

{As with other class experiments in our programme, this is a case where one cannot judge the full value of the experiment, or the time it needs and deserves, until the second round—teaching again to a new class a year later. When one has tried it one year and found out how long it takes and seen the experimenters' delight and growth of knowledge, it becomes easier to run the next year. One will be ready to be patient with questions and to praise the results—and emphasize some results that will be useful later.}

{Those who have used this apparatus assure us that if pupils are given plenty of time and encouraged to experiment informally—the teacher giving neither detailed instructions nor suggestions of what to look for—the yield is rich.}

A strong plea At some stage when pupils are working with ripple tanks, many a teacher feels disappointed with the resulting knowledge of wave behaviour that pupils extract. He longs to give the pupils clear conclusions; and we hope he will not do so, because this is principally an experiment in which pupils learn about experimenting and gain a picture of good scientific work by doing the experiments on their own.

Films There is a still more serious temptation: to show films of ripple-tank experiments which reveal perfect behaviour and suggest the results that the pupils should have obtained. That would indeed be disastrous treatment for young people who thought they were doing their own experiments as 'scientists for the day'.

So, although extremely good films of ripple-tank phenomena can be obtained, we urge teachers *not* to show them either during the series of ripple-tank experiments or at the end. With some groups, it may be advisable to use one or two films for revision in Year 5, if teachers find that ripple-tank experiments have left too scrappy memories. Even then it would be better to get out the real tanks.

Arrangements for class experiments Any number of pupils could watch one tank as a demonstration; but here we want pupils to work with their own ripple tank, make their own waves, and watch what happens. So, the teacher should not even have a demonstration copy of the tank to start the experiment except for a very weak group. He should keep his own ripple tank behind the scenes—unless he only shows how to fill and empty the tank. Just observing ripples made by someone else is not as good as having one's own apparatus and observing one's own ripples. Therefore, there should be one ripple tank for every three pupils or *at most* four.

Our ripple-tank experiments form a long series, with many of the later ones needing only a few minutes. We hope pupils will proceed through these at their own pace—without making notes at this stage but just watching and learning.

Pupils will run through these experiments at different speeds and a fast pupil in a class may get far ahead of others. Therefore we suggest some experiments should be treated as 'buffer options' for faster pupils.

Sometimes an option will appeal to other pupils with special interests; and unless it involves major changes of apparatus, any who wish to try it should be free to do so—as long as they do not fall far behind the rest.

In any case, a slower pupil who has not reached the end of the series when the rest of the class are ready to proceed to other experiments will not suffer greatly: he will have gained a good share. Remember that the object of these experiments is not so much to provide a store of knowledge of wave behaviour, as to give pupils experience of working on their own at their own experiments, making their own mistakes, choosing and enjoying their own observations.

Ripple Tanks: Description of Equipment

TANKS. The tank should be large so that pupils can do their own experimenting easily. Four pupils to a tank may be necessary on account of laboratory space, but four should be a maximum. The tank should be transparent—observing by oblique reflection from an opaque tank is much more difficult.

SUPPORTS. The tank needs strong legs firmly attached. It should not be supported on tables. Vibrations due to weak supports or carried up from the floor spoil the ripples being studied.

LAMPS AND VIEWING. A small lamp with bright filament *above* the tank shows the ripples as 'shadows' on the floor. (A pattern thrown on the ceiling is *much* less comfortable for observers.)

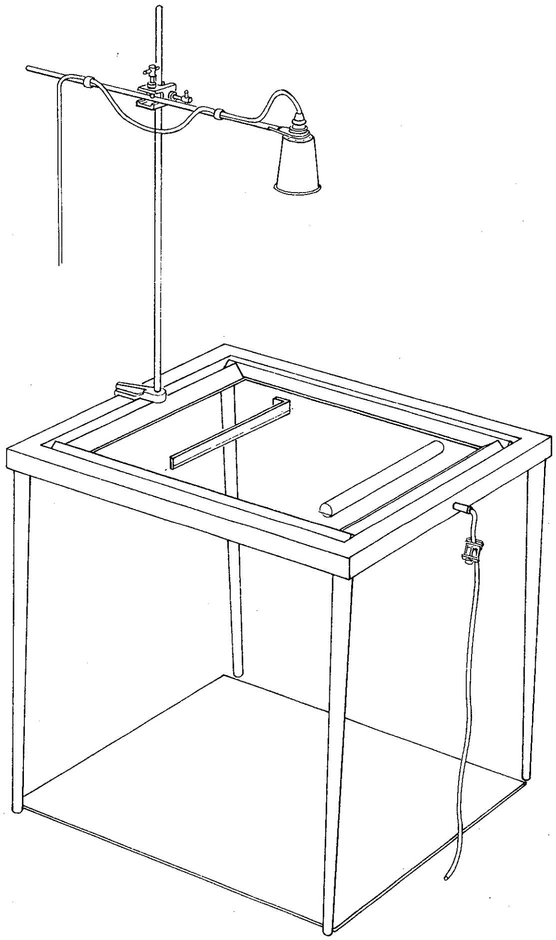
Pupils watch the shadows on a large piece of white paper on the floor under the tank to show the ripples. (A piece of hardboard painted white is just as good.)

The height of the lamp should be adjusted to give the best picture. It should be about 50 cm above the tank.

Pupils should *not* view the paper *through the water*—the pattern on the water and the pattern on the paper may combine to produce moiré fringe effects.

BEACHES. Vertical edges of the tank will produce unwanted reflected waves. Reflections can be eliminated by a gently sloping beach at the edge—the ripples run up the beach and die—but that adds cost, weight, and size. A good substitute is a 'sea wall' of gauze or other absorbing material.

MOTOR VIBRATOR. When continuous waves are wanted, pupils install a wooden beam hung above the water by springs or rubber bands. The beam carries a small electric motor. The motor's shaft has an eccentric load, so motor and beam vibrate.



ELECTRIC SUPPLIES. Some manufacturers supply special power units which provide the necessary voltage for the lamps and a variable voltage to drive the motors. Some teachers prefer those; others use a transformer for the lamp and a dry cell and rheostat for the motor.

Ripple Tanks: General Instructions

In all the series of experiments the tanks require firm supports, supply for the lamp, beaches, paper for the shadow, beaker of clean water, sponge and bucket for emptying.

ROOM. If possible darken the room. If not, it is best to use 36-watt lamps.

WATER. The water needs to be clean. Grease or dirt makes the ripples damp out quickly.

Pupils should fill each tank to a depth of 5 mm of water (about 1000 cm^3). With depths below 3 mm (about 800 cm^3 of water in most tanks) there is no trouble from reflections, but the ripples damp out in a small distance. With depths above 6 mm (1300 cm^3) reflections from the edge of the tank can be troublesome; and the absorbing beaches produce multiple weak reflections, which may be more troublesome than a slightly stronger clear reflection produced without beaches.

LEVELLING. Level the tanks quickly by matching the two reflections of the lamp, one from the glass the other from the water surface.

EMPTYING THE TANK. A quick way is to put a rubber tube on the outlet and tilt the tank so that the exit pipe is under water. Some teachers prefer to let pupils use large sponges.

DRILL. There is one aspect of the work in which some drill is valuable and welcome: taking equipment from and to storage. All the experiments in this series use the same simple ripple tank. Pupils should soon be able to get out their tank and get it going quickly; and of course they must be ready to put it away (and mop up water that has spilled) at the end of the period. Particularly if the lab is used for single periods, getting tanks out and clearing up afterwards can take a large fraction of the period. Teachers report successful economy and speed where pupils have themselves organized this work—and that cooperation in the 'housekeeping' aspect of practical work may form a very valuable part of a pupil's experience in physics.

AUXILIARY EQUIPMENT. When first introducing the ripple tanks, do not provide all the accessories for later experiments as well. The reflecting walls and motors, for example, will divert attention and may spoil the important introductory stage of pupils becoming familiar with the tank.

CAFETERIA. Here, as in other class experiments which have a series of many parts, a cafeteria of auxiliary equipment at one side of the lab will enable pupils to fetch what they need. This is particularly valuable where pupils are expected to progress through a series each at his own pace. With the ripple tank, and with the ray streaks, and with the long electromagnetism series, a cafeteria will help a lot if it can be arranged. Although it may seem at first less efficient it will ultimately save trouble and give good training in working in a lab.

The cafeteria should have *necessary* equipment. There are other items of equipment that teachers find ingenious pupils asking for when they devise an extra experiment of their own. Those should *not* be on display in the cafeteria—it is worth the trouble of fetching them to praise the bright idea.

Open beginning Begin by asking pupils to try anything they like with water ripples in the tank. Show them how to set up the tank with legs firmly attached so that there are few vibrations to disturb the water. And show how to arrange the lamp to throw a 'picture' of the tank on the floor. Tell pupils to fill the tank with water to a depth of $\frac{1}{2}$ centimetre. To get the investigation going quickly, provide a large tin can or other 'dipper' which holds the right amount of water. Then give 15 to 30 minutes for open play—however discouraging it may look.

Class Expt 4a Exploring the Behaviour of Ripples— First Acquaintance with a Ripple Tank

Apparatus

8 ripple tanks	item 90
8 lamps	47
8 transformers	27
8 buckets	533
8 deep beakers (1000 cm^3)	513
8 sponges	90R

Pupils work in groups of 3 or 4. Laboratory space will limit the number of ripple tanks; but if there are more than 4 pupils to a tank (or if a single tank is used as a demonstration) our aim for these experiments—to let pupils have personal experience of experimenting—will be lost, and we suggest the series should be omitted.

Preparation

To avoid *unwanted vibrations* make sure the tanks stand firmly on the floor. Stray vibrations ruin the experiments.

Procedure

Pupils put water in the tank to a depth of about $\frac{1}{2}$ cm.

Ask them to watch the ripples they can make with their fingers.

Explain that the 'tartan plaid' patterns produced by jarring the tank are too complicated to yield much scientific knowledge, however pretty they are. Urge pupils to avoid spoiling their work of discovery by making those patterns.

Circular pulses and straight pulses After enough play for pupils to develop a sense of ownership—that the tank is their own apparatus for their own experiments—suggest making circular ripples carefully. And suggest making straight wave-front pulses by rocking a rod. While pupils are experimenting it may be good to ask some questions:

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

Note that in asking questions—an activity that may help discipline in the half-dark room—we are not breaking our resolve to avoid detailed instructions. We are merely encouraging pupils to think and extend their observations. (If pupils answer the last question by suggesting lycopodium spores, praise them for remembering that 'waterproof powder' from another use in Year 1.)

Class Expt 4b Circular Pulses

Apparatus

8 ripple tanks	item 90
8 water droppers	90H
8 pencils	

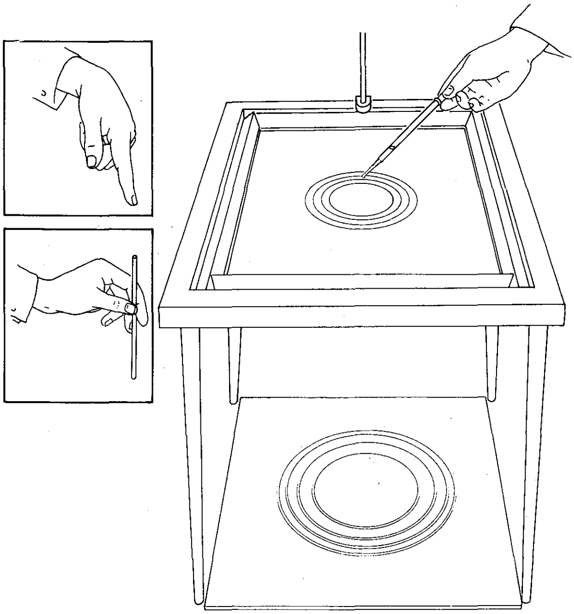
The usual accessories will be required: legs, beaches, lamps, supports for lamps, transformers, deep beakers, buckets, sponges.

Procedure

After some general play (Expt 4a), suggest starting a single ripple somewhere in the middle of the tank and then making several such ripples one after the other. Pupils try:
(i) a finger,
(ii) a pencil to touch the water,
(iii) a drop of water from an eye-dropper.

After that, pupils use whichever they prefer. The method chosen as best seems to differ from one class group to another, depending perhaps on the teacher's own experience with the apparatus as well as that of the pupils.

Ask if the water moves along with the wave pattern, and leave pupils to suggest their own tests.

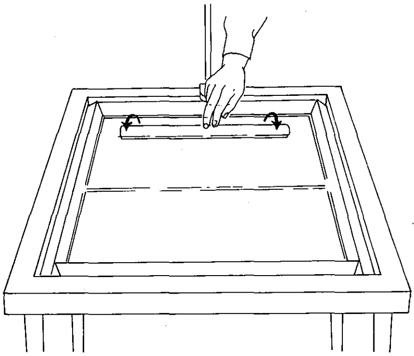


NOTE. If, from our experience of teaching this in an earlier year, we arrange testing materials ready at hand, we are likely to fail in our aim of encouraging pupils to experiment and think on their own. Any materials that pupils suggest for such a test can be fetched quickly; and if they suggest none, the problem is best left unsettled.

Class Expt 4c Straight Pulses

Apparatus

8 ripple tanks — item 90
and the usual accessories
8 wooden rods — 90J



Procedure

Pupils make straight pulses by giving the rod a sharp *roll* forwards and back.

They produce continuous waves by repeating this motion.

Some pupils prefer to *dip* an ordinary ruler.

The crests look rather wide near the rod but become sharper as they move away. They are sharpest when the filament of the lamp is parallel to them.

An unbroken series By now, pupils should see that they have started on a series of experiments; and they should expect to continue at their own pace without interruption. *Pupils' Text 3* gives them a guiding programme.

Where comments interrupt the sequence in this Guide, they are only short notes to teachers: they are not meant to separate one ripple-tank experiment from the next.

Idea of rays as guide-lines It will provide a helpful link with optics if at some stage we suggest the idea of 'rays' as lines that show the directions in which waves travel. That should not interrupt the experimenting; but it can be started by the questions in *Pupils' Text 3*.

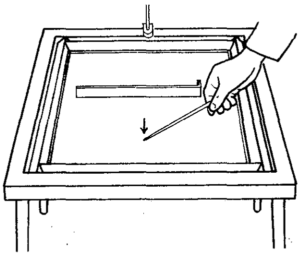
{Both teachers and pupils may feel that rays are an unnecessary concept in dealing with ripples and ripple tanks; but we urge teachers to start sketching rays at an early stage, when pupils are looking at the ways in which ripples (wave fronts) travel. In our optical teaching, we shall make much use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

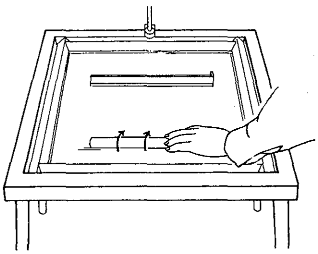
Reflection of ripples Offer reflecting walls —a straight bar of wood and a rubber tube that pupils can bend to a parabola—but do not suggest a law of reflection or the idea of looking for one.

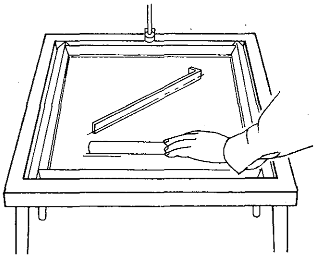
Class Expt 4d A Pulse meets a Wall—Reflection

Apparatus

8 ripple tanks — item 90
and the usual accessories
8 wooden rods — 90J
8 water droppers — 90H
8 straight barriers — 90D







Procedure

Pupils watch what happens when a ripple (pulse) hits a wall. They try that with:
(i) a circular pulse,
(ii) a straight pulse hitting the wall 'head on' (i.e. normally),
(iii) a straight pulse approaching the wall in a slanting direction (i.e. incident at other angles).

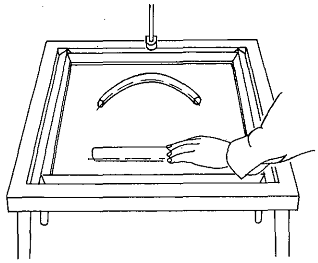
Help pupils to avoid choosing an angle of incidence of 45° because that makes it harder for beginners to see the angle relationship. They should try both a much smaller angle of incidence than 45° and a much bigger one.

This is still a stage of making acquaintance with ripples. Pupils just watch. (See Expt 4g for a definite question.) We trust teachers will not suggest looking for angle relationships—such a result is not something pupils feel is needed yet. And we trust teachers will not dictate, or ask pupils to make notes of, any such relationship.

Class Expt 4e Wall reflects Ripples

Apparatus

8 ripple tanks and the usual accessories	item 90
8 water droppers	90H
8 wooden rods	90J
8 lengths heavy rubber tube (for parabolas)	90T*
8 lengths heavy copper wire (to load the rubber tubes)	90U*



Preparation

Each group of four pupils will need a parabolic wall. Slip a length of heavy copper wire into a length of rubber tube. If the copper wire is irregular from previous use, straighten it out by see-sawing it over a door-knob or similar rod. Leave pupils to bend it to shape.

Procedure

As in Expt 4d, pupils try reflecting a pulse, this time with a curved barrier of rubber tube bent into a parabola.†

Pupils will find a parabola to copy sketched in *Pupils' Text 3*.

No formal results are expected at this stage, but rather the pleasure of unexpected and perhaps powerful effects. The teacher should not suggest, or try to achieve, 'focus' properties.

If some pupils find out more things than others, well and good. This is meant to be their own experimenting.

Ripple tank with vibrator: continuous waves Show pupils how to connect up the vibrator that acts as a continuous-wave generator, both for circular waves and for straight-line waves. After that comes a time to leave pupils to play with the tank and find out things for themselves.

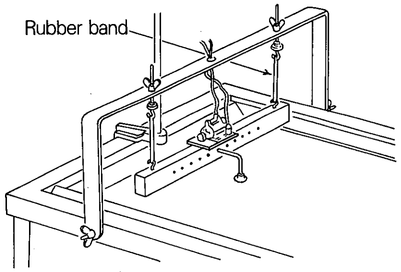
* Some pupils know what a parabola looks like. Those who do not should throw a ball in the air and watch its path.
† New Nuffield items.

Class Expt 4f A Train of Waves: Vibrator to Generate Continuous Waves

Apparatus

8 ripple tanks and the usual accessories	item 90
8 motors mounted on beams	90L
16 rubber bands	90K
8 sets of leads to motor	90I
8 dippers	90G
16 dry cells (1.5 V each)	52B
8 rheostats	541/1

The motor works well from a 1.5-volt cell in series with a 12-ohm rheostat (item 541). Two cells may be needed for the higher speeds but the motor then goes rather fast with the rheostat set at minimum resistance. (Circuit boards from Year 2 might be used to hold the cells.) The polarity of the battery determines the direction of rotation, but that is immaterial. (If a battery with a higher e.m.f. is used, a rheostat with a higher resistance will be required.)



Procedure

Pupils follow these instructions:

* * * * *

(1) *Circular waves.* Hang the wooden beam with the motor attached by two rubber bands of such length that the beam is above the water.

Attach a small spherical dipper to the beam by its L-shaped rod. Adjust the height so that the bottom of the sphere just touches the surface of the water. Watch the waves.

(2) *Straight waves.* Remove the dipper and lower the wooden beam. Keep the motor attached and the beam hanging by the two rubber bands. Fix the beam at a height where it just touches the surface of the water when it is at rest. Then set it vibrating and look for straight waves.

* * * * *

Notes

(i) In (1), if the beam dips too deep in the water (or sits on the glass!) the ripples do not travel far. If the beam is too high and the vibration is vigorous, the ripples are less distinct near the vibrator.

(ii) The filament of the lamp should be parallel to the ripples.

(iii) If the beam does not vibrate enough, increase the eccentric loading on the shaft of the motor.

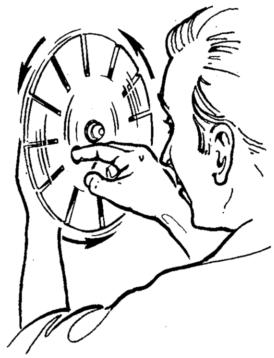
High frequency ripples At low frequencies, it is easy to see the waves; but at higher frequencies the persistence of vision obscures them. Blinking makes them visible. This is the time for a stroboscope.

The Hand Stroboscope

Pupils will find that *continuous* ripples are much easier to see when they use a stroboscope—'strobe disk' for short, in our teaching.

The idea of stroboscopic viewing, or illumination, is unfamiliar but soon learnt with delight if each pupil experiments with his own strobe disk. Its success in 'freezing' periodic waves is startling and satisfying.

{Because the device is unfamiliar, we describe it below in detail and offer suggestions for introductory teaching. But our emphasis in giving details should not be taken to suggest the teaching



should emphasize stroboscopes. They are only useful gadgets which will make learning easy and quick. Teachers are urged to make use of them but not to let them bulk large or present difficulties to slower groups. Fast groups may need little of the introductory practice.}

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

Stroboscopes: Description of Equipment

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

A crude form can be made from a piece of cardboard. A better one consists of a hardboard disk 20 to 30 cm in diameter, with a dozen equally spaced slits cut in from its circumference. A piece of thick wood dowel serves as handle, and the disk is attached to it by a wood screw which acts as an axle, with safeguarding washers.

A hole in the disk a few centimetres out from the centre enables the operator to spin the disk with a finger.

A massive disk is better than a light one because it spins more regularly. (But a disk to be run on a small electric motor should be a light cardboard one.)

For most purposes all 12 slits are needed. When fewer slits are needed some can be obscured by sticking black masking tape over them.

The operator holds the disk in front of his face and spins it by hand and views the vibrating (or spinning) object through the slits. To observe events with a very low frequency, the operator covers up all but one of the slits. Then he sees the thing he is looking at only once in a revolution.

MOTOR-DRIVEN STROBOSCOPE. For demonstrations a strobe disk is driven by a small synchronous a.c. motor (240 V, 300 r.p.m.). Though this has many uses in Year 4, its only use in Year 3 is for the Pulsed Water Drops Demonstration. We should be very sorry if Year 3 pupils missed that; so we trust schools will buy the motor—or the more expensive strobe lamp which serves just as well.

TEST OBJECT: THE SPINNING ARROW. A black disk driven by the fractional horsepower motor has a radial white arrow painted on it. The motor is driven by the L.T. variable voltage supply and pupils practice 'freezing' the arrow with their strobe discs.

PRACTICE. At first, a pupil finds considerable difficulty in understanding how to interpret what he sees when there is more than one slit. So we shall suggest some simple drill, first with a single slit and then with two slits 180° apart, until pupils see that if they 'freeze' a motion with a two-slit disk, the frequency of the motion is twice the rotational frequency of the disk.

Class Expt 5 Introduction to Stroboscopes

AIM. To introduce pupils to an interesting instrument and give them easy practice in using it.

Apparatus

32 hand stroboscopes	item 105/1
masking tape	105/2
1 fractional horse-power motor	150
1 spinning arrow disk for FHP motor	151
1 L.T. variable voltage supply	59
1 compact light source	21
1 large converging lens	93B
1 lens holder	124/2
1 retort stand and boss	503–505

It is very important to have one hand stroboscope per pupil.

The hand stroboscope enables the user to 'freeze' repetitive motions—or to slow them down for study. Here we suggest some preliminary teaching aids. We do *not* suggest the class should make an extensive study of it. Some classes seem to understand strobes at once. Others need a short introduction.

Most teachers advise proceeding to observe ripples almost at once.

Procedure

a. Simple Demonstration to Explain the Principle. Swing one arm slowly round in a large vertical circle.

(i) Ask pupils to close their eyes and to open them briefly each time at the word 'now'. Give

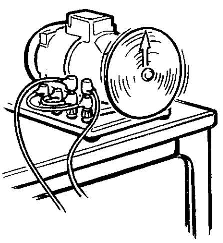
the signal 'now' once each revolution. Pupils see that arm each time in the same position.

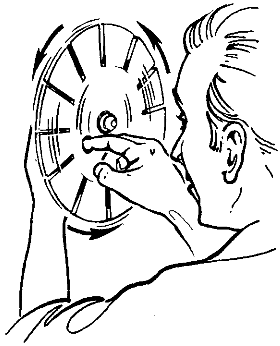
(ii) Say 'now' once every *two* revolutions. Pupils see the same thing but less often.

(iii) Say 'now' once every half-revolution. Pupils see that arm in two positions.

If this does not go well, it is *not* worth while to drill pupils in opening their eyes. The main point is to show the principle of the stroboscope and that should soon be clear.

b. Spinning Arrow. Pupils use their hand stroboscopes to look at a black disk painted with a white arrow driven by the motor. The pupils get 12 glimpses for each revolution of the arrow. Black tape may be used to cut down to fewer slits, but with this experiment it is simplest to use all 12 and adjust the speed of the motor.



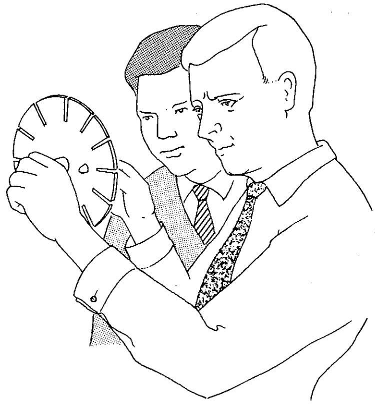


With the motor spinning the arrow at 25 to 30 revolutions per second it is easy for pupils to 'freeze' the motion and see a single white arrow, though the arrow may wander. At the 'correct' speed the number of slits passing the eye per second is equal to the number of revolutions per second of the arrow's motor.

The hand strobe is less likely to judder if the central screw is not too tight and the handle is held loosely.

Extra Help

To give help to those who cannot see the motion frozen, the teacher should work the stroboscope and look through one side of it, while the pupil looks through the other side.



Of course the frequency of the motion the pupil is observing might be a multiple of that; and he has to decide that question by speeding up his stroboscope to higher and higher speeds to find if he can again freeze the motion—if he cannot he was looking at the direct frequency.

HINTS. *(i)* The word 'glimpse' is a useful one.

(ii) If pupils need to count several revolutions of the strobe disk and find those occur too quickly, or find it difficult to pay attention to them, a small flag of card stuck to the edge of the disk and arranged to hit another card once every revolution makes clicks that are easy to count.

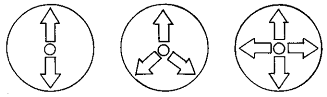
Extensions

c. Other speeds (OPTIONAL). The following demonstrations may occasionally be useful as diagnostic aids in teaching. They show how easy it is to rotate the stroboscope at the 'wrong' speed when measurements are being attempted. We should not tell pupils about these, unless it seems necessary and helpful.

To show the effect of turning the hand strobe at half-speed—also at twice and three times the correct speed—it is necessary to change the motor's speed because the strobe disks are difficult to turn at very high or very low speed. Furthermore, at low speeds the white arrow spreads out and looks indistinct, particularly near its outer end, which is travelling fast.

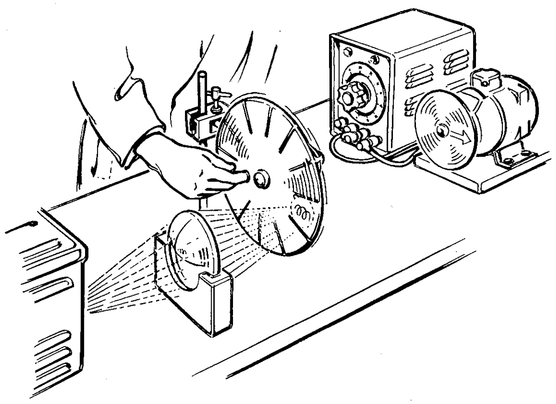
(i) SLOW MOTOR. With the motor running at 15 rev/sec (900 r.p.m.) it is difficult to turn the 12-slit strobe disk slowly enough to see a single stationary arrow. But if the stroboscope is speeded up until it is twice as fast, three times as fast, and

even four times as fast, stationary patterns are seen, as shown in the diagram.



(*ii*) FAST MOTOR. With the motor running at 50 rev/sec, it is possible to see the pattern stationary by turning the stroboscope at the correct speed or half that, or one-third. It is not possible to prove that the highest successful speed *is* the correct speed, because it is too difficult to spin the stroboscope fast enough to get the 'twice-as-fast' pattern.

d. Chopped light demonstration (OPTIONAL) Set up a hand stroboscope (or, better, the motor-driven strobe disk) in a clamp. Darken the room and use the compact light source to illuminate the spinning arrow. Place a converging lens to form a real image of the lamp's filament *on a slit of the strobe disk.** Then drive the strobe disk so that it provides a regular stream of flashes, while pupils look at the spinning arrow.



This shows that roughly the same effect is obtained as when the strobe disk is in front of the eye.

This method will be useful later, where several pupils need to see the same arrested motion. Then a *motor-driven strobe disk* will be used to freeze a repetitive motion.

e. Neon lamp on a.c. mains (OPTIONAL). Pupils look at the lamp through their stroboscopes. A large neon lamp is best for this. It is well to do this in half daylight so that the bulb is visible even when the neon glow is not.

Chopped light. Thus, a neon lamp may be used as a source of chopped light to illuminate a spinning object. However, it is faint.

Various stationary patterns may be seen as the arrow's motor is speeded up, though the arrow seems to broaden, because it moves farther during each flash. The single pattern is reached with the motor running at 100 rev/sec. If the motor is running at a lower speed, we get the effects of a stroboscope going too fast, which were seen in (*c*) above.

f. Further suggestions for discussion and experiments (OPTIONAL).

(*i*) Mention wagon wheels on the cinema screen.

(*ii*) Pupils may look at the cinema screen itself through a stroboscope. They will be able to black out some or all of the picture.

(*iii*) Pupils look at fluorescent lighting or street lighting through a stroboscope and see the fluctuating nature of the light, though it is not possible to turn a 12-slit stroboscope fast enough by hand. A 24-slit disk is satisfactory: so is a motor-driven stroboscope with fewer slits.

(*iv*) Stroboscope disks for testing the speeds of record-player turntables spin very slowly and therefore have a large number of radial white bars. Each bar moves on one place for each flash of the mains lighting (100 flashes/sec).

(*v*) An electric fan with several blades can be 'stopped' with several speeds of the stroboscope. If one blade is painted white it will be seen that some of those speeds do not give the actual speed of the fan.

(*vi*) Pupils may look at the back wheel of an inverted bicycle through the stroboscope. When the wheel is spinning many speeds of the stroboscope will appear to stop it if the spokes look alike.

* The proper optical arrangement includes a lens as in the sketch. However, a simpler arrangement without a lens works fairly well, though it does not give such a sharp picture. Simply place the strobe disk just in front of the lamp.

Return to ripples soon After pupils have practised for a short time with stroboscopes they should try looking at ripples with them. It is wise to return to ripples as quickly as possible, so that pupils do not lose their interest. Some pupils will understand stroboscopes much more easily when they find their relevance to the ripple business upon which they have embarked.

Class Expt 4g 'Freezing' the Wave Pattern with a Stroboscope

Apparatus

8 ripple tanks	item 90
8 motors mounted on beams	90L
32 hand stroboscopes	105/1

Procedure

Pupils try viewing *continuous* circular ripples and *continuous* straight-line ripples. They will need some time to explore possibilities and to develop skill in 'freezing' the motion.

Measurements? At a later class, after pupils have learnt to 'freeze' ripples with a hand stroboscope, and after they have had time to think about the question 'What measurements could you make?', suggest measuring wavelengths (if that has not already been proposed by pupils). Suggest they should 'freeze' the pattern on the floor and measure the crest–crest distance in that shadow.

Make it clear that the idea is to get a rough estimate rather quickly, and not to try to achieve great precision with a technique which cannot really support it.

Class Expt 4h Measuring Wavelength of Ripples with a Stroboscope *(OPTIONAL NOW, but needed in Year 5.)*

Apparatus

8 ripple tanks	item 90
8 motors mounted on beams	90L
32 hand stroboscopes	105/1
8 metre rules	501
white paper	

Procedure

Pupils try 'freezing' circular ripples (for practice), then straight-line ripples (for measurement). They measure a batch of 'shadow' wavelengths (say ten) on the paper on the floor.

Then they should charge their motor to a different frequency and see whether the wavelength is the same. (NOTE. Since the speed of water ripples is a function of their wavelength, we might not expect the simple relationship between frequency and wavelength that we find for sound waves or waves on a rope or light waves in vacuum. However, with continuous ripples in our ripple tanks the wave-speed happens to be near its minimum so it is almost constant over the range of frequencies of the motor.)

Optional extension. If some groups of pupils work fast and get ahead of the rest, they might try this measurement again with much shallower water. For that, give them a sheet of glass to be placed in the tank so that the water above the glass is very shallow. That will anticipate Expt 4t on refraction. Make sure the waves meet shallow water head-on (normally). The change of direction will not appear, but some pupils may notice changes of wavelength and speed without any change of frequency.

The ripple tank as a computer to answer questions Give pupils some questions about waves, to be answered partly from their present knowledge of ripples, mainly by trying experiments in their tank. These questions are stated at the heads of the following experiments and are given to pupils in the *Pupils' Text 3*.

Class Expt 4i Where from? A Question about Reflection of a Pulse by a Wall

Apparatus

8 ripple tanks	item 90
8 water droppers	90H
8 straight barriers	90D

Some pupils prefer to use pencils dipped in the surface instead of the water droppers. A finger is probably best of all.

Procedure

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

We trust teachers will *not* give the answer to that, and will not, at this stage, give any discussion of images. Ask pupils to look for an answer in their ripple tanks.

The barrier should be placed near the middle of the tank and the ripple should start near the barrier so that the image from which the reflected ripple seems to come is well inside the tank.

When pupils have seen this for themselves, suggest a further experiment:

* * * * *

Now that you know where the ripple that bounces back seems to come from, try starting a ripple *at that place.*

Use a finger of your left hand. Let the ripple spread and hit the wall and bounce back. Use a finger of your right hand to mark *the place where the bounced-back ripple seems to come from.* Then start a ripple from *that* place with that finger.

Start ripples with both those fingers at the same moment. Your left hand will start the main ripple and your right hand will start a ripple like the one that bounces back. Watch what happens.

* * * * *

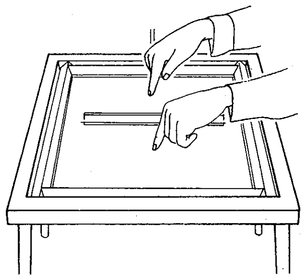
When that succeeds, it is amusing and almost uncanny. We should not spoil the fun by doing it for pupils, *even* though a teacher can probably make the simultaneous ripples—the incident ripple and the image ripple—much more easily, since he knows what he is trying to do.

However, the teacher should help pupils who are unsuccessful by encouraging them to put the second finger at the right place—without using the word 'image' or giving the geometry. Just judge the right distance by eye and point to the right place. Then the pupil can try again and see success and enjoy it. He *may* notice the geometry; but it will not matter if he does not notice it.

AIMS. The main aims here are:
(i) to let pupils do an experiment to answer a question,
(ii) to emphasize the general idea of a 'place from which the reflected wave seems to come'.

If a pupil finds it difficult to mark the position of 'the place the reflected ripple comes from' (the image) let him put a small coin in the tank at that spot.

NOTE. It is best for a pupil to use one finger of each hand for this—for the sake of good teaching rather than for the sake of precision. Teachers might be tempted to devise an ingenious gadget that will start two ripples simultaneously from exactly the right position, but that is *not* what should be offered here. This should still be a stage for simple, direct experimenting.



Class Expt 4j A Question about Reflection of a Straight Wave by a Wall

Apparatus

8 ripple tanks	item 90
8 wooden rods	90J
8 straight barriers	90D

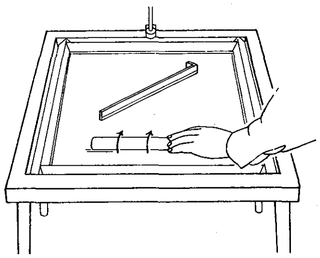
Procedure

Question: 'Can you find a simple story about the *direction* of straight waves before and after meeting a flat wall? How are the angles related?'

At this stage, we do not talk about laws of reflection or ask for measurements of angles or urge pupils to remember what they saw before. We ask them to look for an informal answer in their ripple tank.

Pupils make a straight-line pulse and watch what happens when it hits a straight reflecting barrier. (It is easier to disentangle the story when there is a single pulse like this than when there is a train of waves.)

Pupils first try directing a pulse head-on (normally) to the barrier and then at various



other angles. Help them to avoid 45°, because that is apt to confuse the geometrical interpretation. They should try a larger angle of incidence than 45° and a smaller one.

Most pupils will bring out some answer about angles.

It does not matter whether the angles are angles between wave-front and mirror or wave-front and the normal. Dragging in a reference to the normal in these simple studies of reflection is no help at all. Even with a curved reflector, young people can imagine a *tangent* to the surface at least as easily as they imagine a *normal*! All we hope for here is some idea of 'equal angles'.

Class Expt 4k Parabola: A Question about Reflection

Apparatus

8 ripple tanks	item 90
8 water droppers	90H
8 wooden rods	90J
8 lengths heavy rubber tube (for parabolas)	90T*
8 lengths heavy copper wire (to load rubber tubes)	90U*

As before (Expt 4e) the heavy copper wires should be straightened and slid into the heavy rubber tubes. Pupils have a suitable parabola sketched in *Pupils' Text 3*.

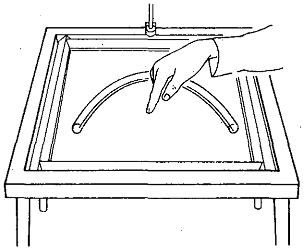
Procedure

Question: 'You saw what happens to straight-line waves when they hit a parabolic reflecting wall. Can you now turn that story backwards and make straight-line waves come *out* from the wall?'

In Expt 4e, pupils will have tried reflecting a straight-line pulse with a (roughly) parabolic reflector. They probably found the wave concentrated after reflection into a circular ripple which closed down to a small size and then spread out again. Whether they did or not, they can start by trying that now. Then they try to answer the question by their own experimenting.

The pupils' problem is to guess what would happen in reverse, and to try that experimentally. This is an exercise in thinking as a physicist; so we should be very careful not to reduce it to an exercise in carrying out instructions. All we should do is ask about the reverse effect.

(After pupils have seen the straight-line ripple reflected into a circular ripple that moves to a point, they have a hint, from their own experiment. That is why Expt 4e was done with straightline ripples and this question is now framed this way round.)



* New Nuffield items

Class Expt 4l Puzzle: What does a Circular Wall do to a Pulse?

Apparatus

8 ripple tanks	item 90
8 water droppers	90H
8 wooden rods	90J
8 circular barriers ($\frac{1}{3}$ of a whole circle, or more)	90F

Procedure

After pupils have tried experiments with a pulse being reflected by a flat wall and a parabolic wall, offer each group a *circular* reflector and ask them to try any experiments they like with it.

The point of deferring this simpler curved reflector until now is to offer a clear simple case to finish up with, a consolation prize that pupils can make something of without any leading instructions.

Note about Policy

We should *not* tell pupils to start a circular pulse from the centre of the reflector but many will do that of their own accord. We should *not* tell them to find the place where straight-line ripples are brought to a point after reflection; and we certainly should *not* ask them to measure that distance and see whether it is half the radius of the mirror—that would be racing ahead into optics, with a danger of spoiling the present flavour of leaving people to their own experimenting.

We believe these experiments yield a very valuable sense of doing science when given plenty of time; but we do not believe that much benefit will emerge if the experimenting is interrupted by theoretical discussion or detailed measurements. So we do *not* recommend—except for extremely fast pupils—giving any discussion of the geometry or asking pupils to locate a 'focus', or asking them to turn the curved wall round and use it as a convex reflector for virtual image effects.

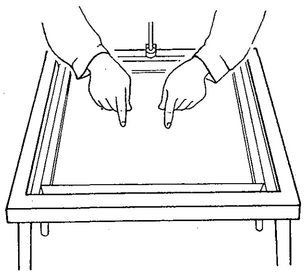
Class Expt 4m A Very Important Question: What Happens when one Ripple Crosses Another?

Apparatus

8 ripple tanks	item 90

Procedure

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



If necessary suggest that pupils should make one ripple (pulse) with a finger, and start another ripple from another place some distance away, perhaps a little later.

{**The long time with ripple tanks** Teachers who have tried this series of experiments with ripple tanks as class experiments find that they take much longer than expected. Yet the longer the time the more the pupils will gain in useful understanding.}

{The first period with the ripple tank may well have seemed completely wasted, with messing about, dabbling in water, looking at patterns, and getting nowhere. Neither teacher nor pupils should be discouraged by that. In subsequent class periods, pupils have developed both skill and knowledge. Later, when we have studied properties of light, we shall refer back to a ripple tank and may set it up and look for some properties again.}

Films of ripple-tank phenomena: a warning repeated There are good four-minute films that show clearly just what we want pupils to find for themselves. Even if shown after the real experiments, for 'revision', these films will undo the result we hope for and damage the pride of learning some physics by investigation. So we advise very strongly against using them this Year. And many O-Level teachers we have consulted endorse that.

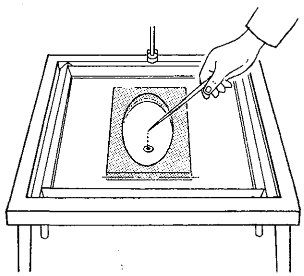
Demonstration 4n Ellipse Reflector

Apparatus

1 ripple tank	item 90
1 water dropper	90H
1 elliptical reflector	90M

The elliptical reflector must be made very accurately. If great care is taken, this demonstration is very rewarding. Some manufacturers supply such an elliptical reflector in the ripple-tank kit as an optional extra. Teachers may prefer to make their own, to be sure of the necessary accuracy—see the note below.

A suitable size is long axis about three-quarters of the length of the ripple tank, short axis about half.



Procedure

Place the reflector in the middle of a ripple tank with very clean water. Start a single ripple exactly at one focus. Pupils watch its progress to and fro.

If a ripple is started from a point which is not one focus of the ellipse, the reflected ripple will have an odd shape and it will not converge to an image point at the other focus or anywhere else.

Therefore it is important to locate the focus accurately and start circular ripples from there with a finger or a pencil or a medicine-dropper. Perhaps the best way to locate the focus is 'trial by ripples'. Once it is located the ellipse should be marked with notches or wires so that the focus can always be located easily.

In the tank, each focus should be marked by a small coin placed there. This is an experiment to see for delight: it will repay the trouble of making a good ellipse.*

NOTE. Image formation by a wide aperture reflector like this depends on the wave-path being the same from object to image by *all* routes, even those that use the extreme portions of the reflector. An ellipse does this—as we should expect from the string-loop construction. However, it fails to give a good image of points a little way off the focus.

If part of the reflecting surface is a little off the true ellipse, the condition fails and reflection there may even harm the image instead of helping to form it. An error of $\frac{1}{4}$ wavelength of a pulse is very small.

Furthermore, an error in the slope of a part of the edge can shift a portion of focused wave to an undesirable place nearby, but not at the focus.

Therefore although rough bending of a metal strip, or sawing of a wooden template, will produce an 'ellipse' that looks good enough, the wave demonstration will be a poor failure. To make a good reflector, proceed as follows:

First draw an ellipse very carefully on paper. Then an expert mechanic can bend a springy brass strip to fit the ellipse, joining the ends with a butt joint and a strap outside. (This type needs very careful storage unless one adds straps across it.)

Alternatively, draw the ellipse on plywood and then cut it out to make an elliptical hole in the sheet. The cutting must be done with great precision.

For the best reflector of all, make a wall of plaster of Paris, shaping it by a moving peg on a loop of wire as in drawing an ellipse with a loop of thread.

Coating the reflector with paraffin wax may improve the regularity of reflection by making an angle of contact with water of nearly 90°.

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* A teacher reported: 'With the ellipse I was asked to start ripples at both "foci" at once. There was then an argument. Did the ripples pass through each other, or were they reflected in the middle? I had the good suggestion from one boy to start one ripple before the other. This then convinced everybody that waves passed through each other and I felt that everybody felt a sense of achievement and common purpose.

I felt they needed to be brought together after working on their own for six weeks, and I think they appreciated this.'

Interference This is not the time to teach interference or even to show it thoroughly. But we suggest a first look now without much prompting and certainly without a careful teaching of 'results'. With a slow group this may be postponed to Year 5.

Young's fringes It would be better to have the first glimpse of interference arise by accident when pupils make ripples with two fingers than to have it as directed experiment. Suggest:

Make two streams of waves, using two fingers of one hand as a 'double source'. Then try that, if you like, with a pair of vibrating dippers.

Try using the stroboscope. Also try blinking your eyes.

We urge teachers not to give a *demonstration* of interference fringes with their own tank. That would hurt the great value of this ripple tank as a medium for pupils to do their own experimenting and arrive at knowledge which they feel they possess personally. Encourage pupils, by direct suggestion if necessary, to look for an interference pattern when two sources a few wavelengths apart run in phase and generate ripples.*

Class Expt 4o Waves from a Pair of Sources, using Two Fingers: Interference
(OPTIONAL NOW)

Apparatus

8 ripple tanks	item 90
32 hand stroboscopes	105/1

Procedure

Ask pupils to use two fingers *of one hand* as sources of ripples which will, therefore, start out 'in tune with each other'. They should first try making a pair of single pulses in that way.

We hope pupils will then, of their own accord, move their hand up and down to make two streams of continuous ripples.

Even with this informal pair of sources, pupils should *try* observing with a hand stroboscope. This method will not produce interference effects that are very regular or easily seen; but it is the proper beginning to give a feeling for what we are aiming at.

This leads on to the use of the vibrator with two small dippers attached to its beam, to act instead of the fingers (Expt 4p).

Class Expt 4p Waves from a Pair of Sources, using the Vibrator: Interference
(OPTIONAL NOW)

Apparatus

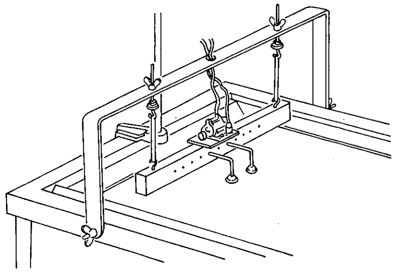
8 ripple tanks	item 90
8 meters mounted on beams	90L
16 dippers	90G
32 hand stroboscopes	105/1

Notes

(i) The waves may be visible farther from the sources if the water is made deeper: for example, 1 cm (2 litres). However the reflections from the sides may then be troublesome.

Procedure

Pupils set up two point dippers on the vibrator as in Expt 4f. They look for 'a strange pattern'.



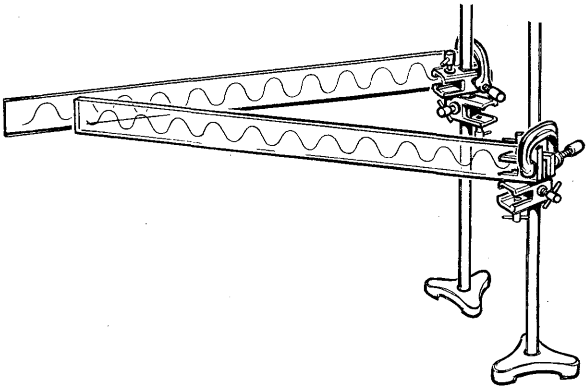
(ii) When the dippers are 3 cm apart and the vibrator running as slowly as possible (about 10 rev/sec), two minima (nodal lines) can be seen with the naked eye. As the vibrator is speeded up, more minima are seen, but at high speeds the stroboscope is needed to see the pattern, except near the dippers.

(iii) The spacing of the dippers can be increased to increase the number of minima and make them closer. This shows best with the vibrator running slowly. At high speeds the pattern is very beautiful, but the minima are crowded close together.

* A teacher reported: 'The weak form got very good interference fringes; they talked of "cancelling out".'

If pupils try this as part of their series of ripple-tank experiments, it should be done quickly for a first glimpse. This is not the time for elaborate explanations with demonstrations of the addition of wave motions.

Teaching interference Interference, which is of such great importance in modern physics, will be taken up again later. Then we will suggest a device (two perspex strips engraved with a wave pattern) to help this teaching.



It is probably better to postpone commentary or explanation. But, in case pupils are specially interested, here are suggestions.

{It is good to avoid the misleading name 'interference' at this stage. It is an unfortunate choice for a descriptive word in science. The principle of interference states that waves *do not interfere* with each other* but can cross each other unharmed. As they are crossing they simply give the sum of their two separate effects. If those effects are both in the same direction the sum is large, but if they are in opposite directions the sum may be small or even zero—which is sometimes called 'destructive interference'. If possible avoid that term at present.}

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

Simply point out that the two sets of ripples seem to add up in some places and cancel out in other places. A useful description is:

Here one ripple arrives as a signal that makes the water go up and down:
flip-flap, flip-flap . . .
and the other ripple arrives also making the water go up and down. . . .
flip-flap. . . .
The two wave-signals add up to:
FLIP-FLAP, FLIP-FLAP. . . .
But here, where the wave from that source has travelled a little farther than the wave from this source, the two do not arrive in step. One of them makes the water go up and down:
flip-flap, flip-flap . . .
and the other makes the water go . . . ?

Pupils give the obvious answer 'flap-flip, flap-flip'.

Then what do you expect where those two motions act together?

Leave things at that stage, simply saying:

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

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

'Young's fringes' with ripples The proper analogue of Young's fringes with light waves would be interference of ripples made by a wave passing through two slits. Pupils will not understand that unless they have seen diffraction of ripples at a very narrow gateway. So this alternative arrangement for interference is given later (Experiment 4s).

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

Pupils will meet interference again later in this Year; and all will meet it for water waves and light. Teachers with slower groups may prefer to omit interference now and move on to new things; then deal with interference in Year 5. There is no serious harm in that, though they may regret their pupils' missing an early qualitative glimpse.

Diffraction Most pupils will have acquired some knowledge of diffraction in playing with barriers. They will have seen waves bending and spreading at boundaries, without realising the importance of the phenomenon. Now all should try, *quickly*, sending waves through a wide gateway, then a narrow one.

Class Expt 4q Waves passing through a Gateway: Diffraction *(OPTIONAL NOW)*

Apparatus

8 ripple tanks	item	90
8 motors mounted on beams		90L
16 straight barriers		90D
16 side barriers (blocks of wood)		
32 hand stroboscopes		105/1

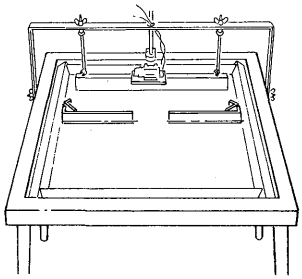
The opening should first be about 10 wavelengths wide; then about 1 wavelength wide.

Waves coming round the outer ends of the barriers are troublesome and they must be blocked off with side barriers. At high frequencies, the barriers themselves may start to vibrate giving misleading effects and this should be avoided.

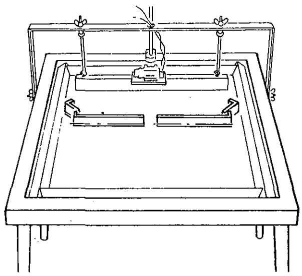
Procedure

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

(i) Wide Gateway. Pupils build a wall of barriers about 5 cm from the vibrating beam, with a gap in the middle about 10 cm wide. They watch waves passing through the gap. At high frequencies, the waves can be seen only with a stroboscope.



(ii) Narrow Gateway. Pupils narrow the gap between the barriers to about 1 cm.



To have the greatest wavelength, they run the vibrator at its lowest speed (10 rev/sec). They watch waves passing through the gap.

Encourage pupils to alter the gap width and see the effect of changes.

Class Expt 4r What does a Very Short Wall do to Waves? Diffraction by an Obstacle *(OPTIONAL NOW)*

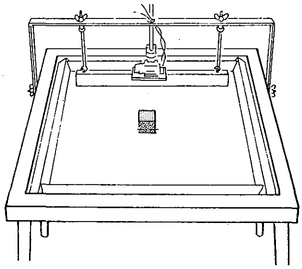
Apparatus

8 ripple tanks	item	90
8 motors mounted on beams		90L
8 small blocks of plastic foam (weighted, about 2 cm × 2 cm × 1 or 2 cm)		
32 hand stroboscopes		105/1

Procedure

Pupils place a short barrier (2 cm) in the tank, near the vibrating beam. This may be a piece of wood or metal, but a small block of plastic foam (weighted to prevent floating) is better because an absorber scatters more clearly.

Pupils use the vibrating beam to send straight waves towards the obstacle. They change the motor's frequency from very slow for longer wavelengths to very fast.



Long waves are scarcely affected but the effect of the obstacle becomes sharper as the wavelength is reduced (or as the size of the obstacle is increased).

With a *very* small obstacle, some pupils may notice the very weak circular ripple that is scattered as the main wave moves past almost undisturbed.

Stroboscopes are needed for high frequencies though at very high frequencies vibration of the obstacle itself can give misleading effects.

Class Expt 4s Two Narrow Gateways to act as a Pair of Sources: Interference using Two Slits *(OPTIONAL NOW)*

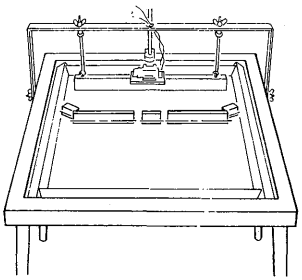
Apparatus

8 ripple tanks	item 90
8 motors mounted on beams	90L
8 dippers	90G
8 short barriers	90E
16 straight barriers	90D
32 hand stroboscopes	105/1
16 side barriers (blocks of wood)	

Extra barriers must be used at the sides, in this and subsequent experiments, to prevent stray edge effects.

Procedure

Pupils use a *single* vibrating dipper to send waves to *two* narrow openings in a barrier. They set up the barriers 10 to 15 cm away from the dipper. The slits should each be about 1 cm wide and 3 to 5 cm apart.



Hand stroboscopes should be available so that the pupils can freeze the pattern if they wish.

The vibrating beam can be used to produce plane waves if the dipper is removed and the beam lowered to the water surface.

The pattern of ripples made is likely to be faint but the arrangement does correspond to the one we shall use for Young's fringes with light waves.

{In that classical method of showing interference, light passes through a single slit and then meets two slits very close together. The two lots of light that spread out from those two slits make a pattern—Young's fringes—on a distant screen.}

{Originally that arrangement was necessary to provide two *coherent* beams (though nowadays a laser makes things easier). Success depended on the spreading of light by diffraction at each of the double slits.}

Future Tell pupils they will meet interference patterns again.

Refraction At a boundary between deep water and much shallower water, ripples change to lower speed. So their wavelength changes and their path of travel is bent—refracted.

This can be seen in a ripple tank if we make a patch of shallower water by placing a thick plate of glass in the water, and send straight ripples towards it. Although pupils will not need formal knowledge of wave refraction until Year 5, they may enjoy acquaintance now, provided the phenomenon is easy to see clearly and quickly.

However it is much harder to show refraction of ripples than reflection; because the tank must be levelled carefully to make the shallow patch uniform, and water friction makes the ripples faint there.

Teachers with Year 3 classes who have proceeded to O-Level in Year 5 almost all report success with refraction of ripples. Some have given considerable help and encouragement to pupils, who then succeeded. Most turned this into a demonstration with a pupil's tank; and that seems the wisest course—in this one case of a difficult experiment, a demonstration will not spoil the spirit of a pupil's ripple-tank work being done 'on his own'.

Demonstration or Class Expt 4t Waves that Change their Speed: Refraction of Ripples *(OPTIONAL NOW)*

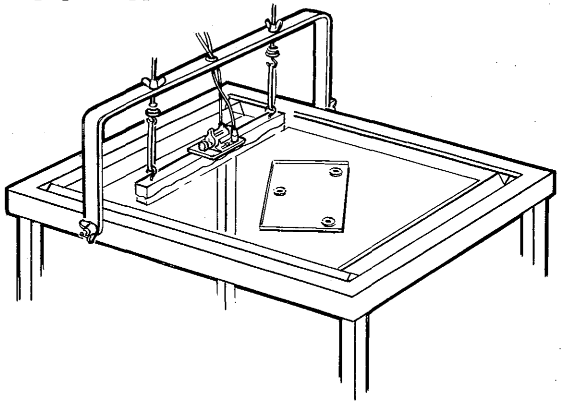
Apparatus

1 or 8 ripple tanks	item 90
1 or 8 motors mounted on beams	90L
1 or 8 plates of glass *(rectangular)*	90P
4 or 32 nuts or washers	
32 hand stroboscopes	105/1

The glass plate should be a rectangle. (The irregular shape traditionally suggested is confusing.)

The nuts or washers which act as spacers should be 3 or 4 mm thick. The water should be very clean. Oil or dirt increases the friction and makes the refracted waves even harder to see.

This is a difficult experiment but it is worth the trouble needed to make it show the story clearly. Either let pupils try it themselves and give plenty of help to each group in turn, or give a demonstration with one of the pupils' ripple tanks.



Procedure

Set up the ripple tank as usual, with the motor and tank. To prevent the plate sticking to the base of the tank put washers or nuts as spacers under it.

Ripples travel slower in shallower water; but to show an appreciable difference in speed the water on top of the glass sheet must be *very* shallow. It is best to pour the water into the tank until it just covers the glass sheet and then take a little water out. With this shallow water, *the tank needs to be levelled very carefully.*

To get sharp waves, adjust the height of the vibrator carefully. It is probably best to have it just below the mean water level.

(i) Normal incidence. Arrange the plate with its long edge parallel to the vibrating beam and a few cm from it, so that waves meet it head on. Pupils watch the waves in the two regions, looking for difference.

The difference of wave speed is most pronounced with a low frequency and large wavelength. If diffraction effects are not too troublesome, it may be best to use about 10 rev/sec and do without a stroboscope.

(ii) Oblique incidence. Arrange the glass plate with its long edge at various angles to the incoming waves. Pupils watch the two regions, looking for changes of *direction.*

Refraction and theories of light Refraction of *light* is important for the arguments of theory which we shall discuss with faster pupils later this year or in Year 5. So we should try to make refraction of water waves clearly visible.

Some pupils will notice a shorter wavelength in shallower water; some will notice a change of speed at the boundary: but these are difficult things to see. The bending of wave-fronts may be more noticeable.

We need not press hard for refraction to emerge from these observations. Pupils can return to it when they want to know about waves meeting a boundary between regions where they travel with different speeds.

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

Measurements? A relationship for waves? *(Optional Advanced Extension)*

Our pupils are older than the explorers of Years 1 and 2. Some will be finding intellectual satisfaction in understanding measurement in science. Those pupils will not ask 'what for?' if we suggest measuring wavelengths of ripples. They are now at a stage of investigating the world when it seems quite sensible to 'measure anything you can think of'.

Our ablest pupils will be ready to make the more difficult measurements of frequency and speed for the sake of finding or testing a relationship.

If some able pupils are keen to do that, and have the time, we should encourage them, and give them some descriptions like the following.

There is a connection between WAVELENGTH and FREQUENCY and WAVE-SPEED—the same relationship for water ripples as for radio waves.

You may have measured the wavelength of ripples already, by freezing the pattern with a stroboscope. If you also measure the frequency and speed of the same ripples, you could hunt for the relationship—or, if you prefer, ask to be told it, and then test it.

WAVELENGTH is the distance from crest to crest. You can measure it on the frozen shadow.

FREQUENCY is a new idea, a new thing to measure, though it has been there all along as an important property of your waves.

How often does the vibrator dip down into the water? How many complete wavelengths does it *send out* in each second? We call that the FREQUENCY of the vibrator. It is the number of complete vibrations (bobs up-and-down) or cycles that the vibrator makes in each second. It is therefore the number of complete ripples (wavelengths) that come out each second from the vibrator. We call that the frequency of the waves.

You could measure the frequency of ripples by watching the pattern and counting how many pass a fixed mark on the floor in one second. It may be easier to measure the frequency of the vibrator by counting revolutions of its little motor.

Frequency is measured in *cycles per second*, and that unit is named a *hertz*. The frequencies of radio waves are so big they are usually given in thousands or even millions of hertz, kilohertz, or megahertz.

WAVE-SPEED (or VELOCITY) is the hardest to measure. Follow a chosen crest as it moves across the floor.

* The PSSC programme in the USA was the result of an early, very extensive, project to offer new physics teaching to American high-schools. That project has influenced teaching projects in other countries and we have drawn some suggestions and some experiments from it. However it emerged as a tight package, a one-year 'course' which does not match the arrangements for physics teaching in the United Kingdom.

In comparing the Optics of Nuffield physics with the the Optics of PSSC, we find Snell's law given great prominence in the latter. The Law of Refraction was specially chosen by the original Physical Science Study Committee in the USA as a very good non-linear example of a physical law, and an avenue to discussion of rival theories.

That was an interesting choice and possibly a wise one for pupils of age 16+. Although our younger pupils can use sines —or at least can handle the graphical equivalent—we think this law would seem too difficult to impress them as a surprising and magnificent clarification of natural behaviour. In Snell's own day, it was a welcome discovery. The time was more than ripe: physics was waiting for a rule to replace some unsatisfactory approximations. But the time is not ripe in our pupils' state of knowledge; they are not yet desperate for a rule to catalogue the progress of rays of light through optical systems. Nor will a discussion of theories appeal strongly yet.

Class Expt 4u Estimating Wavelength, Frequency, and Speed of Ripples *(OPTIONAL ADVANCED EXTRA)*

Pupils find *measurements* with ripple tanks difficult. As explained above, many at this age do not see the need for measurements or the importance of looking for a relationship between them. So the three experiments suggested here should only be optional extensions for a very able, keen group.

Apparatus

8 ripple tanks	item 90
8 motors mounted on beams	90L
32 hand stroboscopes	105/1
16 stop-watches or stop-clocks	507
8 metre rules	501

Procedure

With these three measurements, pupils could discuss briefly the relationship $v = nL$; but the wave speed is very difficult to measure.

The speed changes little with frequency in the range available, but running the vibrator as slowly as possible makes it easier to measure the wavelength and the frequency.

Estimating wavelength. This is a repetition of an earlier measurement, Expt 4h. Explain that the idea is to get a rough estimate quickly, and not to try to achieve precision with a technique which cannot really support it.

Pupils use stroboscopes to 'freeze' the pattern *on the paper on the floor*. They measure a batch of wavelengths (say 10).

Note that in estimating wavelength the stroboscopes are used *only* to freeze the pattern for easy measurement. Their frequency need not be known for that.

Estimating frequency. As the vibrator is running slowly pupils can count the number of vibrations in a given interval and calculate the number per second. A scrap of paper just touching the load on the spindle of the vibrator makes audible sounds which make counting far easier.

Estimating velocity. To judge the speed one pupil runs a pencil along the paper keeping it level with one wave crest. Another pupil measures the time taken to move the pencil between the two points marked on the paper. (The velocity of *pulses* would be easier to measure but they do not travel at the proper wave speed, so they should not be used here.)

The wavelengths and speeds that are measured are not those of the actual ripples but those of their *shadows* on the floor. This does not matter if measurements on the floor are used consistently. Values for the actual ripples could be calculated by proportion, if pupils preferred that.

Test of $v = nL$. It may be best to give pupils this relationship and ask them to see whether their estimates fit it. Remember that the value of v may be different for different frequencies, because v is a function of the wavelength for water waves. However, with continuous ripples in our ripple tanks the wave-speed happens to be near its minimum so it is almost constant over the range of frequencies of the motor.

The 'wave formula' *(OPTIONAL)* Since the measurements are rough, pupils who look for an exact relationship are not likely to discover it. Unless they prefer to struggle with the numbers, it will be better to tell them $v = nL$. Then the experimental measurements may afford a check.

But this is also a case where geometry and argument are not out of place. We might say:

Suppose a man marching along takes 80 strides a minute, each stride $\frac{1}{2}$ metre long. How far does he go in a minute? . . . Yes, 40 metres.

His speed = [80 strides per min] × [$\frac{1}{2}$ metre per stride]
= 40 metres per min

Suppose he takes n strides per minute, each of length L, in metres. Then he travels a distance nL metres in a minute.

His speed = [no. of strides per min] × [stride]
or $v = nL$

Now think of waves. When a train of waves has travelled one wavelength along, it looks exactly the same again. One wavelength is like one stride. If the vibrator turns out n whole wavelengths per second (frequency n in hertz or cycles/second) the wave speed is given by:

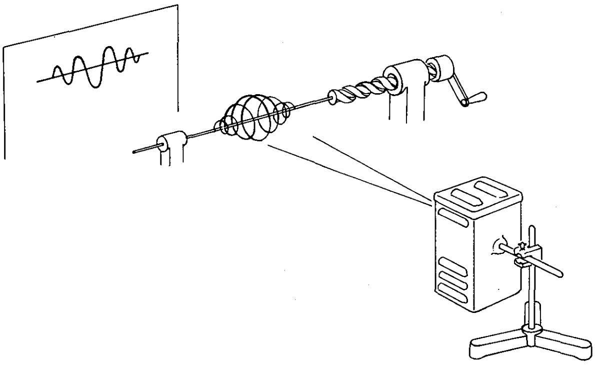
WAVE SPEED = [NO. OF WAVELENGTHS TURNED OUT PER SEC] × [WAVELENGTH]
WAVE SPEED in m/sec = [FREQUENCY] in cycles/sec × [WAVELENGTH] in metres
$v = nL$

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

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

The progress of a ripple: group velocity
(OPTIONAL: very advanced extension)

Some pupils may point out a strange phenomenon. When they start an isolated pulse it seems to have a structure of a few wavelengths in it, and it travels out in a curious way, with the markings of those individual waves *travelling through* the whole pulse—so that they travel at a different speed from that of the overall pulse. We should say:



Yes, that is so, for water waves. Your ripple is a small group of waves, and it travels out as a whole with what we call 'group velocity'. That is a speed you measure for a *pulse* if you use a ruler and a stop-watch. The wave-markings inside the group travel with a speed that we call the 'wave velocity' (or, more correctly, the 'phase velocity').

For many kinds of waves (waves on a rope, waves of light in space, wireless waves, waves of sound) the group speed and the phase speed are the same. But for water waves they are different (and for light waves in other media than a vacuum they are different).

To a very able pupil, we might even say:

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

CHAPTER 2

OPTICS

Images and rays; lenses and instruments

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

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

A Long Chapter?

This chapter on Optics will seem disproportionately long. We do not suggest that the teaching should extend over an extra long time. The chapter is long only because we suggest an unusual approach and we therefore offer more details and explanations.

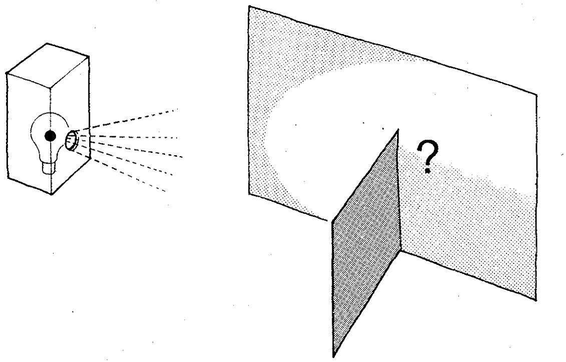
Either start pupils straightaway on class experiments with a pinhole camera or, as an introduction, give a few demonstrations of light rays—without explanation.

Preliminary Demonstrations 6 Beginning Optics

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

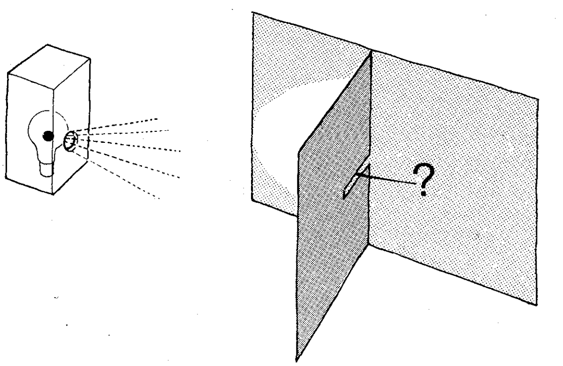
6a Shadow on a Wall

Show light from a bright, compact small source splashing out along a white wall. An obstacle casts a shadow with sharp edges.



6b 'Ray' of Light

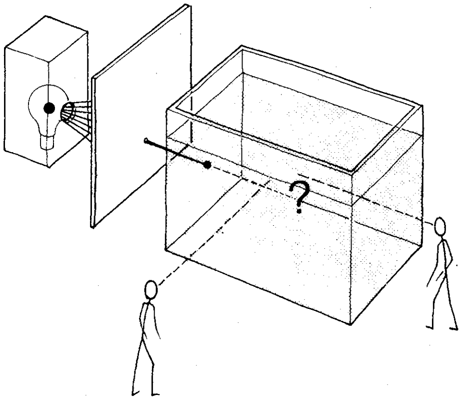
Shine light on a screen with a slit. The slit lets through a single 'ray'. Many pupils will see that the ray looks *straight*, but we should not ask about that yet.



6c Ray of Light in Water

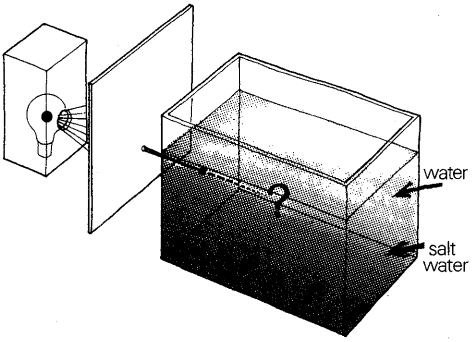
Fill a rectangular glass (or Perspex) tank with water containing a little fluorescein (or a little milk) to scatter light. Show a narrow beam of light (a thick 'ray'), visibly following a straight line in water.

At this preliminary stage, avoid showing reflection or refraction at boundaries.



6d A Strange Ray: Curved in Water

If (c) is shown it is worth the trouble to repeat the demonstration on a later day with a carefully arranged tank of water and brine. Introduce strong *clear* brine gently* under the water in a half-filled tank, and allow the boundary to smooth out a little by diffusion or judicious stirring.



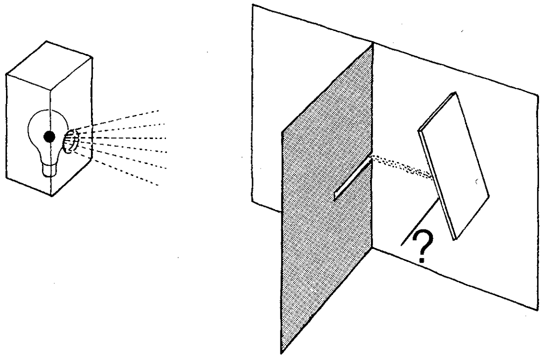
* There is no need to make a special device for inserting the brine. Attach 30 cm of rubber tubing to an ordinary funnel and fit a screw clamp to control the flow. Hold the funnel so that the tube reaches the bottom of the tank and pour in the brine. Gravity will serve to maintain discipline; and anyway we want some mixing.

Then direct a 'ray' from a bright compact source, almost horizontally, through the region of varying refractive index.

With care, the 'ray' will be visibly curved to observers in front of the tank.

To an observer at the end, looking along the 'ray', it is still straight.

Here is an application to mirages and an interesting moral for Relativity.



6e Reflecting a Ray

Show a 'ray' on the white wall being reflected by a plane mirror. Without prompting some pupils may see a rule of reflection. If so, give a word of praise.

(We should *not announce* a rule—and even if pupils tell us one, we should not reword it in formal style. We are in a hurry to get on with class experiments.)

6f 'Reflecting' a Ball

Throw a rubber ball against a hard floor or a hard, massive wall; and ask if it follows any 'angle rule'.

Ideas Ask whether light might perhaps be a stream of elastic bullets, coming from the lamp (or from scattering material) to our eye. However, point out that waves are also reflected like that, as the ripple tank shows.

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

Class Experiments

Pupils now proceed to several series of class experiments. Since these follow a rather different approach to optics from the usual one, we give an account of the treatment and its aims in the section below. A discussion is also given in a note in the Preface.

Note to teachers, on Optics and Optical Instruments

In the usual treatment, the reflection and refraction of rays of light are first studied and codified in clear laws; then those laws are used to predict or explain the behaviour of mirrors and lenses; and after measurements of focal lengths and object-image relationships, then—at a late stage—optical instruments are discussed.

That procedure is sound logical training, but here we are thinking of young people who will carry only a general memory of optics into later life; and we want them to consider that optics makes sense as the science that deals with telescopes and spectacles and eyes and other instruments.

The optics programme Our suggested treatment starts pupils on class experiments with cameras and telescopes straightaway, building knowledge of *images*, rather than formal laws, as the basis of understanding.

THE GENERAL SKELETON

People see by means of rays that their eyes receive; and lenses form images from which rays proceed as if from an object. Rays go straight through a real image, come straight from a virtual image.*

Optical instruments—eyes, telescopes, etc.—are image-formers. To understand them and use them well, pupils need to know about rays, lenses, and images.

Finally, with the help of water ripples, we offer faster pupils some experimental knowledge of light waves, and a taste of theory.

We hope very strongly that this treatment will enable pupils to understand how a camera works (and to know why a cheap camera is likely to give a great depth of field); and to understand what spectacles do for people; and to be able to focus simple optical instruments such as telescopes and microscopes.

Above all, we trust pupils will enjoy seeing real patterns of rays and making their own optical instruments. If all that is our pupils' experience of optics, it is likely to last; and it will not damage the reputation of physics.

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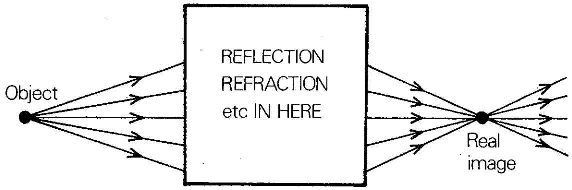
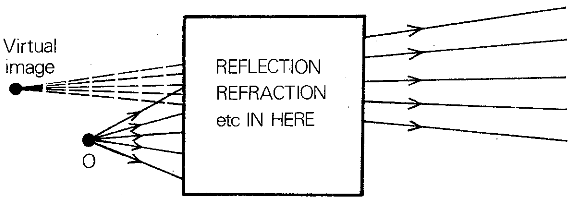
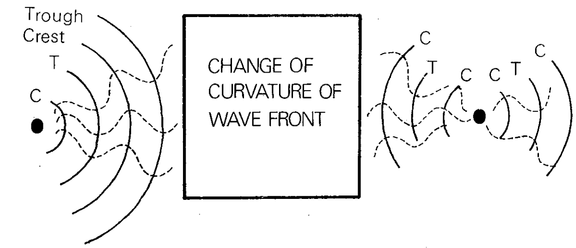
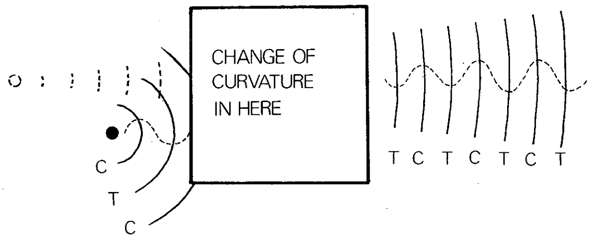
* *Private note to teachers on optical images.* Pupils will learn to understand the use of images very well in their experiments. So we do *not* suggest pupils should be given a formal definition of images.

However, teachers may find the following useful for their own thinking in this teaching.









DEFINITION In terms of *rays* the image of a point is that point to which rays of light starting from the original point converge, or from which they appear to diverge, after reflection, refraction, etc.

In the former case the rays converge to the image-point, continue straight through it and diverge; so the image can be caught on a screen placed there. This is called a *real* image.

In the latter case, the rays only *appear to come* from the image and the image is called a *virtual* image.

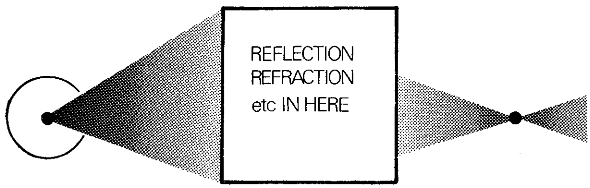
A large object is regarded as a collection of object-points. Its image is the collection of images of those points.

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

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

In terms of *waves*, we may say that the image-point is the region where waves which started as spherical waves from the object-point converge (ideally) to zero radius of curvature and then diverge.

In terms of *energy* flowing originally from an object-point, the image is a region of maximum density of energy-flow.



{Where there are opportunities and time and interest later on—after O-Level—some pupils can embark on a more purely scientific and logical study of optics and explore an interesting field of great laws and rival theories.}

{We intend no disrespect to the conventional treatment, but we offer our present choice both as more practical and as an economy of time. We propose to let some parts of the usual school physics course give place to more teaching of atomic physics; and we have chosen to leave out considerable parts of optics. In defence of that move, we must point out that to many pupils the traditional optical measurements and even the subsequent study of optical instruments are a rather puzzling business—it is not easy to teach geometrical optics for lasting understanding. But we believe our class experiments *can* do that.}

Synopsis of Optics Programme

The treatment we suggest runs like this:

CAMERAS. Start with a home-made pinhole camera as a class experiment to show rays of light 'making a picture'. This graduates into a lens camera, in which a lens clearly picks up many rays from an *object-point* and makes them all converge to an *image-point*.

A SIMPLE ASTRONOMICAL TELESCOPE. Let pupils have a first quick look, just to enjoy making it work. ('Make a real image of the distant object; and look at that with a magnifying glass.') Pupils have a weak spectacle lens and a magnifying glass. The teacher gives considerable help, if needed, in arranging these so that the final virtual image is back at the object.

This is the first try for fun—to remove the mystery, and to promise future success. *The essence of these CLASS experiments is to give personal experience,* enjoyment, and confidence—perhaps leading to skill.

RAY STREAKS. Streaks of light from a small lamp splash across a sheet of paper and hit cylindrical lenses. We give *each pair* of pupils their own simple apparatus. (This is *not* a demonstration with a ray-box outfit.)

Pupils see, by playing with this equipment, how lenses (and mirrors) treat rays in forming images.

COMMON LENS FORMS IMAGE OF A WINDOW. A class experiment of informal drill leads to discussion of image forming. Later, pupils use the same lens as a magnifying glass.

Pupils find the lens forms a real image of distant objects; a virtual image of an object close to it. They also learn something of their own eyes' range of accommodation.

EYES. Simple discussion of eyes and spectacles; demonstration of special model eye; and a dissection of an ox's eye.

SPECTACLES. These are treated as image-formers. They give the eye an image to see at a comfortable distance.

ASTRONOMICAL TELESCOPE. The class experiment is repeated, this time with pupils doing the focusing. And skilful pupils make a rough estimate of the magnification when the final image is back at the remote object.

MAGNIFYING GLASS as an optical instrument. Pupils practice placing the virtual image at a comfortable distance. Some may estimate the magnification.

COMPOUND MICROSCOPE. A crude model with two lenses, for pupils to make it work in the open air.

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

RAY STREAKS AGAIN. Pupils return to their class experiments with ray streaks and set up their own simple model of rays through a telescope and a microscope, using a pair of lamps as object.

OPTICAL DIAGRAMS. In class and in homework, some pupils may learn to draw special optical diagrams that show the true progress of rays through lenses and images. Undeviated rays through the optical centre of a lens are drawn as essential guides; but the principal focus is not used as a construction point—instead of taking focal lengths as data, pupils take suitable image positions and assume the powers of lenses have been chosen to put the images there. Instead of being given u and f and being asked to find v, pupils assume they are given u and v (or may choose suitable values) and are asked to draw correct cones of rays.

A special section of *Pupils' Text 3* gives details of the drawing of such diagrams. Those need considerable practice but pupils who enjoy careful drawing find success with them very satisfying, as a supplement, or as a substitute for more abstract treatment of images.

TESTING THE 'FORMULA' relating u, v and f. (This is an optional advanced topic, outside the normal scope of the programme.)*

This formula will *not* play an essential part in our programme—for one thing it is not regarded by optical experts today as an important relationship.

However pupils who proceed through the other experiments very fast and enjoy optics may like to see whether the 'formula'

$$1/v \pm 1/u = \text{CONSTANT}$$

holds for their positive lens. They will find quite easily that the formula gives a constant total when used with object- and real image-distances. Then they should be challenged: 'Is the total still the same for *virtual* images?' That is the kind of risky extension by which science often progresses. Testing that extension (by using smaller object-distances), will give pupils *practice in locating virtual images experimentally*—the only really valuable outcome of this optional extension.

However, if the use of the formula promotes a series of careful measurements with the use of ray constructions to solve formula problems, our teaching has taken a mistaken turn which will occupy considerable time and deflect attention from the main work—and it would have been far better to do without the formula. But if we can just announce the formula and ask keen pupils to find whether the behaviour of their lens fits with it, they can use it to develop skill which is the key to success in focusing optical instruments.

Only if the formula is used for this mild competitive encouragement should we give it any attention at all.

REFLECTION AND REFRACTION. Simple experiments with rays being reflected and refracted. Pupils acquire qualitative knowledge but need not learn formal statements of Laws.

INTERFERENCE (now or in Year 5). A *qualitative* class experiment with Young's fringes; and comparison with ripple tank.

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* *Note regarding Focal Lengths.* The focal length, f, and the formula $1/v \pm 1/u = 1/f$ do not play important parts in our present treatment. The focal length is only a special case of an image distance. Yet $(1/f)$, which is called the POWER of the lens, is an important quantity. It is the constant value yielded by the formula for *all* pairs of object and image-distances; and it indicates how much the lens will bend rays or change the curvature of wave-fronts of light.

If f is measured in metres, the POWER $1/f$ is in m^{-1} or dioptres. When a pupil first meets a lens he should make a very rough estimate of the value of f. And it would be good if he had a general idea of the position of the image when the object is at a distance $2f$, also when the object is at much greater and at much smaller distances—but that will suffice for our work with images and instruments.

A SHORT LOOK AT THEORIES (now or in Year 5). We describe the 'bullet theory' and point out (without algebra, since momentum has not yet been treated formally) that speed in water 'should' exceed speed in air. Then, when pupils have seen interference patterns, we describe an alternative wave theory.

The First Class Experiment. Pinhole Camera

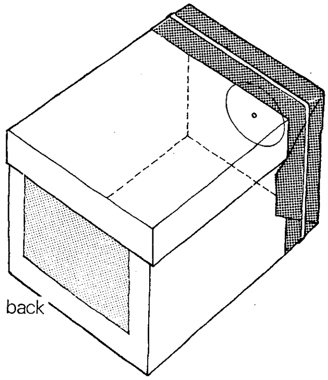
AIM. This Experiment, to be done in a half-dark room, forms the beginning of a series of class experiments. It should be easy and fun to do, rather than a serious discipline in assuring oneself that light travels in straight lines. (For that matter, a real test of rectilinear propagation by use of a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

We want this to lead straight on to the idea of a lens camera having something that gathers up many rays of light from each point on the object to form a much brighter picture on the photographic film—instead of the several faint ones made by the narrow pinhole alone.

Every pupil, or failing that every pair of pupils, should have a pinhole camera. *This should NOT be a carefully constructed tube or box with a sliding arrangement to change its length and a special pinhole provided in front.* That may be a useful demonstration or class experiment in other programmes of optical teaching; but here we need something that is simpler, something that pupils can deal with themselves and easily copy at home.

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

Details of Equipment for Camera



THE CAMERA. A small rectangular cardboard box, with a hole about 4 cm diam. cut in the front and a large square hole cut in the back.

FRONT. The hole in the front is covered with a sheet of dark paper, pasted on, in which pupils themselves make pinholes. After the camera has been used it is restored by pasting or clipping a new sheet of paper on the front.

It is not necessary to use black paper: common brown paper does just as well.

BACK. The hole in the back is covered with some kind of translucent screen.* Kitchen greaseproof paper is good. Kitchen waxed paper may be better still, but it is easily broken. Almost any kind of tissue paper rendered translucent by treatment with paraffin wax or oil will serve. Ground glass is too easily broken. Frosted plastic is unnecessarily 'special' and expensive.

This screen is fixed over the hole at the back with Sellotape and kept there permanently.

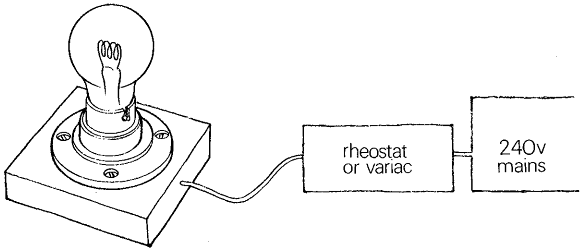
LENGTH. The length of the camera is important because we need to match that length with a lens in the next experiment. The box length must exceed the focal length of the lens by an amount that depends on how far from the object-lamp the camera will be for perfect focusing. That can be adjusted by placing pupils suitably. Our suggestion of a box length of $15\frac{1}{4}$ cm (6 inches) is arrived at as follows.

For general use as eyepieces, etc., we suggest lenses of power $+7$ D (focal length $\frac{1}{7}$ metre or 14.3 cm). In the camera experiment, a class of 32 should be divided into four groups, each group standing in a semicircle round one lamp as object. A pupil holding a camera and lens needs about 1 metre of elbow room. Then 8 pupils need a semicircle of radius about $2\frac{1}{2}$ metres. In that case, the camera lens will be about $2\frac{1}{4}$ metres from the object lamp. Then, for a sharp image at the back, the camera box should be $15\frac{1}{4}$ cm long.

(A weaker lens will require a longer box—much longer if pupils stand close to the lamp. Of course, pupils could hold the lens out beyond the front of the camera but that is not so easy or so convincing as a start.)

LENSES. It is neither wise nor necessary to have very special lenses just to put in front of a pinhole camera. It is better to choose the camera to fit the common lenses that we use. The recommended lenses are meniscus lenses of power $+7$D. They are cheap and are easily obtained from spectacle manufacturers.

BOX LID. The lid of the box should be removable, or absent, so that when distant objects are viewed the lens may be held *inside* the box: the pupil removes the lid and holds the box upside-down.



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

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* *Note on translucent screens.* The pupil will stand behind the camera which he points straight towards the object; so he needs a screen made of material that scatters light through a *small angle* around the straight-through direction. Then the pupil will receive plenty of light.

A screen that scatters through a *wide angle* will distribute light to many observers standing behind, but none of them would receive enough light to see a bright picture.

A wide-angle-scattering screen *is* needed when an illuminated translucent screen is used as a background to silhouette a demonstration for a large class. It is also what is needed for rear projection to a class which subtends a large angle at the screen. For such uses, architects' tracing linen seems to be best of all available materials. It is cheap, easy to install, difficult to break, and it scatters the transmitted light over a very wide angle.

Class Expt 7 Home-made Camera (A Group of Class Experiments 7a-7f)

Apparatus

1 pinhole camera kit:	item 91
32 cardboard boxes	91A
200 sheets of dark paper	91B
4 200-watt carbon filament lamps	91C
4 mounted lampholders with flex	91D
1 gross of pins	91E
32 lenses (+7 D)	112
1 floodlight (for part 7e)	218
paste or Sellotape	

See notes above for details of camera box.

Preparation

Place the four lamps high up on stools standing on tables at ends or sides of the laboratory so that eight pupils may stand round each lamp at a distance of about $2\frac{1}{2}$ metres.

Make sure that each box has a fresh sheet of dark paper fastened over its front end with paste or Sellotape or a rubber band.

The room should be at least three-quarters dark. Unless the room is quite dark pupils should use large pins, not very thin ones.

Procedure

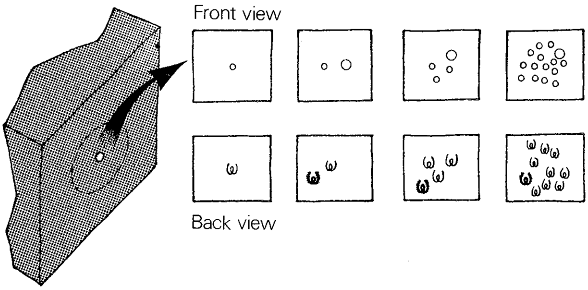
7a Using the Pinhole Camera

This is an experiment for delight. There will be plenty of more disciplined experimenting later this year. We should not cloud the beginning of optics by expecting elaborate reasoning or careful carrying out of exact prescriptions. Just encourage looking at the camera's pictures.

If a pupil forgets he is looking at the screen and holds the camera just in front of his nose, remind him:

'You're looking at a picture on the back of the camera. You should hold it away from you, just as you hold a book away when you read it.'

Pupils stand about $2\frac{1}{2}$ metres from the lamp and hold their camera at arm's length and point it towards the lamp. Each pupil should have a pin and make the following holes in the front:
(1) a small pinhole; then enlarge that to
(2) a big pinhole; then
(3) several small pinholes; then
(4) a whole 'pepper' of pinholes.

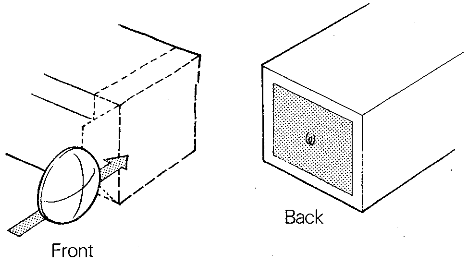


What pupils see on the screen at the back of the camera are *pictures* of the lamp. The name *image* is best reserved for the optical image formed by a lens.

Encourage pupils to move nearer to the lamp and farther away. They will enjoy this experiment more, and gain a better feeling for physics, if they are not given direct instructions or required to make detailed observations but are simply left to try things as they like.

7b Improving the Camera: from Pinhole Camera to Lens Camera

Then give each pupil a lens (+7 D) to slide in across the front of the camera.



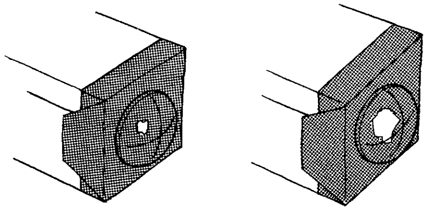
To give the delight of immediate success, make sure before giving out the lenses that the pupils are at the 'right' distance from the lamp for the lens on the front to focus all the pinhole pictures into a single sharp bright image. (They should stand $2\frac{1}{2}$ to $2\frac{3}{4}$ metres from the lamp.)

After that, some pupils will naturally try moving the camera to different distances from the lamp. But the first sight should be of a brilliant gathering-up of all the pinhole *pictures* into one bright sharp optical *image* on the screen. Of course, one should not tell pupils that this is going to happen. One merely places them at a suitable distance before they slide the lens in.

From now on, the name *image* is proper.

7c A Brighter Picture

Then let pupils try a larger hole, made with a pencil, and then a finger, pushed through the peppered region. Installing the lens again, they can get a very bright image on the screen.



7d Focusing the Lens Camera

Encourage pupils to move much nearer the lamp, also much farther away, watching the sharpness of the picture. (Here it is only the *picture* that is fuzzy; the *image* is as sharp as ever but it is not at the screen! However, we should not bother pupils with the distinction now.) Each pupil should then focus his camera for different distances by moving the lens away from the front of the box.

(Remind pupils that if they hold the box upside down without its lid, they can hold the lens nearer the screen, inside the box.)

7e Using the Lens Camera to see 'Portrait' and to see Outdoor View

Let pupils point their new lens camera at a brightly lit face.

Raise a blind so that pupils can look at a view through the open window with their lens camera.

We might offer an 'advanced option' concerning depth of field.

7f Investigate Depth of Field *(OPTIONAL, ADVANCED)*

A pupil trying this should simply continue with his camera; but he will need to paste a fresh front on it.

The pupil makes a large pinhole (2 mm diam.) and holds the lens on it. He finds the range of distances from the object-lamp for which the image looks 'fairly sharp'. Then he enlarges the hole to 10 or 25 mm and again finds the range.

Then ask him about fixed focus camera. If he waits, he will find diagrams to illustrate that.

A suggestion: 'Camera Day' With some class groups, particularly with a group of mixed abilities, it may be very useful and popular to spend a whole lesson on professional cameras, inviting pupils to bring cameras from home and discuss the working of various parts.

A photo to take home We trust pupils of all interests and abilities will enjoy the pinhole camera and its sequel. With less academic pupils the delights of the camera may soon fade as they meet more serious work with patterns of rays and behaviour of lenses. A real photo to take home may produce more lasting enthusiasm to tide them over to later successes. The following experiment—suggested as a useful option for a class of mixed abilities—will fill a single period.

7X Making a Photo to Take Home *(OPTIONAL)*

Apparatus

If possible, each pupil should have his own camera; or, at most, pupils work in pairs.

Each pupil or pair will need the following:

1 pinhole camera	item 91
1 lens (+7 D)	112
many pieces of normal bromide paper	308/3
2 paper clips or hair clips	

Preparation

For every 8 cameras, the lab needs:

2 dishes, photographic (for developer, hypo)	308/4
1 dish of water (or sink)	
developer	308/1
hypo	308/2
large tank or sink for washing	
newspaper or blotter to dry prints	

The lab needs:

red or orange safelights	303
floodlamp (preferably with photoflood bulb)	218

Procedure

a. Pinhole Camera. In the darkened room, the pupil loads his camera with a piece of normal bromide paper, which he clips on the *inside* of the back window. *It is essential to obscure the translucent window at the back of the camera box with opaque paper or metal; otherwise stray light will enter through it and fog the picture.*

The pupil makes a pinhole (1 or 2 millimetres diameter). He rests his camera on the table and points it at the head and shoulders of a 'victim' who sits 2 metres away.

Direct a bright floodlamp at the victim and switch it on for 30 seconds or longer.*

The pupil removes his bromide paper, soaks it in developer; watches it and washes it when he sees the picture; dips it in hypo; gives it a long wash, if possible in a sink with running water. The print can be (partially) dried on newspaper. When dry it is ready for him to take home.

b. Lens Camera. The pupil follows the same procedure with a fresh piece of bromide paper; but he makes a hole in the camera's front with his finger and holds the lens against the hole. (He may hold it there with fingers for the short exposure or use Sellotape.)

Turn on the floodlamp for one or two tenths of a second.

Camera experiments: outcomes We hope for two essential outcomes:
(i) Enjoyment and interest in doing more with lenses and images.
(ii) The *beginning* of the idea that a lens 'gathers up' rays, or bends them to go through an image.

Some pupils will have looked for characteristics such as size of picture, fuzziness, and sharpness, for various apertures and distances. But this is the beginning of acquaintance and all should go straight on to more experiments without delay for discussion or making records.

Seeing things Explain that a camera 'sees' in much the same way as our eyes. Rays of light come straight to our eye from any illuminated object and our eye and brain make use of those that get in. Rays also go out from the object in all other directions but we do not see those rays, unless smoke or fog scatters some of their light.

There are so many rays of light that we can only show some. When pupils experiment with ray streaks on paper, they will usually see streaks from just one object-point, the lamp filament. In the diagrams we shall presently draw, we often show only the rays that enter the eye-pupil—we just draw a narrow cone and fill it with shading to show it is full of rays. (See *Pupils' Text 3* for diagrams.)

Camera focuses rays Pupils should now be ready for some general teaching to summarize. Explain that the picture* on the back screen of the pinhole camera is made by fine bunches of rays, from each point on the object, that get through the pinhole and continue straight on to the screen. There they make a tiny spot in the picture for each point of the object. With a large pinhole we no longer have a spot-for-point copy of the object; we have a patch-for-point one—rather a fuzzy picture.

With several pinholes we have several complete pictures. The lens gathers up all those pictures. *It seems to bend the 'rays'—each of which was proceeding to a separate picture—so that they all run together to one sharp image.*

That idea enables us to make a sketch showing our guess about the action of the lens. The 'rays' through the pinholes are really thin pinhole-passing bundles of rays. Assuming that they travel straight in air before and after the lens, we are forced to think that a lens takes a fan of rays from an object-point (a 'source' of light) and bends *all* of them so that when they emerge *all* go straight to an image-point. Pupils will see that happening soon, in the class experiments with ray streaks; but we should first give a demonstration and some discussion.

Rays in three dimensions For us, that argument from [lens + pepper of pinholes] to the concept of an image is an amusing piece of scientific reasoning and guessing. But it is too great a jump for most pupils. They need to *see* a lens making rays converge. Show them a lens

* A trial beforehand will settle the exposures to use. Those mentioned here are for a 2 mm pinhole and a 12 mm hole for the lens, with strong illumination in each case. (An open window, with distant buildings or scenery as object, will be disappointing: a bright face is better.)

* Since we are giving primary importance to *image-forming* it is best to keep the name *image* for cases where rays from each object-point are bent to pass through an image-point. In the pinhole camera the rays are *not* bent (except for diffraction!) so we call what we see on the screen a *picture*, not an image.

making an image with a fan of rays *in three dimensions.* Do this in a large box of smoke to make the paths of rays visible by scattering.

The smoke box is well worth the trouble of making it. It provides for several demonstrations. (A teacher reports that the idea of rays being bent to pass through an image 'has been accepted readily, *particularly after seeing the smoke box*'.) The box is a large black box with Perspex or glass front and a glass window at one end to admit a fan of rays from a very bright compact light source. The box is filled with smoke and a large converging lens is placed in it.

(Failing that, the smoke may be in the open air of the laboratory—the disturbance is worth it.)

For smoke, the corrugated cardboard used for parcels does well. A bee-smoker—bellows and holder for cardboard—is an easy smoke producer. Or dust of blackboard chalk, shaken out of two dusters clapped together, will suffice. (The trick of doing the demonstration under water containing fluorescein is too confusing.)

Details of Smoke-Box Equipment

The lab must be darkened almost completely except for photographic safelights.

BOX. This is a rectangular box of wood, say 75 cm long by 45 cm high by 15 to 20 cm wide (wide enough to take a small stand to hold a lens or mirror). The front is all Perspex or glass.

The back or the top or both must have a hinged door so that apparatus can be put inside.

At one end there is a glass window (10 cm by 15 cm high); and a slot to hold screens on the window.

The box is painted dull black inside for contrast with the rays in smoke.

There is a hole in the back for the snout of the smoke generator—though a quick smoking through the open door will suffice.

SMOKE GENERATOR. A bee-smoker does well. For fuel use a piece of sacking, or some corrugated cardboard.

LAMP. This demonstration deserves the brightest small source available. A high-temperature source is needed because its light will scatter better. And the source must be small. The compact tungsten-halogen light source is good. A small carbon arc would be even better. (A projection bulb with a larger, cooler, filament may suffice; but one will never know what one has missed.)

The lamp must be well housed to avoid stray light spoiling the demonstration.

SUPPORTS FOR LENS AND LAMP. The lens should rest on a wooden block so that its axis is about 15 cm above the bottom of the box. Then rays emerging from it can slant downward through the smoke as well as upward.

The lamp should be raised so that its filament is level with the centre of the lens.

SCREENS. Two of these metal sheets should have a set of small holes (1 to 2 mm) to select 'rays'. The central hole should be level with the centre of the lens. The other holes should be spaced evenly round two concentric circles.

Screen A	8 holes on circle of diam. about 4 cm
	8 holes on circle of diam. about 2 cm
Screen B	8 holes on circle of diam. about 6 cm
	8 holes on circle of diam. about 3 cm.

There should be one more screen, C, with a single large hole, diam. $4\frac{1}{2}$ cm, to act as a stop to let through a full cone of light. Without any screen, the cone hitting the lens is wider and aberration will be more noticeable. Also the large beam of light entering the window will make interesting but distracting glare in the smoke.

Demonstration 8 Lens and Rays in a Box of Smoke: Real Image

Apparatus

1 smoke box	item 93A
1 smoke generator	93G
1 large plano-convex lens	93B
1 lens holder	93C
1 set of aluminium screens with holes	93D
1 compact light source	21
1 L.T. variable voltage supply	59
1 retort stand and boss	503–505

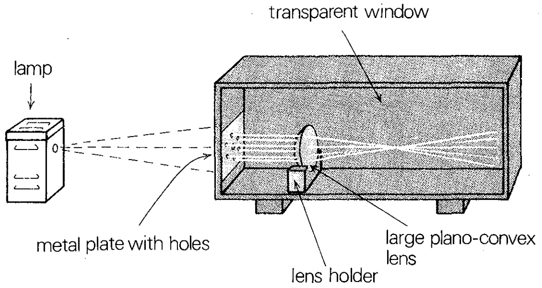
The lens may be of condenser quality, say 10 cm in diameter, 15 cm focal length.

Procedure

Place the lens inside the box, about 20 cm from the entrance end. Its convex side should face the lamp to minimize aberration.

Place the screen with holes on the entrance end of the box.

Light a piece of sacking (about 20 cm^2). When it is burning put it in the smoke generator. Insert the generator's snout in the hole in the back of the smoke box. Several puffs should fill the box.



Arrange the compact light source outside the smoke box about 40 cm from the lens.

Pupils see best if they stand beyond the far end of the box and look 'upstream', towards the lamp. All should have that view in turn, standing quite close.

Move the lamp nearer. Pupils see the image move away.

Remove the screen and show the effect of the lens on the whole beam of light. Show the effect of limiting the beam with a stop.

Smoke box: further work The smoke box will have shown the lens making rays pass through a 'point' image. And pupils will have seen that the rays go straight on—they do not bend at the image as some geometrical-construction methods let pupils think mistakenly.

Pupils who catch the idea with delight may want to demonstrate this at home. They could cut a pepper of holes in a *temporary* window blind at home and demonstrate rays of sunshine hitting a magnifying glass, with smoke produced by home methods. The experiment is worth the sheet of heavy brown paper for the blind.

Other demonstrations with the smoke box can be equally impressive; but they are better postponed so that the forming of a real image has full impact. For later demonstrations:

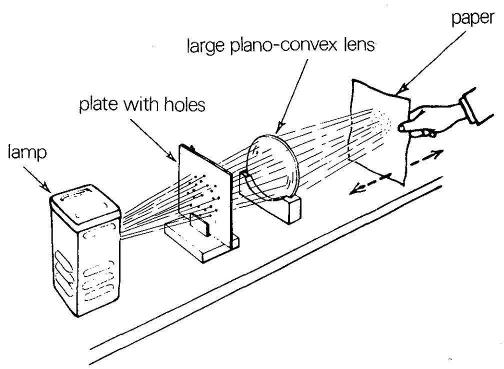
A positive lens can make a *virtual* image (Demonstration 18). The lens must be moved quite close to the front end of the box and the lamp must be closer.

A large *negative* lens in the box will make the concept of a virtual image clear to all. It is worth buying just for that. However, it should not be shown yet, lest it should make pupils think that only negative lenses form virtual images.

A *plane* mirror in the box makes a complicated picture of slanting rays—not so clear as pupils' own ray streaks with a mirror. But a weak *concave* mirror makes a delightful sight.

Sequel to smoke box *After* showing the smoke box, let pupils try a smokeless version in which the smoke is replaced by a sheet of thin paper which they wave in the path of the rays.

Class Demonstration 9 Lens and Real Image: Catching Rays in Open Air *(OPTIONAL)*



Apparatus

1 compact light source	item 21
1 L.T. variable voltage supply	59
1 metal screen with holes	93D
1 large plano-convex lens	93B
3 retort stands, bosses, and clamps	503–506
pieces of thin white paper	

Procedure

Set up the same arrangement as for the smoke box but without the box or smoke.

Light from the compact light source falls on the aluminium sheet with holes. Thick 'rays' of light continue through the screen and hit the lens.

Arrange the position of lamp, screen, and lens so that the lens forms a real image a metre or more beyond the lens, and rays from the outer holes in the sheet meet the lens near its edge.

Although the lens bends these pencils to pass through the image point, neither rays nor image are visible in the dark room without smoke to scatter light. Then show that there are rays proceeding from the screen to the lens by moving a piece of paper to catch those rays in the space *between the screen and the lens.*

Ask what happens to the rays beyond the lens. Let each pupil come to the bench in turn to see what does happen, by waving a sheet of paper in the space between the lens and the image, and on beyond. If a large lens is used in the paper-waving experiment, colour effects may be noticeable. If pupils comment on them, we might say:

> 'You can see the lens is stronger for blue light than red. How would that difference affect a large telescope?'

(The description 'stronger' is a more convincing one than 'smaller f'. It is also more modern optics.)

Rays in a camera By now, pupils can imagine what rays do inside a camera. They should also make a model with real rays. Although the series of class experiments with ray streaks comes later, the camera model is so simple that it can come now. It also forms an introduction to the ray-streaks equipment.

Class Expt 10 Model of Rays and a Camera with Ray Streaks

(See the preface to Experiment 19 for details of equipment.)

As this is an early experiment before the general use of this equipment it would be very helpful if the lamps could be arranged and connected to the transformers beforehand.

Pupils work in pairs.

Apparatus

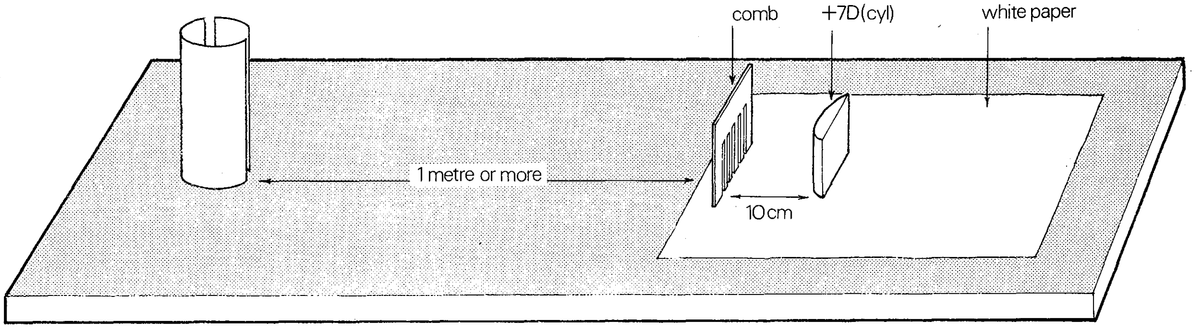
From ray optics kit:	item 94
16 lamps, holders, and stands	94A
8 pairs of housing shields	94B
16 metal combs	94E
16 holders for combs	94F
32 barriers	94G
32 plano-cylindrical lenses +7 D	94H
3 transformers	27
sheets of white foolscap paper	

Procedure

Show pupils how to stand the cylindrical lens on its base, with the comb about 10 cm in front of it.

Pupils then follow these instructions:

* * * * *



Put your sheet of paper at one end of your table. Your model camera will be there.

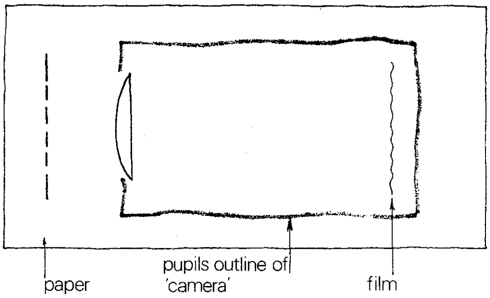
Place your lamp about 1 metre from the paper. *Raise or lower it till light from it shines right across the paper.*

Place your lens, upright, about 10 centimetres from the end of the paper near the lamp.

Place your comb at the end of the paper so that rays of light come shining through it to the lens. *Can you see the image of the lamp, where all the rays meet?*

Now draw an outline of a camera box on the paper with a front opening where the lens is, and a place for the 'film' at the back where the image is.

Borrow another lamp and place it beside your lamp. You can see how those two object-points make two image-points where the film should be. You might imagine those are the head and toes of a person being photographed.



Now move one of the two lamps nearer the camera. See how you get a patch on the 'film' instead of a point. A patch like that for each point of the original object would make an 'out-of-focus' picture.

Keep the two lamps where they are, at unequal distances. Make the front opening of your lens narrower by pushing in some small barriers to stop the outer rays from getting through. See what that does to the 'out of focus' patch on the 'film'.

* * * * *

'Fixed focus' When pupils try that experiment and see the effect that stopping down has on real rays we can discuss the 'fixed focus' advantage of cheap cameras—and mention the disadvantage of long exposures. At a later stage, pupils will see aberration with a wide lens and then we can explain the need for expensive compound lenses.

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

However, we shall presently give a scheme for drawing diagrams that show clearly the rays and images that our eyes use in looking at things with optical instruments.

We provide, in the *Pupils' Text 3*, a series of pictures to show the drawing of such ray diagrams. Those sketches should not be studied or used until pupils have worked with the instruments themselves and with models of those instruments that use real rays of light.

So all we suggest for a class discussion now is a very short talk, with blackboard sketches, of the way in which the lens in the front of the pinhole camera seems to 'collect up the rays' and 'bend them so that they all run together at a sharp point'.

We should now introduce the name 'image', for the place through which rays pass.

If we were teaching much older pupils we should do well to give a formal definition of an image as in the private note to teachers on page 36.

With pupils at the present stage, formal definitions would only spoil their growing intuitive knowledge. The *Pupils' Text 3* is leading them through their experiments to an understanding of images and their use, without formal definitions. And examinations will enquire for informal understanding without requiring definitions.

In describing image-formation now, we should say something much simpler about real images, like the following—virtual images can come later.

You see a thing by receiving rays which come straight to your eye from each point on the thing.

A lens bends the rays that come from a bright point and makes them all pass through another bright point we call the image. You see that image by receiving rays that come straight from it to your eye.

Rays never bend as they go through an image.

That is what a camera lens does for us. It makes an image of the thing we want to photograph, and we put the photographic film just at that image.

But perhaps the image is there anyway, whether the photographic film is there or not, whether the camera box is there or not, whether *you* are there or not. Perhaps you could see the image by letting your eyes receive rays of light that have come to the image and passed straight on through it. Look at that for yourselves.

A lens forms images Give each pupil a positive lens and let him look for the image of a distant window.

Class Expt 11 Viewing a Real Image formed by a Lens

Apparatus

32 lenses +7 D item 112
32 sheets plain white paper
32 small pieces greaseproof paper or oiled tissue paper

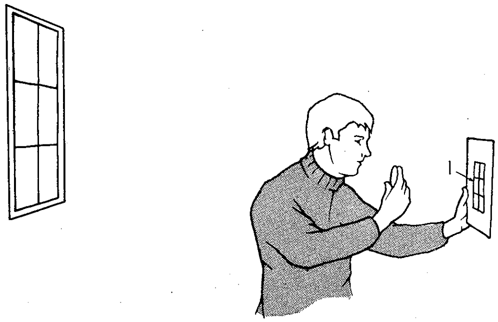
Each pupil should have his own lens, the positive lens that was used for the camera. It will soon be used again.

The room should be a quarter or half dark, the source of light may be a window. (If an electric lamp has to be used the room should be at least half dark and a carbon-filament lamp (item 91C) and mounted lampholder (item 91D) will make a suitable object.)

Procedure

a. Image on Paper. The pupil sits or stands with his back to the window, holding a sheet of paper at arm's length in front.

With his other hand, he holds the lens between the paper and his face, so that light from the window goes over his shoulder, and through the lens, and reaches the paper. He moves the paper nearer and farther till he catches a sharp image of the window on it.

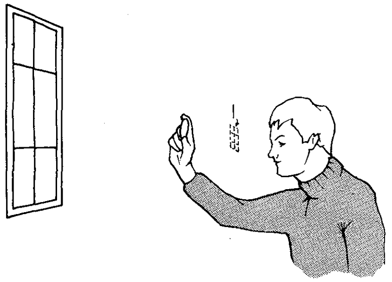


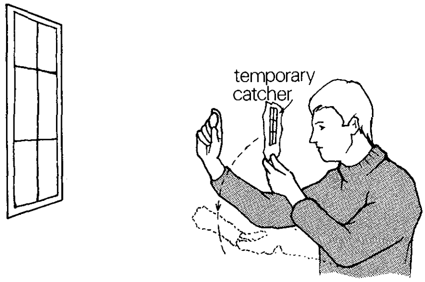
Suggest to him that this is like a camera, without a box.

b. Image in Mid-Air. 'Is the image still there without the paper?' That is the question we are asking in this experiment. The pupil needs to look for the image from behind the paper—an impossible contortion at present. He must turn round and start again.

Facing the window, the pupil holds the lens at arm's length. He hunts for the image.

'If you can't see the image, try to catch it with a scrap of thin paper like the back of your camera. Hold the scrap a little way from the lens, then a little further back, then farther.





Remember that you see a thing with your eyes when it is some distance away. You can't read a book crammed against your face.'

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

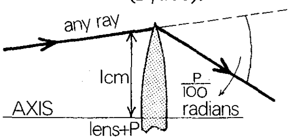
Lenses of different powers In *Pupils' Text 3* there are sketches of different shapes (biconvex, plano-convex, meniscus) and different powers ($+7$ D, $+14$ D) and a negative lens. The D stands for the spectacle-maker's unit, a dioptre. That is a reciprocal metre, m^{-1}, and is 1/ (focal length of the lens, measured in metres).

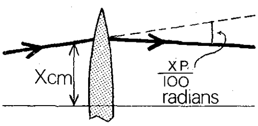
In professional optics the power, $1/f$, which is also the change of curvature that the lens imposes on a spherical light wave, is more important than f.*

When they first meet a lens, pupils should find out something about its power by feeling its faces. But they must then clean it with clean tissue—not a gritty handkerchief—or wash it with soap and water. They will soon have an easier way of judging the power of a lens.

As preparation for making a telescope, pupils should look at the sizes of images made by strong and weak positive lenses: a very quick experiment.

* Also, in formal geometrical optics, where neither rays nor lens-surfaces are very oblique, power $1/f$ gives a measure of the deviations the lens imposes on rays. Suppose the lens has power P, in dioptres. Choose a small part of the lens 1 cm above the axis. *Any* ray that hits the lens there is bent by the lens through an angle $P/100$ radians. At x cm above the axis the deviation is $x(P/100)$.





Class Expt 12 Comparing Short Cameras and Long Cameras

Apparatus

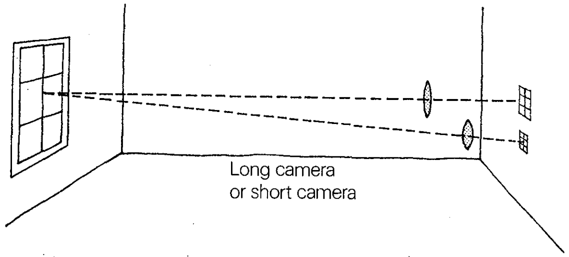
32 plano-convex lenses $+7$ D	item 112
16 plano-convex lenses $+2.5$ D	113/3
cleaning tissue	
bath of water and detergent	

Procedure

Pupils work in pairs but each should try the experiment for himself. They feel their lenses, then clean them. 'Soap and water are good for cleaning: a handkerchief is risky because dust in it may scratch a lens.'

Each pupil holds the $+7$ D lens in his fingers and catches the image of a distant window (or lamp) on a wall or a sheet of paper. He repeats that with the $+2.5$ D lens.

Ask: 'Which lens makes the larger image? Which lens needs a longer camera? What kind of lens would you expect to find in a tiny camera used by a secret agent?'



Now lead to a telescope (as in *Pupils' Text 3*):

Suppose you wish to look at something $\frac{1}{2}$ kilometre away, a cow in a field or a bus in the street. You can use a lens to make an image of that object, as in a camera. But without a film or anything else at the back, the rays go straight on through the image, and you could let them enter your eye. The image is very small, much smaller than a real cow or bus; but it is close to you. You can march right up to the image and look at it with a magnifying glass.

Then you have a telescope.

Making a telescope At this point, or even earlier, pupils should set up a simple astronomical telescope. *Our aim is success*—otherwise optics will make a poor start of peering and doubt. Even if the teacher has to give help to many, even if the focusing is far from correct, immediate success with a practical instrument will give optics valuable interest and encouragement.

Little explanation is needed now. Later, when rays and images have been examined in other experiments, pupils will come back to the telescope. Then we can ask all to do their own focusing if they possible can; and we can expect them to understand what they are doing.

The first simple explanation Pupils have seen a single lens forming a real image at the end of a camera box—and, if they have any sense of delight in science, they will have been upsetting people at home by trying the same thing with every magnifying glass they can lay hands on. (Unfortunately most modern spectacles include a correction for astigmatism so they give a disappointing puzzle when pupils extend their operations to them as well.)

Start pupils on a telescope thus:

The first lens is a weak one that forms an image of the distant lamp (just as a strong lens does, but not as close). You can catch that image on a scrap of tissue paper behind the lens.

[That is why we want a bare filament lamp, for a bright image.]

Look at that image with a magnifying glass.

Equipment for Telescopes, etc.

Pupils need to assemble and adjust a simple telescope and other instruments comfortably, and quickly. For this we recommend the following:

THE MOUNT. This should be a simple bar to carry sliding lens-holders. It should be free from distracting centimetre and millimetre graduations. It need not be as heavy or as long as an optical bench—$\frac{3}{4}$ metre will suffice.

Squatting or bending over to look through a telescope at bench level puts the observer at a considerable disadvantage. He must roll his eyes upward in a way that easily produces headache. Therefore the telescope bar should be held at head height on a tall retort stand, so that the lenses are at eye level. The clamp holding the bar should allow it to tilt so that pupils can direct their telescope at an object higher up.

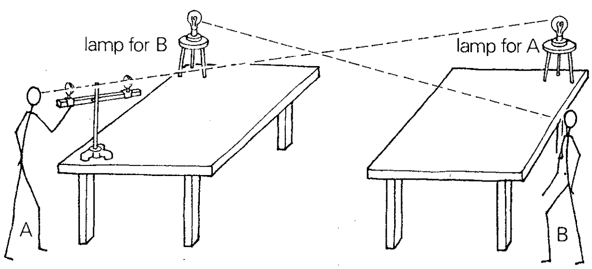
LENS-HOLDERS. These should accept lenses easily and hold them firmly with their axes parallel to the bar. They should be carried on simple saddles or bulldog clips so that pupils can move the lenses easily in a half-dark room.

THE LAMP AS OBJECT. A large carbon-filament lamp run at normal voltage serves very well, in a room that is half or three-quarters dark.

Pupils hunting for an image—which is an unfamiliar thing—find it more easily if the object is very bright.

However, some teachers prefer a less bright filament. For that a variac or rheostat should be inserted in the lamp circuit.

With a small class group, all the pupils can set up their telescopes at one end of the room and view a lamp placed at head-height at the other end.



With a large class group, half the class should be at one end of the room and half at the other end. Then two lamps are needed, one at each end of the room. They should be placed high up, well above head-height, so that pupils at one end of the room can view the lamp over the heads of the pupils at the other end.

LENSES FOR TELESCOPE. The objective is a weak spectacle lens, preferably plano-convex or meniscus, of power about 2.5 D (f = 40 cm). It is placed with the convex face towards the object, away from the observer.

The eyepiece is preferably plano-convex or meniscus (though a biconvex one will do) of power about +14 D ($f \approx$ 7 cm). It is placed with the convex face away from the observer.

{**Note to teachers: eye ring** With telescopes, and some other optical instruments, there is an optimum position for the observer's eye that gives the largest field of view. That is the 'eye ring' or 'exit pupil'—a small region through which all the emergent light goes. Although there is no need to teach the meaning and use of the eye ring, some pupils may notice it; and teachers will find a knowledge of it valuable in helping pupils to use instruments. This is especially important in our models of telescope and microscope, where the eye ring is a long way beyond the eyepiece.}

{*To see the eye ring,* hold a telescope at arm's length and point it at white sky. Look towards the eyepiece. There will be a small bright disk of light just outside the eyepiece. The disk can be caught on a scrap of paper; so it is the real image of something round.}

{*The eye ring is an image* of the face of the objective lens, formed by the eyepiece. *All* the rays of light that go through the telescope come in through a round 'hole', the aperture of the objective lens. Then *any* ray that hits the eyepiece comes straight to it from some point on the face of the objective lens. And when such a ray emerges from the eyepiece it must go straight through the image of that point on the objective lens. (Any ray from an object-point goes through the image-point—that is the nature of an image!) Thus, all rays which come in through that round hole and hit the eyepiece must then go through the image of that round hole that is formed by the eyepiece. That image, itself a disk, *is* the eye ring.}

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

{*The observer's own eye-pupil* is also a limiting disk. If it is smaller than the eye ring he will use only part of the light that goes through the telescope, the part that goes through a smaller 'hole' in the objective than the full aperture. In that case, one might economize and reduce the aperture of the objective.}

{If the observer's pupil is larger than the eye ring he will receive all the light that enters the objective, and could profit from a still wider objective. However, a wider objective will cost more and its outer regions will produce aberrations, unless the lens is a well-designed compound one, increasing the cost still more.}

{*Most instruments* are designed to have the eye ring close to the eyepiece, for convenience—exception: telescopes on guns! But in our models the weak eyepiece forms the eye ring a long way out; so a pupil may need help in placing his head.}

{*To locate the eye ring of a model quickly,* hold a frosted or opal lamp up against the objective, and explore with a scrap of paper beyond the eyepiece.}

Class Expt 13 Making a Telescope (First attempt)

Apparatus

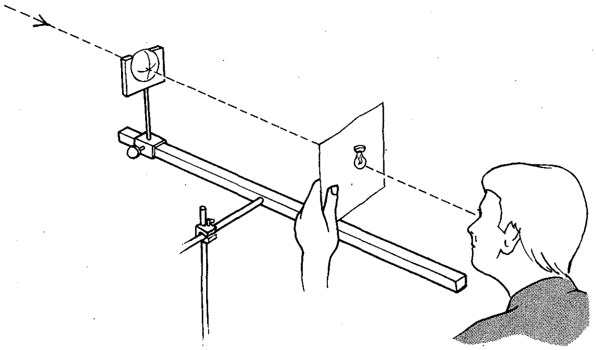
16 telescope mounts	item 115
16 tall retort stands and bosses	503–505
16 plano-convex lenses (+14 D)	113/1
16 plano-convex lenses (+2.5 D)	113/3
2 200-watt carbon filament lamps	91C
2 mounted lampholders	91D

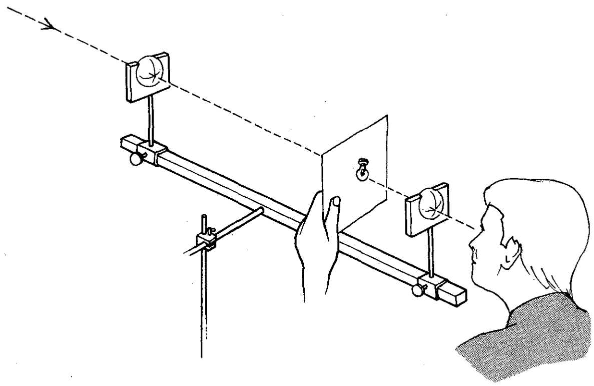
Pupils work in pairs. (If more than two share the apparatus some will miss the personal experience, or else the experiment will drag on too long; and in either case future experiments will be damaged.)

Procedure

Pupils put the weak +2.5 D lens in a holder at the far end of the mount. If it is plano-convex the convex face should be towards the object.

Pupils raise the telescope mount to shoulder height. They turn and tilt the mount till it is aimed at the distant lamp. They catch the real image of the filament on a scrap of tissue or greaseproof paper—'like the back of the pinhole camera'.





They install the eyepiece, +14D, as a magnifying glass to view the scrap of tissue.

Each pupil in turn then 'makes the telescope work', with help from his partner and, as much as is needed, from the teacher.

Instructions for Pupils

The *Pupils' Text 3* offers a lot of help. *For some pupils the following instructions will suffice:*

* * * * *

Hold the scrap of tissue where it catches the image. Slide the magnifying glass nearer and farther till you see the scrap clearly magnified and in focus. Take away the tissue and you will be looking through a telescope at the lamp.

Help from a partner. Let your partner hold the tissue and catch the image of the lamp, while you move the magnifying glass until you can see the tissue clearly magnified. He should remind you again and again to 'WATCH THE PLACE WHERE THE TISSUE IS'.

Keep your magnifying glass there while he takes the paper away (or half away), leaving you to look at the image there.

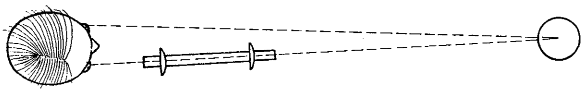
For comfortable use, the magnifying glass must give you a final image to look at which is far away. It should be as far out in front as the object itself.

If you find it difficult to focus your eyes on something far off in mid-air ask your partner to point to the distant lamp and say 'The image should be back THERE.'

What should you do with the other eye, the eye that is not looking through the telescope? The best thing of all is to behave like a professional telescope or microscope scientist and teach the other eye to be 'blind' for the moment while you are using the instrument.

Until you have learned how to do that, the best thing is to cover the other eye with a hand or an eye-patch. (If you just close the other eye by tightening up the muscles round it, you will also tighten up the muscles round the eye that you are using for the eyepiece. You will torture both eyes. That will make it difficult to see well.)

When you have made the telescope work, so that you can see the distant lamp, open the other eye and use your two eyes to get the telescope properly focused.



The eye at the eyepiece looks through the telescope at an image of the distant lamp; while the other eye, the naked eye, looks straight at the distant lamp. Can you see them both together clearly? *If you can, does the telescope picture of the lamp look larger than the picture seen by the naked eye?*

If they are not both in focus at the same time, move the eyepiece forwards or backwards a little until you do see both clearly at the same time.

The naked eye is the one to pay attention to when you are trying to focus a telescope with both eyes open. It is not easy at first to keep both eyes open and see those two different things. Your partner can help. He should stand beside you and tell you to keep both eyes open. He should say: 'Remember, the naked eye is looking at something far across the room. Keep on paying attention to the NAKED EYE and move the eyepiece until your telescope-eye sees something clearly at the same time.'

Your partner should also watch your eyes and if you try to shut one eye he should say: 'Open both eyes *with wide-eyed surprise.*'

That will help you to raise your eyebrows and keep your eyes wide open, and that in turn will help you to succeed.

You may need some extra help from your teacher; but once you have learned to focus your telescope you will find that it grows easier and easier; and you can soon use your telescope for many things.

If you see only a little of the lamp (a small field of view) try pulling your head a little farther back from the eyepiece. There is a good place for your eyepiece-eye which gives you the widest picture. Move your head back and see if you can find that place.

As soon as you have made your telescope work, ask your teacher to come and look at it. Then your partner should have his turn with it.

* * * * *

Ensuring Success: Helping Pupils

Success is paramount at this first try; and skill and confidence are closely connected. Many pupils will need help and encouragement from the teacher and it may be best for their learning if the teacher makes the adjustment for them, lets them look, then undoes the adjustment and encourages them to try again.

The three main difficulties for novices are:
(1) There is a large range of eyepiece positions which will give a final virtual image within the large range of accommodation of a young pupil.

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

(3) The observer's eye needs to be at the right distance behind the eyepiece or else the field of view will be small. It should be at the 'eye ring'. We can see that eye ring, and even catch it on a piece of paper, if we hold any telescope at arm's length and direct it at a bright sky: the eye ring is the bright disc of light just outside the eyepiece. A good telescope is designed to have the eye ring only a short distance outside the eyepiece, so that the observer can bring his face close to the instrument. But in our simple telescope, the eye ring will be about 8 cm thick.

If the teacher has practised placing his own eye at the eye ring so that he gets a large field of view, he will find it easy to guide pupils to a suitable position. If he faces a pupil who is adjusting a telescope he can see the eye ring on the pupil's eye, when the latter is at the best position.

To deal with difficulties of focusing or image-placing say to the pupil, when he is placing the final image:

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

And, to find the place for the observer's head,

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

After adjusting the eyepiece for the pupil let him have a good look. Then move it and say: 'Now it's your turn; you have a try.' Stay beside him and knowing roughly where the eyepiece is for the right adjustment, help him by encouraging remarks or just an anxious tense movement—which the pupil picks up. When he succeeds, even poorly, give praise. ('Look how skilful you can be.')

This is a place in teaching where we have found strong *suggestion* often leads a pupil to skilful independent success.

Then ask that pupil to shift the eyepiece and try to teach his partner. Move on to other pupils.

This first time, the telescope should just be used for looking at things. When they return to it later, pupils will try estimating magnification; and some may practise moving the final image to a different distance, such as $\frac{1}{4}$ metre.

Using the Telescope

Pupils should direct their telescopes at familiar objects. One teacher reported that not until pupils looked at the printing on spines of books across the room were they willing to agree that their telescope really magnified.

Let pupils look out through an open window with their telescopes.

A look at the Moon is not only a special delight; it can persuade pupils who found focusing their telescope too difficult to succeed at last. (Half moon shows the mountains: full moon glares.) We hope schools will find it possible to let pupils take a telescope home for a night or for the weekend.*

* *Insurance for Apparatus taken Home.* To encourage home experiments by pupils as an important educational activity, a small private fund is available to underwrite

Pupils' own eyes. Accommodation Pupils have been exercising the accommodation of their eyes. Now ask each pupil to find his own range of comfortable vision.

Those who wear spectacles might well do this with their glasses on and then without. We hope our optics teaching will be of interest and value to spectacle wearers.

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the possible loss or damage of apparatus while on loan.

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

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

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

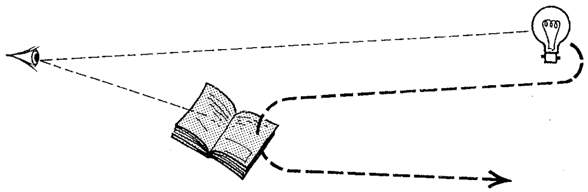
The Westminster Electromagnetic kit provides excellent material for some experiments at home. Some of the simpler components can probably be replaced by things made at home or bought by pupils; but the magnets will be essential for success with the little motor. We hope that teachers will let the magnets go home on loan despite their reputation for disappearing. The insurance fund is intended to make it easy to enable schools to allow such loans.

Reimbursement. Where a school lends items of apparatus to a pupil to take home for experiments and finds that they are not returned or that they come back damaged or broken, teachers should apply to:

The J. Willmer Home Experiments Endowment, c/o The General Secretary, Association for Science Education, College Lane, Hatfield, Herts.

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

Class Expt 14 Pupil's Range of Clear Vision: Accommodation



Procedure

First, ask each pupil to *feel* a change of focusing—which we call accommodation:

> 'Look at a book and read a few words. Then look quickly at the far wall of the room. Then back at the book . . . at the wall . . . book . . . wall . . . book/wall. Can you feel your eye lens being squeezed and let go?'

Then ask each pupil to find his own range of comfortable vision.

Pupils already know their farthest limit: a distant tree or bus at the end of the street, or a star—we call that 'infinity'.*

Ask each pupil to hold a book and bring it closer until he can no longer focus it comfortably. (He should cover one eye, to make this test easier.) Then he should make a note of his range: from there to infinity.

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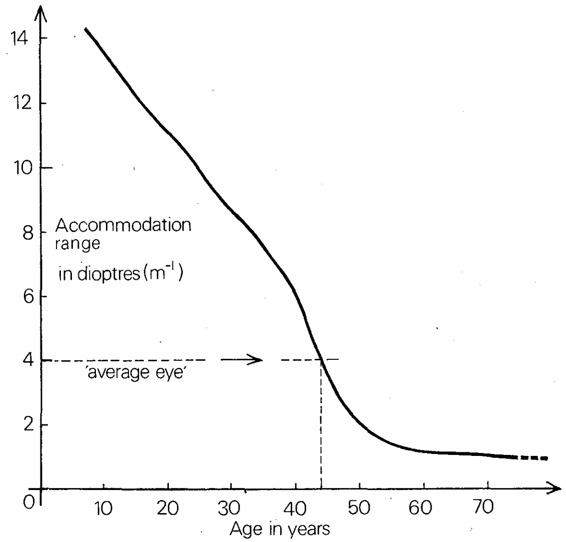
* Young children and some older people with long sight can focus 'beyond infinity'. There is no paradox, except in the name. This merely means that the lens system of the eye is so weak that it can bring to focus on the retina a group of incident rays that are already *converging*. Instead of *diverging from* an object-point at some distance in front of the person, those rays are *converging towards* a point some distance behind his head. We might call that a 'virtual object'.

(The Boy Scout's Baden-Powell telescope trades on this: it is a very weak positive lens held out at arm's length. The lens is so weak that it produces a real image some distance behind the boy's head. His eye intercepts the light on its way to that image—which acts as a 'virtual object'. The virtual object is within his range, at his age. His eye forms a retinal image which is larger than the picture of the countryside formed without the lens.

This device can also be used by a long-sighted adult without his spectacles—or he can just hold his own spectacles out in front.)

Accommodation and age Young people have a tremendous range of accommodation. Any attempt to settle on $\frac{1}{4}$ metre as the closest distance of comfortable vision will lead to confusion and disbelief. We should accept the actual range that each pupil finds.

But then we tell pupils that older people do not have such a large range. They cannot see a printed page clearly when it is held so close. Also it may be uncomfortable for their arms; and it is likely to be poorly lighted. And ordinary printed type will look very large when held so close. Books are printed with type that will look a comfortable size when held about $\frac{1}{4}$ metre away; and at that distance the reader's arms are comfortable and the lighting can be arranged fairly easily. So we pretend that an 'average eye' likes to have things $\frac{1}{4}$ metre away, or farther, for comfortable vision.



The graph shows the range of accommodation of a human eye, plotted against age. The range is in dioptres, reciprocal metres (metre^{-1}). Although people of a given age differ widely in the placing of their near point, their *range* [1/ (near point distance)—(1/ (far point distance)] is much the same for most of them.

At age 40 the *range* is about 4 D. So we may think of an 'average eye' as belonging to a person of age 40 with a near point at $\frac{1}{4}$ metre and a far point at infinity. Another 40-year old person whose near and far points are different can bring his range to that of an 'average eye' with a single pair of spectacles.

Spectacles Ask pupils what a short-sighted man's spectacles really do when they change his seeing to that of an average eye. The answer we hope for is: 'When the *object* is *in the average eye's range* his spectacles give him an *image* to look at *in his range*.' Asked now or earlier, that question could have a title that we recommend for good teaching: '*A question for thinking ahead*'. But we should soon discuss the use of spectacles.

Short Sight, Long Sight, and Spectacles as Image-Formers

Pupils will need teaching and discussion, such as the following (as in *Pupils' Text 3*):

Short sight and long sight Some people have extra strong eyes so that their range for comfortable seeing is closer; for example, from 15 to 40 centimetres (6 to 16 inches). And things beyond 40 centimetres (all the way out to a tree, bus, or mountain at infinity) would be too difficult to focus; they would look fuzzy. So we call them short-sighted.

Such a person could read a book because the convenient distance, $\frac{1}{4}$ metre, is within the range for *his* eyes. But he would need spectacles for looking at things far away.

A long-sighted person has a range which starts farther out, for example from $\frac{1}{2}$ metre out to infinity (and, in a certain sense, beyond 'infinity'). So he can see a distant view or stars without spectacles; but he needs spectacles to read a book held at $\frac{1}{4}$ metre.

Spectacle wearers have their lenses designed to add just the right amount of lens POWER, so that the combination (spectacle lens + eye) has the same range as someone of the same age who does not need spectacles.

Spectacles are image-formers Spectacles, like all other lenses, form images. They take the object that you want to look at and move it, *optically*, to an image for you to look at instead. The image is then at a place where it is comfortable for your eyes to see it.*

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* Many people need an extra piece of help from their spectacles for clear seeing, because they have what is called '*astigmatism*'. That just means that their eyes have a front surface shaped more like a rugger ball than a soccer ball. That is common and harmless. It is corrected by spectacles with a surface that is curved more strongly in one direction than another.

Contact lenses take the place of the front window of the eye, for bending rays of light. So, contact lenses with spherical faces can usually 'remove' astigmatism.

If you have astigmatism, you should keep your spectacles on for optical experiments. If you have little or no astigmatism you may take your spectacles off for some of our experiments.

If you find an old spectacle lens and try using it to form an image of a window or the Sun, it may make something like an image but with streaky lines instead of a clear sharp shape. Then that may be a lens made for a person with astigmatism. You should not use it for your optical experiments because it will complicate things.

The Logan experiment There is a simple way to let a pupil see what the world looks like to a short-sighted person, or a long-sighted one, without correcting spectacles. With our method of using images and lens-powers it is obvious; but few teachers used it until it was suggested by T. H. Logan. Teachers who try it will be surprised at the charitable understanding it gives of 'the other man's view'.

Class Expt 15 How does the World look without Glasses? *(OPTIONAL)*

Apparatus

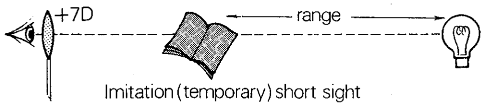
For each pupil:

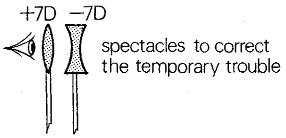
2 positive lenses +7 D	item 112
2 negative lenses −7 D (see below)	211

Procedure

A person who normally wears spectacles keeps them on. Then we are dealing with people who have, effectively, average eyes for their age.

Short Sight To see the world as a short-sighted person sees it without his correcting glasses, the pupil holds positive lenses, +7 D, in front of his eyes (or in front of his own glasses). The +7 D lens makes images for the pupil to look at.





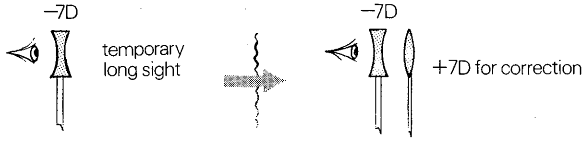
The 'average-eye' range is from infinity in to $\frac{1}{4}$ metre or, in terms of power of the incident fan of rays, from 0 to 4 D. The extra +7 D lens brings that range in closer so that it runs from $(0+7)$ D to $(4+7)$ D or from 7 D to 11 D. Then these modified eyes are short-sighted with range from $\frac{1}{7}$ metre to $\frac{1}{11}$ metre. Instructions:

> 'Hold the +7 D lenses in front of your eyes (in front of your spectacles if you usually wear them). Look at the view through the window. That is what a short-sighted person sees.
>
> 'Now add spectacles to correct your temporary short sight: hold −7 D lenses in front of the lenses you are already holding.'

At age 14, a pupil has a much larger than average range; but the +7 D lenses bring his near point and far point in still closer, just as effectively.

Long Sight. To imitate long sight, the modifying lenses must be negative—the opposite of a real long-sighted person's correcting spectacles. If the pupil holds negative lenses in front of his eyes (or his own glasses) they will push his *range* outward.

The choice of power for those negative lenses depends on the pupil's own range, and therefore on his age. At age 14 the range will be much greater than the 4 D 'average-eye' range from $\frac{1}{4}$ metre to infinity. We want the modifying lens to push the pupil's near point out beyond a usual reading distance, say to $\frac{1}{2}$ metre.



For the best choice of lens, find the individual pupil's near point for clear seeing. Suppose it is 11 cm from his eye. Rays from there to his eye arrive in a fan of power 1/(0.11 metre) or 9 D. To make him temporarily long-sighted with a 'resultant' near point at $\frac{1}{2}$ metre, taking a fan of power 2 D, the modifying lenses should have power −7 D to carry 9 D away to 2 D. A negative lens −7 D with $f = -14$ cm, or any stronger one, would do well. (But a weaker lens with $f = -20$ cm would only carry *his* 'resultant' near point to a usual reading distance $\frac{1}{4}$ metre, so it would not be impressive.) Instructions:

> 'Hold −7 D lenses in front of your eyes. Try to read a newspaper. Then add spectacles to correct your temporary long sight. These should be +7 D lenses, held in front of the others.'

The short cut. An able pupil who understands the idea of this quick experiment may say: 'The easiest way is to borrow someone else's spectacles and hold them in front. If he is *short*-sighted, I then see what a person with *long* sight sees. If he is *long*-sighted I then see what a person with *short* sight sees.' He is right.

The 'cure' when correcting spectacles are added is even more impressive than the 'blur' that pupils see with their modified eyes uncorrected.

{**Note to teachers: 'focus' and 'focal length'** We have not so far suggested any mention of the image of a distant object being at the 'focus' or 'principal focus'. That is an intentional omission. In the usual elementary optics 'the focus' is apt to assume a peculiarly important position in pupils' thoughts; rather like 1066 in History. It becomes a mysterious, important place through which 'parallel rays'—rays parallel to anything, in the mind of a confused pupil—must pass.}

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

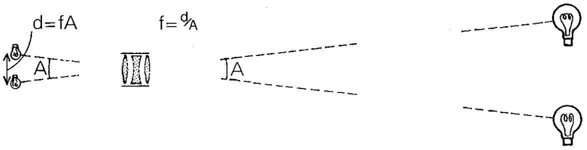
{Nor in this programme should we make the 'focal length' too strong an object of worship. In practical use, a lens has a great deal more than just a focus and a focal length. Long ago The Physical Society of London issued a Report on the Teaching of Optics* which wisely directed attention away from the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

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

{It also tells us the *deviation* each part of the lens imposes on *any* ray that is not very oblique. Any ray striking the lens at a height h above the axis suffers a deviation $h(1/f)$ radians.}

* That report gave the excellent general method of measuring f of any lens, thin, thick, or compound, positive or negative, a method used by professional testing labs. Here it is, not for pupils, but in case teachers find it useful:

Set up a pair of objects, far away, one above the other—two lamps, or the bars of a gate. Measure, once and for all, the angle A subtended at the test bench by the height between those remote objects. Direct the axis of the lens under test towards the objects and measure the height between their images. That height is fA.



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

Meeting a lens Nevertheless pupils should know how to make a rough estimate of f for a positive lens. *Pupils' Text* says:

> Professional scientists make measurements of each lens they use. You will not need to do that, because you will be using lenses to make things like telescopes without needing exact measurements. Yet you should try the strength of a lens roughly when you first meet it rather like shaking hands with a person when you first meet him.

Class Expt 16 Meeting a Lens and Judging its Strength

Apparatus

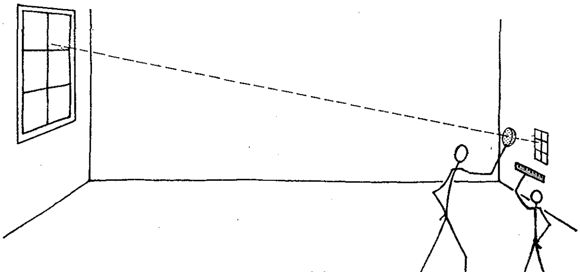
32 lenses, +7 D	item 112
some positive lenses of other powers should be available also (e.g. +14 D, +2.5 D)	
bright window (or lamp, such as 92C, D)	
light-coloured wall or pieces of white paper	
32 centimetre rulers	502B

Procedure

Pupils follow these instructions.

* * * * *

Take the lens to a wall opposite a window or lamp. (Or hold a sheet of paper in one hand and hold the lens in the other hand towards a window or a lamp.) Move the lens until you catch an image of the window (or lamp) on the wall or paper.



Rough estimate of 'f'

Look at the distance from lens to image and measure it roughly. We call that the 'FOCAL LENGTH' of the lens.*

* * * * *

* If some pupils have previously started optics in a different scheme of teaching, it may be necessary to assure them that here the emphasis is on the way in which lenses make rays form images and the use of images to explain the working of telescopes, cameras, eyes, etc. Here, they will not need to learn definitions of F and f or use $1/v \pm 1/u = 1/f$ or make constructions using a ray through F.

Discussion Tell pupils they can do the same thing with the Sun as object, instead of the window or lamp. 'Let the lens form an image of the Sun on a piece of paper. In bright sunlight, the paper will soon catch fire. You are using the lens as a burning glass.'

Class Expt 16X Burning Glass
(OPTIONAL)

If circumstances are favourable, let each pupil use a +7 D lens as a burning glass. Give lenses of other powers to those enquirers who ask for them.

Pupils' Text 3 says:

The image of the Sun is like a burning fire in a hearth, so it is given the Latin name for a hearth, 'focus'. When any object is far away, like the Sun, the image is *at* the focus of the lens, F; the distance from lens to focus is called the 'focal length', f. The stronger the lens, the shorter the distance it needs to bring rays to a focus at an image, the shorter its focal length.

In your work with telescopes and spectacles and eyes, you will not need to use the focus for drawing diagrams; and you will not find the focal length very important, except as a rough measurement that tells you how strong a lens is.

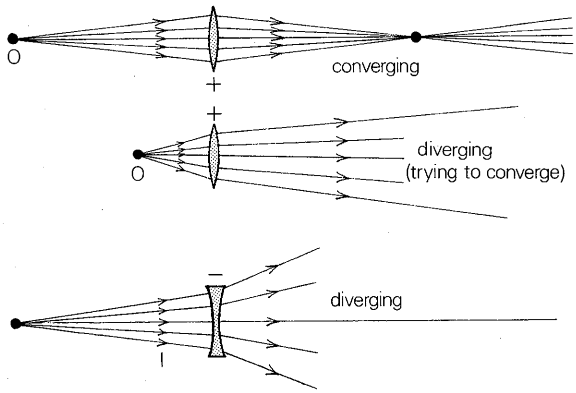
Power of a lens Tell pupils that if f is measured in metres, $1/f$ gives the POWER. Giving the units as metre^{-1} will invest lens POWER with an unwelcome air of being difficult, when in fact pupils can comprehend and use +7 D, +17 D and even −17 D quite easily. At this stage, we should avoid reciprocal metres in any form, and just label those units 'dioptres', D for short, as spectacle-makers do all over the world.

Give pupils very brief practice with a few examples—but not enough to bring focal lengths into prominence. For example:

What is the power of each of the following: f = 2 metres; f = 0.2 metres?

What is f for each of the following: power 2 D; power 7 D? (Perhaps ask whether their answer for 7 D fits with the box they used for a camera.)

Positive and negative lenses So far we have labelled a lens +7 D without explaining the + sign. Sketch for pupils a positive lens and show it making rays *converge* to a real image point—also, if they are ready for it, show the lens *'trying to make rays converge'* when it forms a virtual image.



Then sketch a negative lens making rays splay out. This should be *very* quick and rough—no constructions, just sketches—because pupils will soon see real ray streaks for themselves.

Point out the difference for distant objects: a positive lens makes a real image that can be caught on a wall or a sheet of paper. A negative lens fails to do that—so to estimate its focal length and power we would have to proceed in a roundabout way.

Suggest pupils might find a neighbour who is short-sighted and ask him to try whether his spectacles will form a real image of a window or the Sun.

> 'Then, which kind are those spectacles for short sight? Long-sighted people need the opposite kind of spectacles.'

Virtual image Then pupils should look at a virtual image. This is a very important experiment for their understanding of instruments. At this stage we should just let them do the experiment. We should not insist yet on a clear grasp of the concept of a positive lens making a virtual image; there are supporting experiments ahead.

Class Expt 17 Magnifying Glass: Virtual Image

Apparatus

32 lenses, +7 D item 112

Pupils work singly.

Procedure

Pupils follow these instructions:

* * * * *

The positive lens that you have been using to make real images will also act as a magnifying glass—as you know from your telescope experiment. Find out how it does that. Use it to look at your thumb. (If you wear spectacles for reading it is best to keep them on for this experiment.)

Hold the lens *very close* to your eye with one hand. Hold the thumb of your other hand at the right place for looking at it with this magnifying glass. Move the thumb nearer and farther away until you see it clearly in focus. Then whip the lens away and see whether you can still see your thumb.

Without the lens, you can see that your thumb is still there; but it looks fuzzy. It is too close for you to see it in focus. It is much closer than your eye's near-point of comfortable seeing. You cannot change the lens inside your eye enough to focus it.

Now put the magnifying glass back. You can see your thumb comfortably and it looks large. You are looking at an image of your thumb. Where must that image be?

* * * * *

Discussion Argue that the image must be out in front—a virtual image—but do not labour the point at this stage. *Pupils' Text 3* says:

You know that you can see things comfortably if they are anywhere in your own range (from, say, 15 cm out to infinity). You can see your thumb's image clearly with the lens. So it must be somewhere out in front of you, in your range.

(If you had an 'average eye', your thumb's image would have to be somewhere between $\frac{1}{4}$ metre in front and infinity; but you will probably have to wait till you are about 40 for your range to have decreased to that.)

In any case, the image is out in front, on the same side as your thumb and farther away than your thumb. It could hardly be on your side of the lens—behind your head!

So now you have the lens making an image on the *same side as the object*, when the object is very close. And that image is *farther away* from the lens than the object.

That is a virtual image. (Virtual is a useful word. It is not easy to define virtual, but it has a clear flavour of '*not really, but as if . . .*'.)

Rays of light come straight from your thumb to the magnifying glass, are bent a little there, and continue forward on to your eye. The rays don't go back to the virtual image and *then* come to your eye. They only *seem to come from* the image. So you cannot catch a virtual image on a piece of paper.

Virtual images are a little harder to think about than real images. We shall return to them when you watch lenses doing things with rays.

Rays from a virtual image Nothing helps to clarify the nature of a virtual image so much as seeing actual rays that seem to come from one. It is well worth while to fetch the smoke box out again and show the positive lens forming a *virtual* image with rays in three dimensions.

Then, when pupils see a two-dimensional version with ray streaks (Experiment 19f), they will be ready to appreciate it.

Demonstration 18 Virtual Image in a Box of Smoke

Apparatus

1 smoke box	item 93A
1 smoke generator	93G
1 large plano-convex lens	93B
1 lens holder	93C
2 aluminium sheets with holes	93D
1 compact light source	21
1 L.T. variable voltage supply	59
1 retort stand and boss	503–505
sacking	

Procedure

To show rays diverging from a virtual image the lamp must be at most 12 cm from the lens. Move the lens close to the entrance window, and place the lamp near the window. Insert the screen with the smallest circle of holes. Fill the box with smoke as before. The convex side of the lens should face away from the lamp, to minimize aberration.

If a large negative lens is available, show it making a virtual image.

(A concave mirror making a real image is a delightful sight, but that demonstration is better postponed. It will fit in better later, and it would distract from this showing of a virtual image now.)

Thinking about virtual images Ask pupils what kind of image spectacles make for the person who wears them. Where do pupils often see a virtual image at home? (That is difficult because they have not yet seen what a plane mirror does to rays; and most beginners regard a mirror's virtual image as quite different from the kind formed by a lens.)

> 'In the telescope, what did the objective lens do? What kind of image did the eyepiece make? Where was it?'

Experiments with Ray Streaks

Tell pupils they will presently have another turn with their telescope; to focus it without help and measure its magnification. But, to understand how telescopes and spectacles and other instruments benefit their eyes, they need to know clearly what happens when rays pass through a lens.

To reinforce that growing knowledge, pupils should see the behaviour of rays in their own class experiments. The ray-streaks equipment provides that experience.

Light from a small lamp splashes out across the table. A tall comb is interposed to let through 'rays' which are intercepted by lenses. Each such 'ray' is not an ideal ray of light, but a narrow pencil of rays: it is a thin, vertical, 'knife-blade' of rays. Since the lamp is above the paper that 'knife-blade' cuts the paper and makes a long visible streak where light is scattered by the paper. That visible *ray streak*, with many others like it, will enable pupils to see how rays behave when they meet lenses, etc.

A cylindrical lens, with axis vertical, bends the 'rays' *horizontally* to pass through an image. But since it does not bend them *vertically* those blades of light continue to make a streak on the paper beyond the image.

Pupils see the image-forming behaviour of lenses when they look at those ray streaks on paper on their table in a fairly dark room.

By using two or more lenses, pupils can see the way in which an optical instrument such as a telescope treats rays of light and forms images.

The apparatus suggested for these experiments differs considerably from the usual arrangement of a ray box with a lens and a set of slits. Our series of class experiments is intended to go much farther than a demonstration or even a class experiment to trace rays through a lens.

Treated as an 'open' experiment, the series lets pupils see for themselves the way in which real rays of light behave with real lenses as used in optical instruments.

Pupils see rays coming straight out (in all directions) from an object point, becoming fainter as they go farther; being bent by a lens so that they all converge to an image point and stream straight on through it; or being bent so that they splay out as if from a virtual image point.

They see that the real behaviour of rays falls short of the ideal of passing through images exactly; and they learn a little about correcting for that 'aberration'.

Finally they make models, with real lenses, of optical instruments such as telescope and microscope, seeing in each case how the lenses treat a sheaf of real rays.

This series of experiments is meant to act like an interpreter taking young people for a real trip through a foreign land. In such a trip, the contact is artificial in several ways: the views are chosen for the tourists and pointed out to them; and the interpreter modifies the reality. Here we *suggest* arrangements of lenses and we *choose* lenses that will show interesting things clearly. Yet we then leave pupils alone to try things, and they learn a lot without realizing it. After using the instruments with spherical lenses, they will return to these model experiments and gain further understanding.

The equipment, for 16 pairs of pupils, is expensive; but we believe it is well worth the cost because it enables each pupil to do his own experimenting. Every pupil, whether he extracts much optical knowledge or little, will feel he is doing science, trying things and finding out—with, we hope, enjoyment. Many pupils will miss that if we give cookery-book instructions—anything beyond the 'sailing orders' suggested in *Pupils' Text 3*. And replacing the pupils' own work—which will take a long time—with a quick demonstration using a ray box would miss the point of this series: personal experience.

Equipment for Ray-Streaks*

LAMP. For 'object' we use the vertical line filament of a lamp. To make rays that will form long visible streaks across a sheet of paper we need a bright lamp: 24 watts is the minimum; 36 watts would be better, but is less easily obtainable.

Light from the filament, which is raised 10 cm or so above the table, spreads across a sheet of white paper on the table.

The filament must be straight as well as vertical. A crooked filament makes misleading 'rays'. The lamps should be tested at intervals and unsatisfactory ones replaced.

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

SHIELDS FOR LAMP. Since stray light is unwelcome the lamp must carry its own shade, with a wide slit at one side.

There must be an outer shield resting on the table to stop stray light. That must have a tall wide slit to allow the lamp and its shade to be raised and lowered.

The outer shields must be made in pairs, left-handed and right-handed, so that two lamps can be placed very close together.

COMB TO MAKE 'RAYS'. Pupils to not use a single slit for most experiments, but have a comb of many parallel, vertical, slits.

An ordinary hair-comb does poorly, because its slits are not long enough; so we use a painter's graining comb of steel, which has beautifully even slits. These combs are still available and we hope schools will obtain them and not be content with fewer slits or shorter ones—or the very narrow slits that are easier to manufacture. Home-made slits should not be used, even if cut very skilfully with a saw; because there will be unevenness which will spoil the experiment.

SLITS. For a few experiments—less important than the main ones with a fan of rays passing through each image point—pupils use a single ray to see how it is treated by various parts of a lens or by a plane mirror. That is made by a single slit in a metal screen.

(For a few more difficult parts of the series, some teachers prefer to replace the comb by a screen with just 3 slits.* This *conceals* spherical aberration and gives a simplified picture—untrue but perhaps a help in learning.)

HOLDER FOR COMB AND SLITS. Pupils will move the lamp to various distances, so the comb or slit must not be attached to the lamp. A small block of wood carrying a bulldog clip with vertical jaws does well.

BARRIERS OR STOPS. Although the lamp is housed in a shade and shielded, light from it will spread over a fairly large angle and some light will miss any lens pupils are using. Therefore they need some blocks to act as barriers or stops, to shut off unwanted light.

No special shape is necessary. An L-shape of metal is probably most convenient. (The triangular blocks of wood supplied in some kits do well, but are confusing in diagrams because they look like glass prisms.)

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* Since this list will remind teachers of various forms of ray-box equipment, we wish to warn them again that the use to which we put our 'ray-streaks' apparatus is much more general. Ray boxes are not flexible enough for pupils in these class experiments. Therefore, we hope that teachers will not substitute ray boxes for our simple equipment.

* Some manufacturers offer the triple slit and the single slit on the same plate. This economy is undesirable: pupils are working in a dark room and they deserve every help to avoid confusion.

The barriers can also be moved in to narrow the aperture of the lens that is used; therefore they are essential parts of the equipment.

PAPER. The ray streaks are made visible by white paper which they hit very obliquely. The paper should be smooth but not glossy, at least of foolscap length. It is spread on the lab table. There is no advantage in raising it on a drawing board.

The paper is not supposed to have rays marked on it with pencil lines, because that would delay the progress of the series and would not produce reliable drawings—it is better for pupils to keep their eyes on real 'rays'.

LENSES. The lenses suggested have been chosen carefully after extended trials. Their sizes and powers are chosen to provide for good illustrations of instruments, as well as of simple lens behaviour, in the space available on ordinary laboratory tables.

To show the paths of rays to an image *and beyond it* a cylindrical lens must be used, placed with its axis vertical. With spherical lenses, rays are bent in a vertical plane as well as in the horizontal plane and the picture of rays-streaks will disappear beyond a real image point. That is because light that would show the streaks *beyond* the image would have had to come up through the paper. (And the lower half of the lens would have had to be below the paper.)

So *cylindrical lenses* are essential; but teachers will find that pupils do not seem to regard that as spoiling the story—particularly since we also suggest a very good three-dimensional demonstration with a spherical lens in a smoke box.

The lenses needed for this series are plano-cylinders of glass. (Plastic lenses are equally suitable if they are made of clear *uniform* material optically figured and polished; but they scratch very easily. Cheap castings with uneven surfaces and internal striae will spoil the experiments.)

Each lens should have a large aperture: the width should be 5 cm—so that aberrations are obvious and then the aperture can be cut down by barriers. The height for most should be 5 cm, so that the streaks can be quite bright along the whole length of the paper.* But the negative lens (-17 D) can be half height with a saving in both cost and risk of breakage.

* Some manufacturers offer lenses of half height (25 mm) as an economy. They would be false economy. They give poorer visibility and are not recommended.

The lenses needed for 16 pairs are:

Positive (converging), plano-convex, cylindrical

32 lenses $+7$ D ($f \approx 14$ cm) for general use and for the objective of telescope model

16 lenses $+10$ D ($f = 10$ cm) for general use and for the objective of microscope model

16 lenses $+17$ D ($f \approx 6$ m) for general use and for eyepieces

(or 32: if the model microscope is to be made with a stronger objective, two $+17$ D lenses will be needed.)

Negative (diverging), plano-concave, cylindrical

16 lenses -17 D to show what a negative lens does, and in particular to help to teach the idea of a virtual image.

Teachers will easily distinguish the lenses of different powers from each other; but pupils, working in a half-dark room, will not. A small colour-coded label stuck on the plane face will help pupils. It will also be useful for storage. Or the power may be written on the top and bottom ends.

PRISMS. Small, cheap, glass prisms are needed to show refraction of ray streaks and give a hint of a spectrum. In pupils' own hands this gives far more lasting teaching than a demonstration.

PLANE MIRRORS. Each pair should have a small piece of plane mirror, about 10 cm × 3 cm. The mirror can be propped up against a block of wood.

CYLINDRICAL MIRRORS. These should be a few centimetres high, of large aperture, *at least* 120°, and radius 5 or 6 cm. Each pair will use one, but since pairs will proceed at different rates there could be fewer mirrors, to be borrowed in turn from a cafeteria.

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

Alternatively, extra lenses can be placed on a side bench as a 'cafeteria'. Pupils can then help themselves to a lens, try it, and return it.

This illustrates an important point in the management of this series of experiments: that pupils should be expected to proceed at their own rate, occasionally drawing upon extra apparatus when necessary.

ROOM. The lab needs to be half or three-quarters dark.

Class Expt 19 Ray Streaks. See what a Lens does to Rays. (A long series of Class Experiments)

AIMS. (i) To let pupils find out, or see for themselves, some simple, important properties of lenses, rays and images.
(ii) To enable pupils to illustrate with real rays the behaviour of some optical instruments.

Apparatus

Items marked * are needed for most or all parts of this series. Other items are listed in the description of each part.

1 kit for ray optics, contents:	item 94
*16 lamps (34 or 36 watts, 12 volts, vertical filament), holders, and stands	94A
*8 *pairs* of housing shields	94B
*16 metal combs	94E
16 metal screens with a single slit	94C
16 metal screens with 3 parallel slits	94D
*16 holders for combs and plates	94F
*32 barriers	94G
plano-cylindrical lenses:	
*32 of power +7 D ($f \approx$ 14 cm)	94H
16 of power +10 D (f = 10 cm)	94I
*16 of power +17 D ($f \approx$ 6 cm)	94J
16 of power −17 D ($f \approx$ −6 cm)	94K
*3 transformers	27
16 plane mirrors	116
16 holders for mirrors	117
16 cylindrical concave mirrors	118
*white paper (foolscap or longer)	

Pupils work in pairs.

The experiments of this series are intended to be carried out as a continuous programme, with pupils proceeding at their own speed from one to the next. The division here into separate parts (a), (b), (c) . . . is an artificial one, intended only to help teachers when they are making preparations.

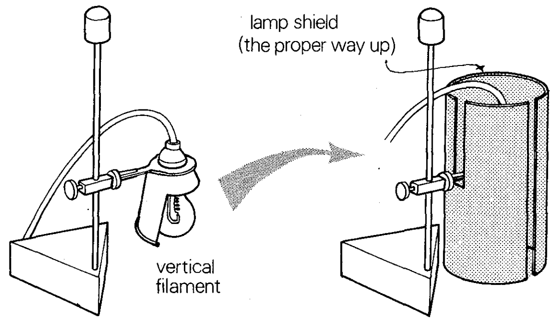
It is unwise to give pupils all the lenses, slits, etc., straightaway. Pupils need lamp, comb, barriers, and white paper for each part of the series.

At the beginning they should have one lens, +7 D. Then they should be given samples of all the lenses for a short period of general play, with a warning that lenses are rather fragile.

After that it is best to provide only those lenses, etc., that are needed for each experiment.

For all the experiments, three-quarters blackout is strongly advised.

Preparation



Before the first experiments, and again from time to time, make sure the lamps are in good order:

(i) Tighten the holding rings of the lampshade so that the shade cannot wobble or twist and let the light out in a wrong direction. Unless this tightening is done, both pupils and teachers will suffer frustration and waste much time. (The looseness is a fault of design; but we chose this design because the whole lamp assembly was available from an earlier set of equipment and would therefore save schools money.)

(ii) Make sure the lamp hangs vertically.

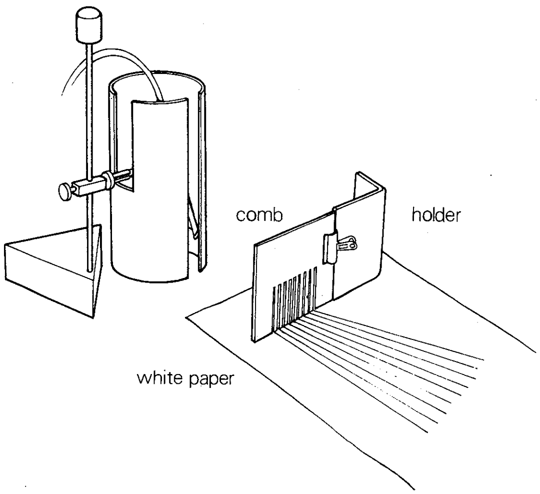
(iii) Light the lamp and look at the filament. The filament *must be straight* as well as vertical; otherwise the ray streaks will be fuzzy and may even be curved—and thus mislead pupils hopelessly. Replace any unsatisfactory lamps.

Class Expt 19a Look at Rays

Pupils arrange the lamp and comb so that rays of light cross the paper. They raise or lower their lamp to get long bright streaks.

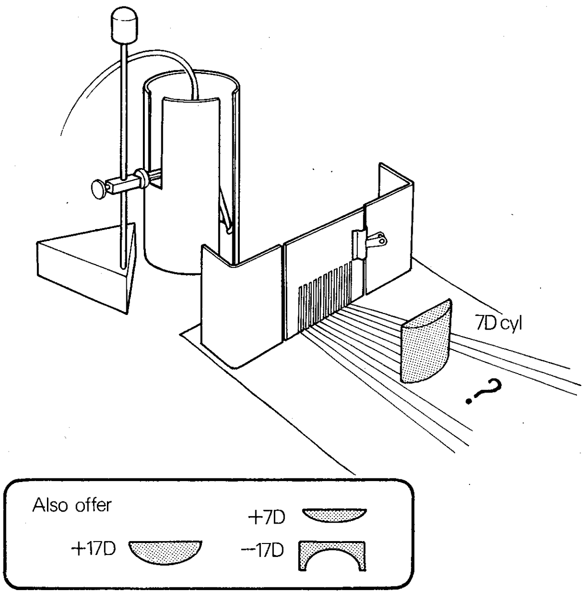
We do not tell pupils to observe that the rays are straight; but we might *ask* whether the rays look straight or curved. We should *not* ask them to make a record of their observations—this is a time for a lot of experimenting with growing confidence.

(If the rays look curved examine the lamp. A crooked filament may ruin the experiment. Also, home-made slits are apt to produce crooked streaks.)



Class Expt 19b Explore Lenses with Rays of Light

Pupils place a +7 D lens in the fan of rays. Let them try placing the lens in various positions.



Visiting Visit pupils individually and offer helpful suggestions, but no warning of what to look for. If any have placed their lens flat on the paper help them to set it up on its base—that mistake does happen, but it is unlikely if pupils have already made a camera model with the lens.

After pupils have played freely for some time, visit each pair again and suggest placing the lens 'across' the fan so that it receives rays more or less normally. (Although that seems to us the natural, right position, pupils may be delighted with the lens twisted at a large angle so that the emergent rays touch part of a caustic curve. If so, we should praise their enjoyment of that but should then suggest that the symmetrical position will be good for later experiments.)

Offer barriers, so that pupils can shut off some rays if they wish.

Then give pupils several other lenses to play with for a time: +17, −17 (remarking that −17 is more fragile), an extra +7, and perhaps +10.

This is a new amusing game for young people and they will do many things with the lenses which do not seem sensible or profitable to a physicist. They do not know what properties of lenses and rays they are looking for and we should respect that ignorance and let them play quite freely for a while.

Finally ask pupils to go back to one lens, the weak positive one, +7 D.

After plenty of time for open play—which will bring its reward in later parts of this series—ask pupils to look more carefully at the way a lens forms an image.

Class Expt 19c Good Image with a Lens

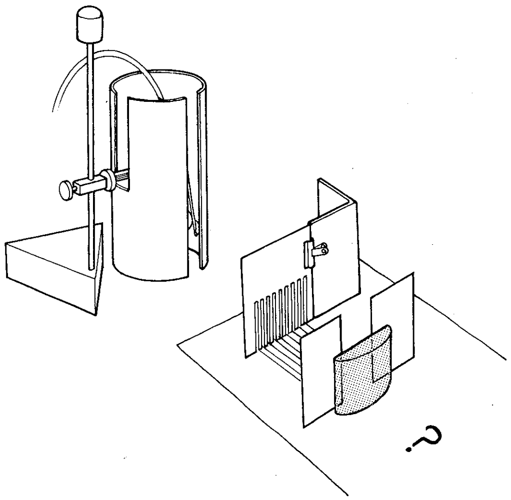
Apparatus

As before, with lens +7 D.

Procedure

Ask pupils to treat the lens more carefully: first make sure its face is perpendicular to the central ray of the fan, and then cut down the aperture until all the rays seem to go through one point—which we name a *real image* of the filament.

Pupils may fetch another +7 D lens (or borrow one) to see what two lenses in series do. They may try them several ways round. We should not hurry that.



Visiting While pupils are experimenting with lenses receiving a fan of rays it may help if the teacher moves round among them, to straighten a lens or offer an extra lens to try.

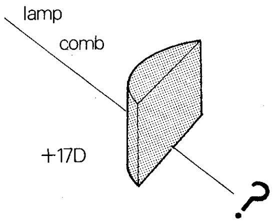
Slide a small piece of card in across a pupil's rays, cutting off ray after ray. This seems to help some pupils to see what the rays are doing—the pattern is less static.

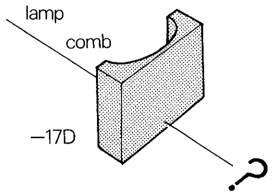
Class Expt 19d Stronger Lens

Apparatus

As before, with lens +17 D ($f \approx 6$ cm).

Pupils try the strong lens alone. They will certainly see spherical aberration, and we hope they will discover, without prompting, how to lessen it.





If necessary, suggest limiting the aperture with barriers.

Pupils should also decide which is the 'best way round' for such a lens *when the object is far away*.

When pupils complain about spherical aberration, we may say:

'Yes, that is a real "disease" of lens behaviour. We have to learn to live with that.* We either use a small aperture of lens (as in a cheap camera) or try to put several lenses together so that the misbehaviour of one lens compensates for the opposite misbehaviour of another. That is a very difficult business and if you tried fitting several lenses together yourself you would find it difficult. We shall not go into it here.'

---

* Of course spherical aberration ought not to be called a 'disease'. It is natural optical behaviour. It results from rays of light being bent at the surfaces of a spherical lens according to the natural laws of refraction. It is our wish that the lens should form a perfect image; but it happens that that is not the natural result of combining Snell's Law ($\sin i/\sin r$ = constant) with the geometry of spherical surfaces.

Fortunately that combination produces an *almost* perfect image, for rays from a point object, when the object is near the axis of the lens and the aperture is small, so that none of the rays hit the lens surfaces very obliquely.

Thus spherical aberration is an unwelcome natural behaviour, not a misbehaviour and certainly not a disease.

Class Expt 19e Negative Lens

Apparatus

As before, with -17 D lens ($f \approx -6$ cm).

Pupils shoot a fan of rays at the negative lens. Ask if there is an image.

We suggest a *negative* lens now, at an early stage, partly for general experience, partly to introduce the idea of a virtual image without complicating matters by making it seem a special case of behaviour for a *positive* lens. Pupils see the ray streaks splaying out steeply from a virtual image and can point to the position of that image when we ask them.

This is a stage to visit pupils, ask questions about that image, and ask whether, from the point of view of eyes looking at it, it would seem any more invisible than a real image.

Suggest that pupils should go to the end of the table, squat down, and look backwards towards the lens—looking along the emergent rays. They will think each ray is completely straight, not even bent by the lens. That may help in the discussion of virtual images. It may be helpful to say:

'Suppose you are looking head-on at on-coming traffic, and do not know whether the cars have come from side roads or directly along the main road when you look *head-on* towards the lens. Your eyes cannot tell if the light has been bent.'

Class Expt 19f A Positive Lens CAN make a Virtual Image

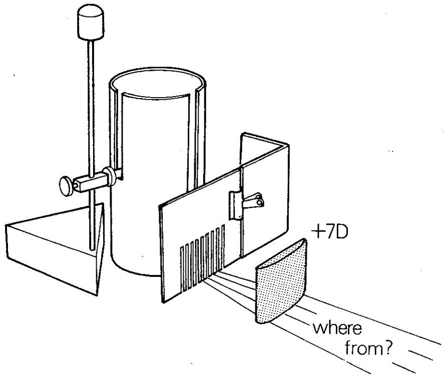
Apparatus

As before, with $+7$ D lens.

Pupils move the lamp and comb very near to the lens and see a picture of the lens making rays that seem to come from a virtual image behind the lamp.

Pupils will have already seen that with a lens in the smoke box; but this gives important reinforcement, because pupils are managing the rays themselves. They have seen a plane mirror making a virtual image with ray streaks and they will use a plane mirror again soon. So we are building up familiarity with virtual images. If we leave these impressions to brew, the concept of virtual images will be accepted without any unwelcome feeling that they are difficult.

The close placing of the lamp and the interpretation of the pattern of rays are both rather difficult. So pupils should be asked to show their pattern to the teacher when they have it arranged. That gives an opportunity for an encouraging question about the virtual image.



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

Optics at home If a pupil wished to take the whole outfit home with him for the weekend—lamp, transformer, and all—that would probably be very valuable if it could be allowed.*

* 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 The General Secretary, Association for Science Education, College Lane, Hatfield, Herts.

The General Secretary, administering this fund, will only ask whether the apparatus went on loan with permission, whether the class is following a complete Year of Nuffield O-Level Physics, what was damaged, and how much the cost is. 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.

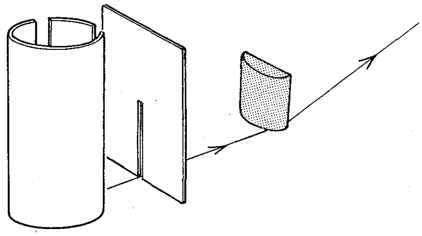
We do not have in mind the fastest or brightest pupils in particular for that. A slow pupil may gain even more by developing a sense of being an expert, a feeling that he or she is 'the person who knows what lenses do'. This may be very valuable in its effect on parents and what they think we are doing.

One might fear that parents would consider such experiments childish and messy and inconclusive; but in that we are forgetting the way in which a parent can encourage a child to pose as expert.

Class Expt 19g Single Ray hits a Lens

Apparatus

As before, with single slit.



Pupils watch what happens when one ray hits a lens at various places. (Again, this is not the time for taking notes or for a demonstration even if pupils do not learn any definite story.)

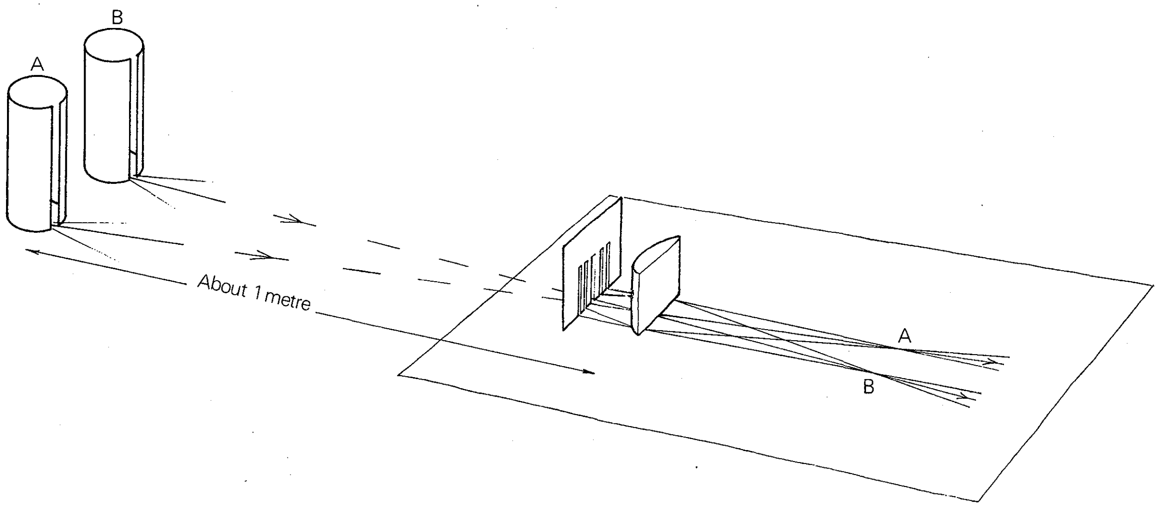
Ask pupils to look for the place on the lens where a ray must hit to go *straight through without bending*. Pupils should fire a ray at that point from several directions—easiest done by twisting the lens. Name it the 'optical centre', and describe such rays as 'undeviated rays'.

Point out the use of undeviated rays—or let questions do that. They help us to draw realistic diagrams.

Suppose we know the distances of an object and its image from a lens. Then undeviated rays through the optical centre that start from the head and feet of the object will give us the height of the image, and thus the magnification.

Pupils should illustrate that with *two* object lamps side by side. Either provide extra lamps or ask pupils to double up with neighbours in groups of four, just for this one experiment.

Class Expt 19h Two Object Lamps and a Lens



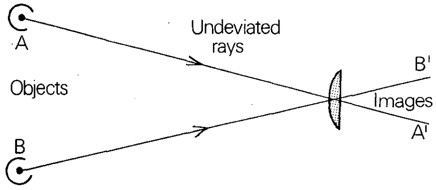
Apparatus

Pupils work in groups of 4. *For each group:* 2 lamps, +7 D lens, comb, barriers.

The lamp shields come in right- and left-handed forms. Each group needs one of each kind, so that the lamps can be placed very close together.

Procedure

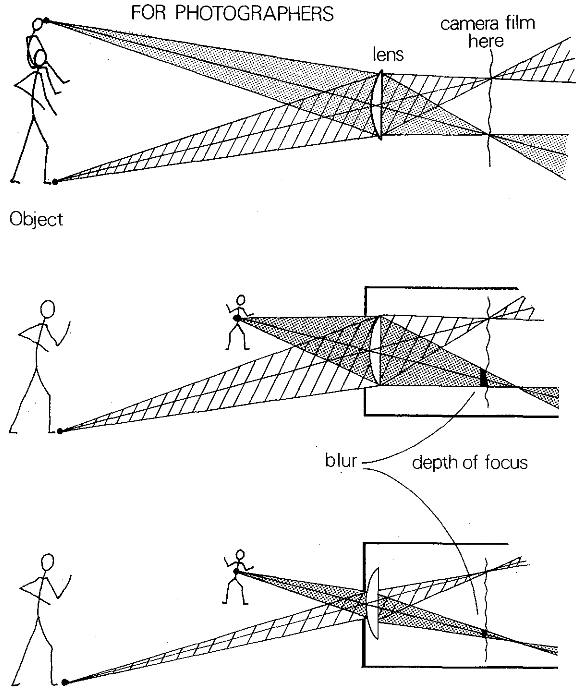
Pupils place the lamps side by side, about 1 metre from the lens, and look at the images A′ and B′. A piece of pale colour filter placed in front of one lamp makes it easier to tell which rays come from which lamp.



Arranging the lamps for this presents considerable difficulties and pupils may need help.

Explain to pupils that the two lamps may represent the top and bottom of an object, or any two specimen points on some object.

It is not obvious to beginners that we know a great deal more about the behaviour of an optical instrument when we see what it does with two such points, or with an extended object. To us it is clear that we then know something about the magnification the instrument provides; but pupils need a few words and a sketch. Also explain that this object lies 'across the axis', it is not an object lying along the axis of the lens.



Pupils interested in cameras may place a ruler across the two image points, to represent a photographic film. Then if they move one lamp much farther or nearer they can see the out-of-focus patch on the 'film', made by light from that object-point. They may bring in barriers to stop down the lens aperture and show why a cheap camera has 'fixed focus'.

Class Expt 19i Object moves towards the Lens

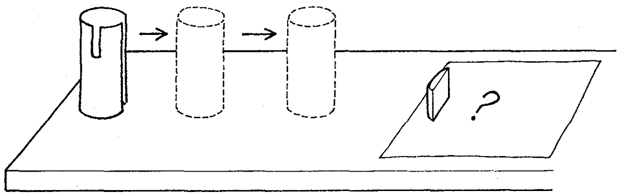
This brief qualitative experiment is not optional but any quantitative investigation would be entirely optional.

Apparatus

Lamp, comb, +7 D lens.

This is meant to give a qualitative glimpse of the relation between object- and image-distances.

Pupils start with the lamp 1 metre or more from the lens; then move it closer and closer, watching how the image moves.



For success, pupils must make a preliminary trial to choose a suitable height for the lamp for the whole range.

Pupils should not make any record of the changes of image-distance. The purpose of this experiment is to let pupils see that a clear image is always formed (using the name image in the sense of a place through which all rays cross), and that the distance of the image from the lens depends on how far away the object is.

(The longitudinal formula, $1/v \pm 1/u = 1/f$ is of little use in our approach, so we let it fall outside our programme. Therefore we do not advise extending this experiment to measurements.)

Object- and image-distances for a lens Teachers may wish to give a quick demonstration to extend this general acquaintance, but rather than interrupt the present series of experiments, this is given later (Demonstration X). It could be postponed indefinitely and brought in to fill some short time when the lab is not available.

Class Expt 19j Flat Mirror and a Ray

Apparatus

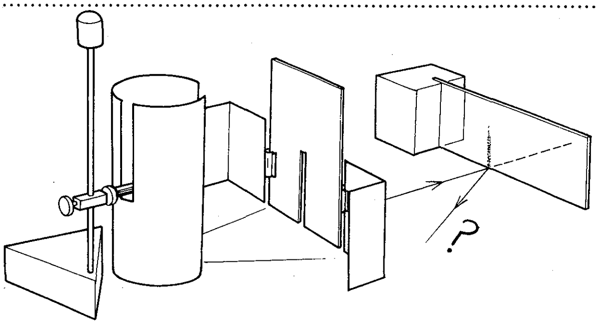
Lamp, screen with single slit, plane mirror, support block.

Pupils return to working in pairs.

Procedure

Pupils support the mirror in a vertical position and shoot a single ray at it.

Some will see an obvious rule of angles. Others will just enjoy seeing the ray reflected—and they will be surprised if they look back along the reflected ray.



This is not the time to ask for measurements or to suggest a rule that is to be discovered or tested. Simply leave empirical knowledge to accumulate in each pupil's own way, at his own speed.

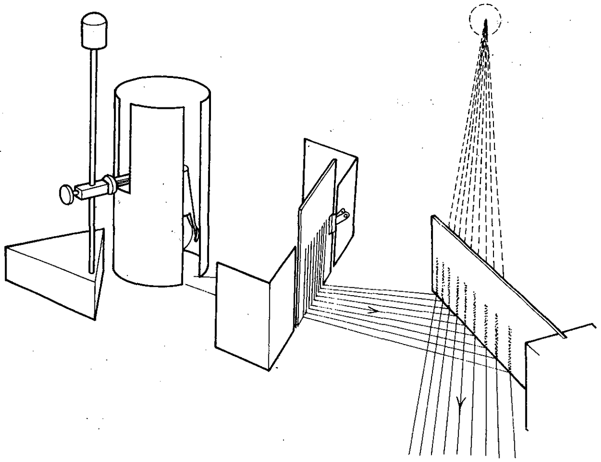
Class Expt 19k Flat Mirror and a Fan of Rays

Apparatus

Lamp, comb, plane mirror and support.

Pupils shoot a fan of rays at the mirror. Ask them to put the lamp *on their sheet of paper,* quite close to the mirror. (Then the virtual image of the lamp may well be on the paper too, which will make discovery easier.)

Ask pupils to squat and look along a reflected ray with one eye 'to see where it seems to come from'. Also to look down on the rays, again to see where all the reflected rays seem to come from.

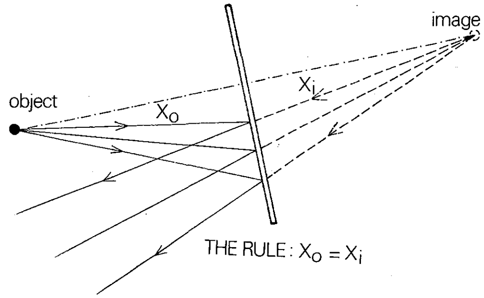


If they like, pupils may put a marker such as a wooden stick at the place the rays seem to come from.

Give the name 'virtual image' and ask pupils if they can describe in words where it is. But do not insist on their learning a rule, yet.

It would be unwise to ask pupils to draw pencil lines where the ray streaks run along the paper and then do a construction of running those pencil lines back, because the actual drawing would be either very tedious or too rough to show the story clearly.

In a more 'mathematical' form of physics teaching we might let pupils *assume* a law of reflection and ask them to *predict* the position of the image by geometry; but that would carry the class away from direct observing. This is their chance to see the facts and enjoy seeing them.



We hope that many pupils will of their own accord see that a plane mirror forms a virtual image as far behind the mirror as the object is in front.

The plane-mirror rule is not something to ask pupils to look for, or to verify; it is not even something to tell them after the experiment. If this kind of practical work is to have any value in showing what science is, we must wait until pupils find this for themselves. We might urge them towards it by a hint if necessary; but even slow pupils can 'discover' this, and will have great delight.

To the rare pupil who says at this point, 'I saw that when I watched circular ripples being reflected at a straight wall', we give high praise. To the still rarer one who then says that this suggests that light may be waves we need give no praise: he already knows he is to be a scientist.

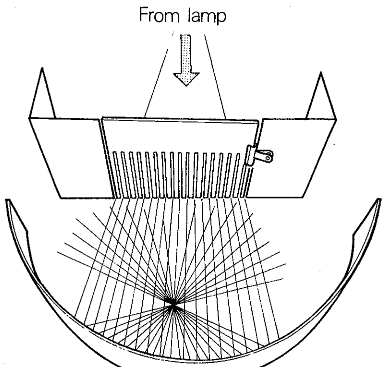
Soon pupils will look at a virtual image 'in the flesh': a real candle in front of a plane mirror. Remember that our ray streaks are only for investigation and illustration, to make the three-dimensional optics of everyday life clearer.

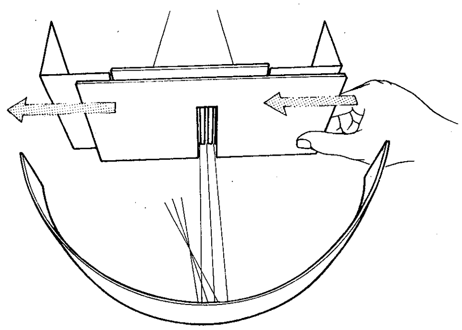
Mirrors

Although we shall not use spherical mirrors for instruments, we suggest two demonstrations with them, and a class experiment with a plane mirror.

Class Expt 191 Curved Mirror and a Fan of Rays

(This is F. A. Meier's famous 'mirror and comb experiment'. It is a delight to see and contains, in what it shows, a range of quite advanced optics.)





Apparatus

Lamp, comb, cylindrical mirror, card.

The mirror should have a large *angular* aperture but should not be of large diameter. A semicircle of diameter 6 to 10 cm at most will do well.

Pupils work in pairs. (Since this is the only time cylindrical mirrors are used, the lab might have fewer of them and offer them from a cafeteria to pairs of pupils in turn. However each pupil deserves to see this beautiful experiment with only one partner at most. Pupils should have plenty of time to try variations.)

The illustration shows the arrangement of apparatus but the rays, *which are incorrectly drawn there,* do *not* show the true surprising behaviour.

Procedure

Pupils place the lamp 30 to 50 cm from the mirror. They place the comb where it makes a fan of rays wide enough to fill the whole aperture of the mirror. The reflected rays touch a caustic curve.

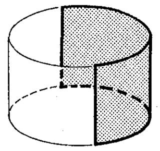
Each pupil slides in a card as an obstruction in front of the comb to cut off ray after ray. Then two pupils slide in two cards from opposite sides, to narrow the aperture used and show the forming of a good image.

Then each pupil uses a card with a wide slit in it to let a narrow fan of rays proceed to the mirror. As that card is moved across the comb the image slides round the caustic curve.

Home Expt H191 Curved Mirror and a Fan of Rays

We hope pupils will try their own version of this at home, with a teacup or a small tin with part cut away.

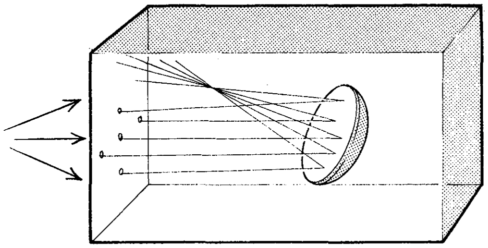
With a tin, the pupil should remove the top and bottom with a tin-opener; but to cut down the sides and obtain a half cylinder he should bring the tin to school and ask to have the cuts made with snips.



An ordinary comb will make the rays. The Sun may serve as source; but it will be better if pupils can also borrow a transformer and lamp from the lab. (That loan is completely covered by the J. Willmer Home Experiments Endowment.)

Demonstration 20 Curved Mirror in a Box of Smoke

This is so fine a demonstration that we hope pupils will see it. A concave mirror, 7 cm diameter or more, will suffice.



Apparatus

1 smoke box	item 93A
1 smoke generator	93G
1 aluminium sheet with holes	93D
1 large concave mirror	93F
1 compact light source	21
1 L.T. variable voltage supply	59
2 retort stands, clamps, and bosses	503–506
sacking	

Procedure

Fill the box with smoke and place the mirror in it. Place the lamp some distance outside the window end and direct a fan of rays at the mirror.

If there are amateur telescope-makers in the class this is a very important experiment to link physics with their hobby.

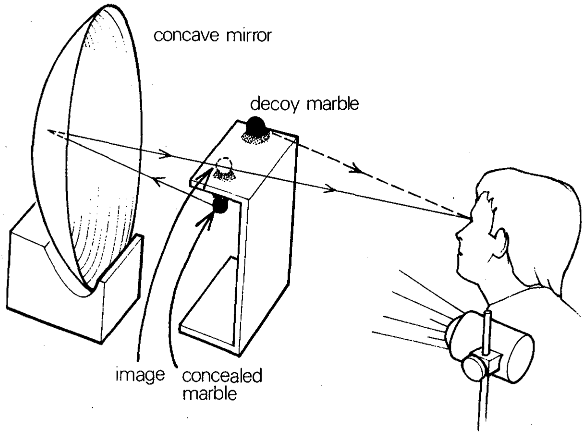
If possible, let pupils see an optical illusion in which a spherical mirror forms a real image.

Demonstration 21 Optical Illusion with a Concave Mirror *(OPTIONAL)*

Apparatus

1 large concave spherical mirror (good optical quality) with holder	item 302
1 red marble	12B
1 blue marble	12B
1 small cardboard box (5 cm or larger); e.g. matchbox	
1 stand for box	
1 small reading lamp	
plasticine	570

The concave mirror should be as large as possible and preferably have an aluminized front surface. The larger the aperture the better. For the additional effect with a lamp, the aperture diameter across the mirror's face should be at least as big as the mirror's radius of curvature.



Procedure

A small object such as a red marble, R, is fixed with plasticine on the *under* side of the top of the small box. The box is placed with its open side facing the mirror at such a height that the red marble is near the centre of curvature of the mirror, a very small distance below the mirror's axis.

Another marble, B, of a different colour, say blue, is placed as a decoy, to catch the observer's eye. It is fixed with plasticine to the top of the box. Then B is the same distance from the mirror as R, but a little above the axis and a little to one side. (As B is above the box it is clearly visible to an observer.)

When the observer faces the mirror and looks at the visible marble, B, he sees what he thinks is an equally real red marble beside it. Careful placing of the blue marble is essential so that the two do not seem to overlap, but appear side by side. There should be a little empty bed of plasticine beside the blue marble, that will look like a support for the red marble's image.

Some pupils will enjoy looking at the image with a magnifying glass. (They will not know they are then using a Newtonian telescope.)

As an effective additional touch turn on a small lamp spotlight to illuminate the visible blue marble. It will be found that the 'imaginary' marble is illuminated as well. The lamp should be placed beside the observer's head to light up the visible marble B. Any rays from the lamp which hit the image beside the visible marble pass right through that image, continue to the mirror, and are reflected to the concealed marble R. (These rays thus follow, in reverse, the paths of rays that make the illusion.) Therefore, the lamp which illuminates the red marble's *image* also illuminates the red marble itself.

With a concave mirror of small aperture, the concealed marble needs to be illuminated directly by a lamp concealed somewhere between the marble and the mirror.

Both marbles must be located correctly. And shields of black paper or card should be arranged to limit the observer's view. Therefore it is best to construct a frame for the demonstration as a 'set piece'. This is particularly important if the spotlight is to be used.

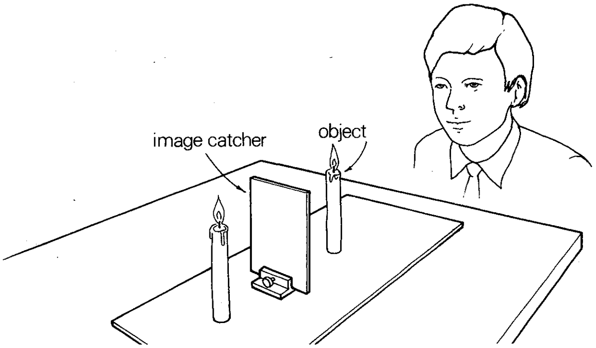
As a contrast to looking at ray streaks, pupils should look at an actual luminous object reflected in a mirror.

Class Expt 22 Candle and Flat Mirror: Where is the Image?

Apparatus

16 plane mirrors	item 116
16 supports for mirrors	
16 holders for mirrors	117
32 candles	

The identical lighted candles should stand upright. They must be less tall than the mirror. (Failing candles, screws, pieces of chalk, or bulldog clips might be used as poor substitutes; pins should not be used as they are too small and it is difficult to keep them vertical.)



Pupils work in pairs.

If the candles cause trouble by falling over, cut them to half length, or substitute night-lights.

Procedure

Pupils place a candle in front of the vertical mirror. They use the other candle as an 'image-catcher' to locate the image of the first candle.

Each pupil in turn moves the image-catcher candle about behind the mirror until it exactly replaces the image when the pupil raises his head quickly and looks over the top of the mirror. Or the pupil may look round the side of the mirror.

(Avoid the quicker no-parallax method here because it does not teach beginners the important idea of an image so well.)

Pupils should ask for a visit from the teacher when they have succeeded in placing the image-catcher. On such a visit, ask: 'Suppose you sit and stare at the candle in front of the mirror. What will you see happen to the image if the mirror is suddenly whipped away?

Further comment: *u* and *v* for a lens Pupils will not need to know or use the formula $1/v$ . . . etc., but in *Pupils' Text 3* there are sketches to show the general behaviour of the image as the object 'walks towards the lens', and pupils may have seen something of this with ray streaks. This is useful qualitative knowledge. If teachers like to give a quick, qualitative demonstration it will reinforce this knowledge. However pupils should not be expected to learn details by heart.

Demonstration X The Object Walks Towards the Lens *(OPTIONAL)*

Apparatus

1 lens +7 D	item 112
1 lampholder and lamp carbon filament	91C, D
or tungsten filament in clear bulb	
or ray-streaks lamp	94A
movable white screen	102

Procedure

Place the lamp about 30 cm from the lens and catch its real image on the screen. This will provide a life-sized image to show what is going to be done.

All through this experiment keep the screen twisted so that all pupils can see the image. In some rooms it may be better to use a *small* translucent screen.

Then start with the lamp very far away. Ask a pupil to move it slowly towards the lens. Ask another pupil to carry the screen and catch the image on it.

When the lamp is near the principal focus, the screen may become just the wall of the room.

Move the lamp still nearer and ask where the image is. If pupils are uncertain, suggest that the image is now virtual. There *is* still an image but we can't continue to catch it.

The lens formula As explained in the outline of our optics teaching, this is outside the normal scope of our programme. However it could have one valuable use in the hands of pupils with special abilities or interests: to promote practice in locating *virtual* images. For all other pupils, we urge teachers to omit all mention of the formula.

Experiment Y Testing the Lens Formula *(OPTIONAL)*

Apparatus

Each pupil who tries this will need:

1 lens +7 D	item 112
1 telescope mount	115
2 retort stands and bosses	503–504
1 metre rule	501
1 lamp and holder	94A
1 transformer (to give 6 volts)	27
white card for screen	566
reciprocal tables	

Preparation

The lamp must serve as object. So it must be set up somehow on the telescope mount; but the exact method depends on the particular make of mount.

The lamp run at 12 volts is too bright for viewing directly when looking at its virtual images. Run at 6 volts instead of 12, it works well. Some teachers may prefer to use pea-lamps. A special optical bench lamp would be unsuitable elaboration.

The screen can be made by cutting a white card and fixing it in a lens holder on the telescope mount.

Purpose

This experiment is suggested with a special aim: to provide an amusing game that will give pupils practice in locating virtual images—the essence of so many optical instruments.

Our aim is *not* to encourage a long series of tedious, accurate measurements of object- and image-distances. Our aim is *not* to bring out the longitudinal formula and make it important in our teaching.

Our aim is only to supply the formula ready-made and ask pupils to see whether a few quick measurements with real images fit the formula; and then ask pupils to make some more difficult measurements with virtual images to see whether those also fit the same formula for the same lens.

Able pupils, presented with the problem in that form, may enjoy the challenge of the virtual-image measurements. In the arithmetic, they will find the necessary change of sign amusing. And they will gain practice in locating virtual images. We should tell them that such practice is the object of the experiment.

We suggest that this should be tried only with a very able group. Other groups are likely to give too much importance to the formula and the arithmetical manipulation, and thus lose more than they gain.

If some pupils try this experiment the teacher should make it quite clear that problems involving this formula will *not* be set in examinations; nor will geometrical constructions that imply this formula be used. It is only an empirical game to see whether a particular relation can be extended to other cases; and a game which gives useful optical practice.

Procedure

Start by telling pupils that object distance, u, and image distance, v, are said to be related, for a simple lens, as follows: *$1/u + 1/v$ has the same value* for all object distances.

Tell pupils that this constancy of $1/u + 1/v$ is a property of lenses. We may tell them that this can be found out by geometry from a knowledge of the way in which rays of light are bent at each surface of a lens. Or, it can be predicted from the way in which a whole lens always bends a fan of rays to pass through an image point. Or, it could be extracted from a large number of experimental measurements. We might add that it can be predicted by working out geometrically what a lens will do to waves of light.

Tell pupils that they will not need to remember the formula or prove it geometrically or verify it experimentally in great detail. We just want them to see whether it does seem to be true for their lens.

The measurements should be quick and rough. Corrections for the thickness of the lens should be omitted. (Pupils should not even repeat the same measurement several times unless they themselves wish to.) The use of a proper optical bench with distance rods and an engraved scale should be avoided: instead, measurements should be simple and direct.

Pupils follow these instructions:

* * * * *

Set up the lamp and screen on the axis of the lens; and move them to obtain a clear image of the lamp filament on the screen. Measure v and u. Calculate the value of $1/u + 1/v$. Repeat for several different values of u.

Now move the lamp much closer to the lens so that a real image cannot be formed. Look at the virtual image of the lamp through the lens. Place a retort stand as an object-catcher behind the lamp and move it till the virtual image of the lamp is caught on it.

Make the lamp much dimmer by inserting a rheostat or feeding it with lower voltage. Or change from the lamp to a vertical rod for object. It will now be easier if you fix the *catcher* where you choose and move the *object* till its image sits on the catcher.

Keep both eyes open. With one eye up against the lens, look at the virtual image of the lamp. With the other, naked eye, look at the retort stand round the side of the lens, or above it.

Again measure u and v and try them in the same formula. If the numbers don't fit, come and ask for help.*

Then try one or two different lamp positions.

* * * * *

Pupils who try this should calculate value of $1/u \pm 1/v$ quickly so that they can see whether their experiment 'works'. Therefore, we should provide reciprocal tables for easy use. If possible, these should be three-figure tables without any columns for differences. Then reciprocals of two-figure or three-figure measurements can be read off easily. (Pupils who find reciprocal tables difficult to use will probably find the whole idea of this experiment confusing; and in that case they should not do it.) Alternatively, calculators should be used.

* With these able pupils it would be a pity to issue a warning that the value of v must have a negative sign. Let them meet trouble; then give helpful questioning.

The series of class experiments with ray streaks continues with models of telescope, magnifying glass, and microscope. Those are the culmination of the series. Pupils could do them now, but we suggest postponing them until after pupils have built and used the real instruments. See Experiments 31a, b, c.

A Return to Real Instruments

Astronomical telescope: second round We hope the first experiment that pupils did with a 'real telescope' was quick and successful at all costs. That was not the time for either drill or detailed explanation. We hope the motto then was: 'Get the telescope set up and enjoy looking at things with it. Ask for help if you need it.'

Now, after playing with ray streaks, pupils should treat it more seriously. If they are to understand how a telescope works and to have confidence in making it work, we must now ask them to return to it and do the focusing themselves. And fast pupils should try to place the final image at a near-point as well as infinity.

Some teachers warn us that this return to the telescope may seem boring or unnecessary: pupils think they have already done the telescope and want to go on to something else. Therefore at this stage we should offer a carrot—magnification—to encourage advanced work. Post a vertical scale on the wall and tempt pupils with the taunt that they will not agree with each other about the magnification.

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

Both the placing of the image and the estimate of magnification are challenges to the optical skill of these young people and if we present them like that we may hope for hard work and success at this new level.

Class Expt 23a Astronomical Telescope (Second Look)

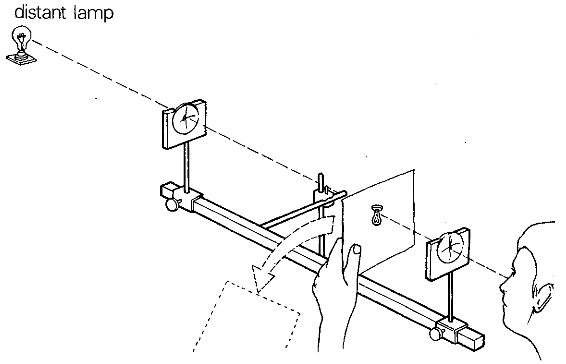
Apparatus

16 telescope mounts	item 115
16 plano-convex lenses, +14 D	113/1
16 plano-convex lenses, +2.5 D	113/3
16 retort stands and bosses	503–505
2 200-watt carbon-filament lamps	91C
2 mounted lampholders	91D

Pupils work in pairs.

Preparation

Set up the carbon-filament lamps, one at one end of the room, one at the other end. They should be well above head-height, so that pupils at one end of the room can view the opposite lamp over the heads of pupils at the other end.



Procedure

Each pupil directs his telescope at a lamp and focuses it so that the final virtual image is back beside the lamp itself.

At this stage give encouragement but only sparing help. See just below for suggested forms of help.

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

Then pupils should go straight on, in the same period, to estimate magnification (Expt 23b).

Teaching Focusing: Placing Images

There are a number of teaching tricks that can be used here to help focusing:

a. Remind pupils that they should:
(i) Catch the real image that the objective lens forms of the distant lamp on a piece of paper.
(ii) Look at that piece of paper with the eyepiece.
(iii) Then take the paper out and put it back repeatedly, while dealing with the eyepiece—better still, *take the paper half-way out.*

b. Urge the observer to keep both eyes open. Explain that this is something irritating and difficult at first, but easy to learn.

This is not a case where the 'unused' eye learns to be temporarily blind (as with monocular microscopes). Here, we want that eye to look straight across the room at the distant object, and *continue to watch it.*

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

Keep this eye open. Look at the lamp over there with it. Go on looking at it. Think about looking at that lamp.

Don't bother with the other eye, but just hold it in front of the telescope.

Go on looking at the lamp with the naked eye, this eye. . .

Now begin to think about the other eye as well, that is looking through the telescope. It is looking at a magnified image of the lamp.

Move the eyepiece until the image looks just as clear as the actual lamp that you see with the naked eye.

Go on thinking about the naked eye, but move the eyepiece.

Many a pupil will succeed after some such personal encouragement, with the teacher beside him.

But there will be some who say that they simply cannot set the image with one eye while looking at the original object with the other. Most of these just need confidence, and we must give them full help, or they will be discouraged. Adjust the telescope for them and let them look through it with one eye, keeping the other eye open. Talk to them about seeing both the image and the lamp 'over there on that wall'; and try showing them some trick methods that may be helpful (see below).

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

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

c. As a trick to help pupils to keep both eyes open and focused for objects far away say:
'Raise your eyebrows and keep your eyes open, with "*wide-eyed surprise*".'
That phrase seems to be helpful.

d. Many amateurs use some form of 'no-parallax method'. Try saying:

Look at the lamp over there with your naked eye. Look through the telescope at the big image. Now move your head sideways, this way, that way.

If the image is back there on the wall with the lamp, the two of them will stay together when you move your head; but if the image is much nearer to you it will slide across when you move your head.

Hold your hands in front of your face at different distances and stick each thumb up. Wag your head from side to side and watch how the nearer thumb moves to the right as you move your head to the left. If your two thumbs are at the same distance, just side by side, they stay together when you wag your head.

Now try that when you are doing a different job with each eye, one eye looking at the lamp, the other looking through the telescope at the image.

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

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

e. Professionals often use their sense of where their eyes are focused. When they look through an instrument at an image $\frac{1}{2}$ metre away and see it clearly, they know their eyes are focused for objects at $\frac{1}{2}$ metre. This is not likely to be directly useful to a beginner; but occasionally it helps to tell him.

f. If the observer uses only one eye, and keeps the other eye covered, he can still compare the (virtual) image and an image-catcher (here, the original lamp) placed where he wants the image. He bobs his head up and down rapidly, thus looking alternately at the image and at the image-catcher in rapid succession.

This is the only method for those pupils who have very unequal eyes or one eye that does not see well. (Those form a very small fraction of the population. The much bigger fraction who say they cannot place the image are most of them just in need of confidence and a first experience of success—as for swimmers.)

g. With those who lack confidence, we can usually succeed if we give a great deal of help and *suggestion*: place the image for the pupil and let him look at it; then move the eyepiece and watch while the pupil tries to place it. Keep in mind where the eyepiece was for correct placing. Saying 'now' as the pupil passes the correct place would spoil it for him; but a momentary tension of breath will convey a hint, and he may stop there. Look through his telescope and give praise if it is anywhere nearly correct—even though the success is not really his own unaided work. Ask him to try again; and again give lavish praise for success. Encourage him to succeed once more, this time with little or no helpful hinting. Then say, with honest delight, 'Look how skilful you can be.'

'The image is blurred' Pupils will often say that the image is fuzzy or blurred. With any good lens (or a poor lens used with a small aperture) any object near the axis leads to a good sharp image. Saying that the image is fuzzy or blurred merely means that one is trying to look at it with one's eye at the wrong distance from it—the image is outside one's range of comfortable vision.

We should not correct that mistaken remark fiercely or insistently at this early stage, but we may ask, 'Does a book become fuzzy because you move it too close to your eyes or because you hold it behind your head? Does your thumb really become blurred just because you whip the magnifying glass away?'

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

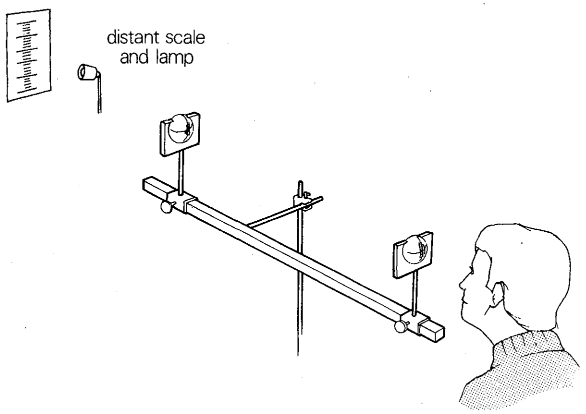
Class Expt 23b Telescope Magnification

Apparatus

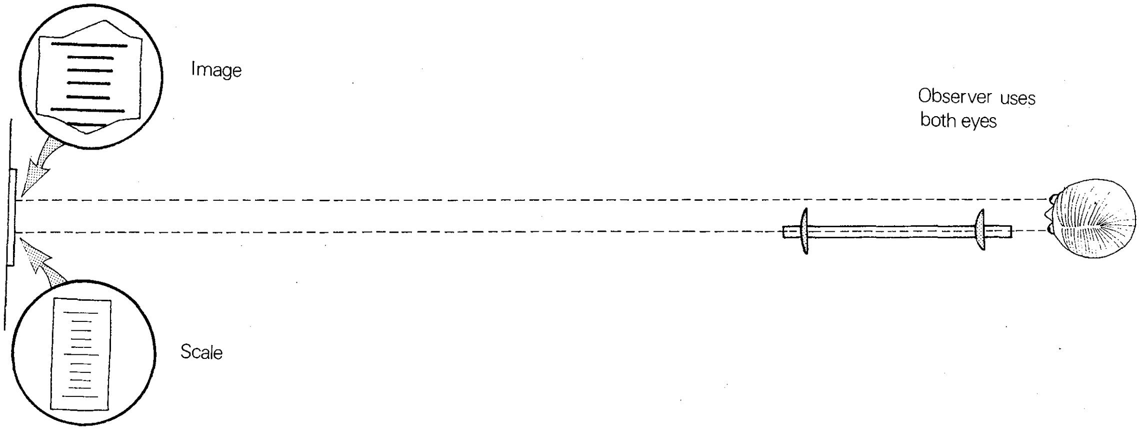
16 sets of telescope equipment as for Expt. 23a with carbon-filament lamps for preliminary focusing
2 tall paper scales
2 reading lamps, with shades, to illuminate scales

Each scale should be vertical, with horizontal lines on it to act as object when the pupils estimate the magnification. Use a strip of shelf-paper, or several sheets of foolscap taped end to end. Rule thick horizontal lines on it every 10 cm, to make a coarse scale. The lines should be numbered. The experiment is easier if successive lines are drawn in different colours.

Pupils work in pairs.



* See the footnote about 'beyond infinity' with Expt 14.



Preparation

Post the scales, high up, at each end of the room. Illuminate them; with shaded lamps to prevent glaring the observers' eyes.

It helps if the room is three-quarters blacked out. Since the scale is vertical, it may be viewed obliquely, so telescopes may be spread out at the other end of the room.

Procedure

Each pupil directs his telescope at the scale and focuses it so that the final virtual image of the scale rests on the scale itself. Then, *still keeping both eyes open*, the pupil estimates the magnification by concentrating his telescope eye on one division of the image and seeing how many divisions of the original scale that covers.

His partner should make a fresh start. Then they should compare results.

Suggest to very fast pupils they might measure focal lengths f_1 and f_2 of objective and eyepiece—just roughly, by catching a window's image on an opposite wall—and see whether f_1/f_2 agrees with their estimate of magnification.

Class Expt 23c Re-focusing the Telescope *(OPTIONAL ADVANCED experiment, suggested only for fast pupils who are keen to try their skill.)*

Apparatus

The apparatus is the same as for Expt 23a.

Each pupil or pair needs:

1 telescope mount	item 115
1 retort stand and boss	503–505
1 plano-convex lens (+14 D)	113/1
1 plano-convex lens (+2.5 D)	113/3

For the whole group:

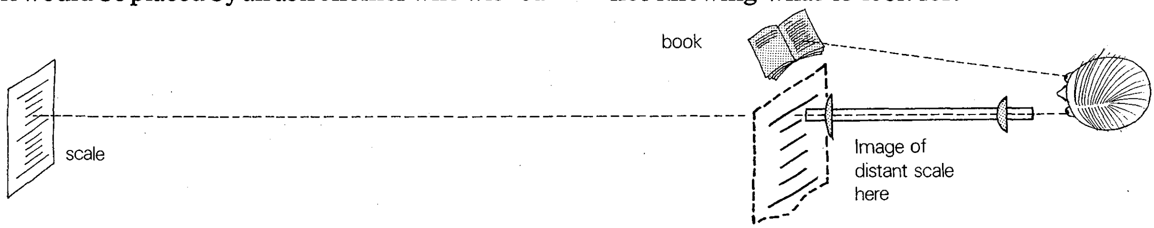
1 200-watt carbon-filament lamp	91C
1 mounted lampholder	91D

Procedure

This is the same as Expt 23a but pupils try to place the final virtual image only $\frac{1}{4}$ metre away—as it would be placed by an astronomer who wished to make sketches in a notebook. Point out to interested pupils the plight of such an observer. He wants to move quickly from telescope to notebook without having to re-focus his eyes.

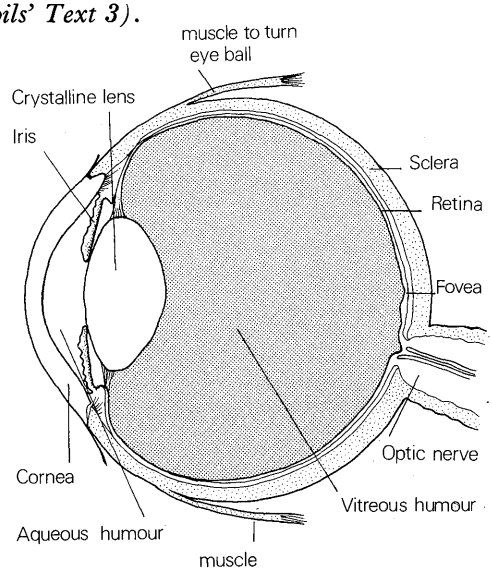
The pupil holds a page of print beside the telescope, about $\frac{1}{4}$ metre from his eye. He looks at the remote lamp through the telescope with one eye while he reads the print with his other eye. Urge him to *concentrate on the naked eye* while he moves the telescope eyepiece.

If a pupil finds this too difficult, yet wants to succeed, *do the focusing for him*; let him have a good look, with both eyes open; then move the eyepiece and let him try for himself. That is a good cure for a pupil who is merely inhibited by not knowing what to look for.



Structure and Working of the Eye

Now or earlier, continue the teaching about eyes. Tell pupils about their eyes as optical instruments. We suggest for this teaching:
(i) A labelled sketch (provided here and in *Pupils' Text 3)*.



(ii) Our demonstration model, made with a large flask of water to illustrate normal sight, short sight, long sight, and correction by spectacles.
(iii) Dissection of a fresh bullock's eye. This is by far the most important for many pupils.

Dissectable plaster models are commercially available, but we do not advise any school to buy one for Nuffield physics teaching—our working model, *(ii)*, is optically simpler and more valuable in physics teaching.

Description The sketch here (and in *Pupils' Text 3)* is labelled with the technical names. These need not be learnt.

Here are brief teaching notes; some of them going farther than we need to go with pupils.

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

The clear front window, the *cornea*, does most of the bending of rays. It is tough and sensitive to pain, but it has little sense of touch.

The black centre is just a hole to let light in—called the *eye-pupil*. It looks black because the eye is almost a closed ball and is black inside—like any good camera—to lessen stray reflections.

The coloured *iris* round the pupil is an adjustable diaphragm. ('Watch your eyes in a mirror and flash a bright light into one of them.') However, our eyes can vary their sensitivity over a range of 1 to 1 000 000 between sunlight and almost complete darkness; and most of that adjustment is made chemically in the retina.

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

Behind the iris there is the *crystalline lens*, made of tough material like jelly. A camera lens must be moved in and out to focus on objects at different distances. The eye changes the power of its lens system by means of muscles which squeeze the crystalline lens to make it stronger when the eye is to focus something nearer.

There is salt water, *aqueous humour*, between the cornea and that lens.

The rest of the eyeball, behind the crystalline lens, is filled with watery jelly, *vitreous humour*, which helps to keep the eyeball firm and round.

The light is brought to an image on the *retina*, a sensitive film of nerves at the back. (*Note*. Most cameras have a flat film at the back; but some small cheap ones hold the film on a curved back to allow for the curvature of the image field of their simple lens. The eye has a curved back.)

The retina's nerves are led into a fat 'telephone cable', the *optic nerve* that runs to the brain, where much of the interpretation is done.

Where the optic nerve leaves the retina there is a *blind spot*. But that gives no trouble in seeing because our eyes shift the picture on the retina rapidly, a tiny distance to and fro.

Pupils can learn that their blind spot is really there by staring fixedly at X with their right eye while they move the page nearer and farther. The spot disappears.

The retina is fed by blood vessels which curiously enough are just *in front* of the nerves, so that light forming the image goes through them before reaching the nerves. (Some people observe a difference of colour, due to that red filter, when they lie on one side on a sunlit lawn and compare the hues that they see with upper and lower eyes.)

However, the human eye has a small patch of retina, the *yellow spot*, where there are no blood vessels in front. That is the patch used for accurate seeing, as in reading. (Pupils can learn about the size of that patch if they stare fixedly at a book with one eye and find the longest word they can see in focus without moving their eye.)

Inverted image on the retina. As in a camera, the image on the retina is inverted. There is no paradox there about 'learning to see upside down' because a baby learns to interpret optical sensations only by association with tactual ones.

(Professor Cannon, who fitted his eyes with inverting spectacles, found it took him a little time to learn to see things the right way up while wearing them. Then, when he took the spectacles off, he found the lesson well learnt—the world looked upside down for a while.)

The usual experiment to illustrate this is surprising but pupils find the reasoning obscure unless they see a demonstration with a model eye. See Demonstrations 24–24XX, below.

NOTES. (These are details outside our suggested teaching.)

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

{*(ii)* We should bear in mind one peculiarity of real eyes: they do not have air in them. The materials inside do differ from one to another in refractive index, but the main refraction is at the front surface—hence the success of contact lenses. (Since most astigmatism is due to unequal curvatures of the cornea, a spherical contact lens can 'remove' astigmatism.)}

{We cannot draw undeviated rays through a real eye as we did for a thin lens with air on both sides. We need not mention this to pupils. For elementary teaching we may think of an air-filled eyeball with an adjustable lens in it.}

Model eye A working demonstration model makes this teaching much clearer. Our model is a large spherical flask filled with water containing a little fluorescein to make the path of light visible. The flask of water would not be a strong enough 'eye' by itself, so a more strongly curved 'cornea' is made by attaching a meniscus spectacle lens to the front.

Model Eye: Details of Construction

All the lenses used must be chosen carefully to fit the size of the flask and the object-distances.

FLASK. A suitable flask is a round-bottomed 5-litre flask. Its diameter will be about 21.8 cm. With that the lenses given below are suitable. The flask is best supported by a padded ring placed under it.

LENSES. Attach three lenses to the front of the flask, for 'normal eye', 'short sight', 'long sight'. These should be cheap spectacle lenses of diameter 45 to 55 mm as follows.
Normal eye: meniscus lens of power $+8$ D ($f = 12.5$ cm)
Short-sighted eye: meniscus lens of power $+11$ D ($f = 9$ cm)
Long-sighted eye: meniscus lens of power $+5.5$ D ($f = 18$ cm)

Attach the lenses to the flask with plasticine. To save trouble, attach them at different places round the equator. Then the flask can be rotated, by twisting its vertical neck, to bring each lens into play in turn.

IRIS. Paste a ring of brown paper round the rim of each lens, as an 'iris'. (Or the iris may be represented by a screen with a hole in it, placed in front of the flask.)

OBJECT LAMP. This must be a bright compact light source such as the tungsten-halogen lamp. When it is about 20 cm away, its filament will be focused on the back of the flask. At other object distances, there will be a blur-patch on the back of the flask.

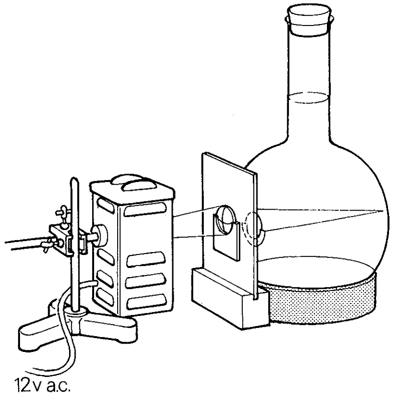
SHIELD. Install a shield near the lamp to cut off light that would miss the eye's 'pupil'.

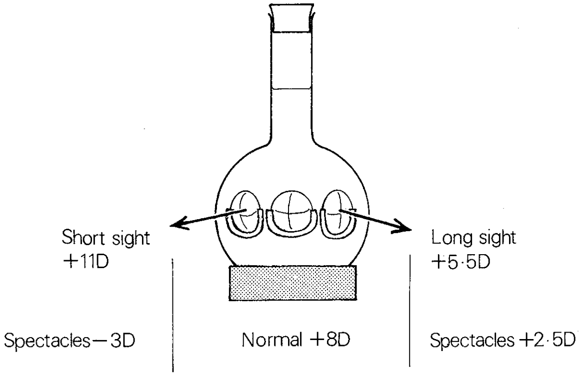
'SPECTACLES'. These are extra lenses, to be hung just in front of the model, to correct short sight and long sight.
For the short-sighted model: a meniscus lens of power -3 D ($f = -33$ cm) to make up the difference
(8 D normal -11 D short sight $= -3$ D)
For the long-sighted model: a meniscus lens of power $+2.5$ D ($f = +40$ cm) to make up the difference.
(8 D normal -5.5 D long sight $= +2.5$ D)

Demonstration 24 Model Eye with Flask of Water

Apparatus

1 model eye kit:	item 114
1 5-litre round-bottomed flask	114A
1 cork ring as stand for flask	114B
1 bottle fluorescein	114C
1 packet plasticine	114D
meniscus lenses, 48 to 50 mm diam., one each of the following powers:	
+11 D, +8 D, +5.5 D for eye	114E, F, G
+2.5 D, −3.0 D for correcting spectacles	114H, I
1 compact light source	21
1 L.T. variable voltage supply	59
1 lens holder	124/1
1 retort stand and boss	503–505
1 slotted base	30
1 large card with central 45 mm hole (for iris)	
1 beaker for fluorescein solution	512





Preparation

Fill the flask with clean water containing a *very* small quantity of fluorescein. The dilution of the fluorescein must be such that the whole path of the rays in the flask is clearly visible.

(Beware of water running down the outside of the flask and filling the spaces between the lenses and the flask; that makes a disconcerting change of power.)

Arrange a stand for the 'spectacles' to be hung in front of the eye.

Make sure the lamp can be moved easily over the range 10 cm to 50 cm from the front of the flask.

Procedure

Normal eye model. Turn the flask so that the 'normal' lens, +8 D, is in use. Place the object lamp so that the 'eye' focuses the filament on the back of the flask. A piece of wet paper placed on the back of the flask helps to show that clearly. But the chief thing to see is the path of the cone of rays through the interior of the model.

Pupils who stand at the side, and those who stand a little beyond the eye and look 'upstream', will see better than those who look 'downstream'.

Short-sighted model. Keep the lamp *at the same place* but turn the flask so that the stronger lens, +11 D, is in use.

This 'eye' makes an image of the filament somewhere inside the eyeball, and the fluorescein shows that clearly.

Then hang the spectacle lens (−3 D) in front to correct for the short sight.

Remove the correcting spectacle lens and move the lamp nearer to show that the short-sighted 'eye' can see clearly without spectacles if the object is nearer (about 12.5 cm from the 'cornea'). A piece of wet paper on the back of the flask may make the focusing there easier to see.

Long-sighted model. Move the lamp back to its original position. Turn the flask so that its weaker lens, +5.5 D, is in use.

This long-sighted 'eye' fails to bring the light to an image inside the flask. The light only converges weakly to a round patch on the back of the flask. (A piece of paper held farther back behind the flask will catch the image but refraction to air will have modified its position.)

Then hang the spectacle lens (+2.5 D) in front to correct for long sight.

Remove the spectacle lens and move the object lamp farther away until its image is on the back of the flask. That shows a long-sighted eye seeing a remote object unaided.

NOTE. The order suggested above is probably the best for the teacher's preliminary practice; but pupils are apt to be confused if moves of the light source alternate with the adding of correcting spectacles.

It is probably better to defer moving the light source until pupils have seen how the three versions treat rays and how appropriate spectacles succeed. Then dispense with 'spectacles' and move the light source so that each version in turn focuses it on the 'retina'.

Demonstration 24X Model Eye with a Goldfish Bowl *(Economy alternative to Expt. 24. Cheaper but much less useful for teaching.)*

Apparatus

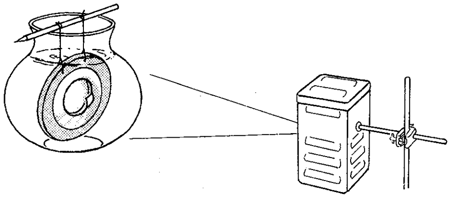
1 compact light source	item 21
1 retort stand and boss	503–505
1 goldfish bowl	
1 convex lens, f = 5 cm or less (item 113/2 or larger)	114C
fluorescein solution	

The lens should be as large as will fit in the bowl.

Preparation

Cut a hole, smaller than the lens, in a disk of plywood or metal, to make a frame for the lens. Attach the lens to the frame. Hang the frame by threads from a pencil placed across the top of the bowl.

Fill the bowl with water, and add a *very little* fluorescein.



Procedure

Change the focusing by moving the lens forward and back inside the bowl.

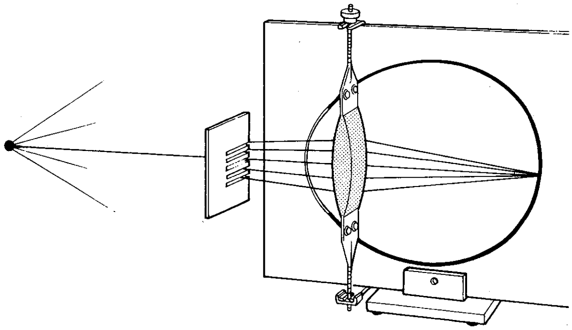
Demonstrating accommodation Most of the refraction occurs at the front of the cornea; but *changes* of focusing are made by the crystalline lens. The Skelton eye model has a 'crystalline lens' of variable power which illustrates accommodation well. In other respects it is apt to be misleading, since the rest of it is diagrammatic, with air in its 'eyeball': so we suggest it may be shown as an adjunct to the flask model, not as a replacement.

Demonstration 24XX Variable-focus Eye

Apparatus

1 Skelton variable-focus eye	item 125
1 compact light source‡	21
1 L.T. variable voltage supply‡	59
1 retort stand and boss‡	503–505
‡ Alternatively:	
1 ray-streak lamp holder and stand	94A
1 transformer	27
1 slotted base (for model)	30
1 comb (for ray streaks)	94E
1 *cylindrical* lens +7 D	94H
1 retort stand, boss, and clamp (for lens and comb)	503–506

The 'crystalline lens' of the model is a cylindrical lens of jelly enclosed by thin flexible sheets of Perspex which can be pulled by a screw to different curvatures. (Apparatus drawing sheet for construction at school is available from A.S.E.)



Preparation

The jelly lens is not very strong optically, even at its fattest. So to focus the lamp at convenient distances extra power may be needed. If so, tape a cylindrical lens (+7 D from ray-streaks kit) on the comb.

If the ray-streak lamp is used it must be turned so that the filament is horizontal.

Procedure

Set up the lamp and model. Arrange the lamp and comb so that ray streaks cross the model.

Start with the jelly lens at its strongest. Move the lamp towards it until the ray streaks converge to an image at the 'retina'.

Then move the lamp farther away and show how the curvature of the jelly lens must be decreased to bring the rays to a focus on the 'retina'.

To renew the jelly. Warm the following together by heating in a hot water bath, but do not boil: parts by volume: glycerine 13, water 10, good quality gelatine 3, cane sugar 2.

Dissecting Eyes

A real dissection is better than any model and we urge teachers to make every effort to try it. Once they have seen how it goes with a class they will continue.

One can easily learn to make a simple dissection of an eye. It is not a messy business; and, if one tells pupils they need not look at it, all will watch.*

One can get cattle eyes from the butcher. The eyes should be dissected within a day or two of slaughter, or there will be a confusing cloudiness. It would be a great mistake to use pickled eyes from a biological supplier: easier to obtain but quite unrealistic for our purpose—we are teaching optics. Butchers take some persuading and may charge for their extra time but the result is worth all that.

Demonstration or Class Expt 25 Dissecting a Bullock's Eye

Apparatus

3 or more cattle eyes	
1 single-edged razor blade	item 3H
1 Petri dish or crystallizing dish	528
1 pin on handle	
1 sharp scalpel	
1 pair of tweezers	
The following may be useful:	
1 pair small scissors	
paper towels	
(spotlight or floodlight)	

Preparation

Obtain cattle eyes from a butcher or a slaughter house. The eyes should be dissected within a day or two of slaughter, otherwise there will be a confusing cloudiness.

Four eyes are usually necessary for one class and more for each subsequent class. The teacher needs to practise on at least one and often needs to dissect two in the class.

Razor blades (single-edged) are easier than a scalpel for the main cutting. Some amateurs prefer to use nail scissors.

Since the things to be seen are small the placing of pupils is important. Pupils 2 metres away would have a very poor view—they would deserve to come up and have a close look at intervals. Unless the dissection is to be done twice, for half the group at a time, arrange for some kind of amphitheatre, such as: a circle of seated pupils, a row standing behind them, and then a row standing on benches.

Procedure

A colleague in Biology will provide instructions; or the dissection can be done easily as follows:

Make a cut with a razor blade or nail scissors in a circle where the clear cornea joins the tough, white coat of the eyeball. This will remove the clear front window, the cornea.

At some stage, according to the exact placing of the cut, the liquid aqueous humour will run out. Or one may puncture the clear cornea with a sharp pin first of all to release the liquid.

If the cut is made a little forward of the boundary, the cornea will be removed but the iris will be left with the rest of the eye. Cut round the edge of the iris to remove it.

If the cut is made a little behind the boundary, the iris will be removed with the cornea. Its black rear surface will be visible, with radial muscles like mushroom gills. Remove it by scraping or cutting round the edge with a scalpel or razor blade.

Wash the iris in water and turn it over to show the coloured front side. Point out that the eye's pupil, the black spot in the middle of the iris, is simply a hole—through which all the useful light enters the eye.

Pick the crystalline lens out with tweezers or a pin; or push it out from the thin sac which holds it. Hold it on a pin and show how it can focus a window or a ceiling light on a piece of paper. This gives an incorrect idea of its effective focal length because in the living eye the crystalline lens is immersed in materials (aqueous and vitreous humours) of not-very-different refractive index,

* A teacher reported: ' "Please can we do it again?" was the comment.'

so its contribution to the lens system's refraction is small—though it is very important because it is variable. Most of the refraction occurs at the open-air face of the cornea. Therefore, it is fairer to hold the lens in water and then focus the ceiling light with it.

Then remove the jelly-like 'vitreous humour' from the eyeball, with a scalpel.

Show the retina, with its surface layer of very fine blood vessels.

Cattle, and many other animals, have an extra coating behind the retina to reflect light back through it—that is the iridescent layer that one sees.

Starting again with another eye, show the three sets of muscles (red meat) on the outside of the eyeball. (As a ball in a socket, it has 3 degrees of freedom—3 rotations—so there must be 3 sets of muscles, otherwise successive rocking and swivelling motions could twist it more and more and damage the nerve.)

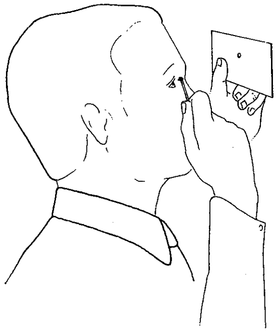
Show the optic nerve as a fat white 'telephone cable' emerging at the back. Later, cut along the nerve to the retina and show that it arrives at a special place, the blind spot.

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

Class Expt 26 Experiment with Pupils' own Eyes: Retinal Shadow

Apparatus

32 small cards   item 566
32 pins



Procedure

Pupils follow these instructions.

*   *   *   *   *

Make a pinhole in a small card. Hold the card a few centimetres from one eye and look towards bright white sky. You will see a fuzzy round patch.

The pinhole is far too close for your eye to form an image of it on your retina. Rays of light from different parts of the sky come straight through the pinhole, spread out as they go to your eye. And your eye lens only bends them enough to make a bright round patch on your retina.

While you look towards the pinhole, hold a pin *very* close to your eye. Hold it by the point, with its head among your eyelashes. What do you see? Light from the hole in the card is casting a shadow of the pin on your retina.

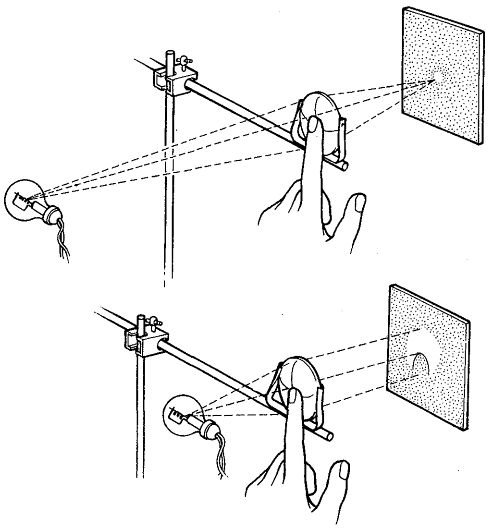
Since the pin is very close, your eye cannot possibly form an upside-down image of it on the retina. All you get is a shadow of the pin, the same way up as the pin. But what does your brain, having learnt its lesson long ago, do with that?

*   *   *   *   *

That *will* seem puzzling. The following experiments illustrate what is happening. They should persuade pupils that when their eye is focused on an object its image is upside down on the retina.

Class Expt 27a Model of Pin's Shadow

AIM. To help pupils to understand how the pinhole-and-pin experiment proves the inversion of the retinal image.



Apparatus

16 lamps, holders, and stands (from ray optics kit)	item 94A
16 *spherical* lenses +7 D	112
16 sheets of white paper	

Preparation

Since the lamp filament represents the bright pinhole and a vertical finger represents the pin, the effect will be clearer if the filament is horizontal. Preferably turn the lamps to that position beforehand.

Procedure

Explain that this is a rough model of the pinhole-and-pin experiment.

The bright lamp represents the bright pinhole
The common lens represents the eye's lens system
A sheet of paper will represent the retina
A pupil's finger will represent the pin

Pupils work in pairs. One pupil holds the lens to receive light from the lamp; the other holds a sheet of paper beyond the lens. They start with the lamp far from the lens, about $\frac{1}{2}$ metre in front. The pupil with the paper 'retina' moves it till the image of the filament is on it. *They then hold lens and paper in those positions throughout the experiment.*

They move the lamp much closer, say $\frac{1}{4}$ metre from the lens. The lens can no longer focus the filament on the paper, but makes a round illuminated patch on it.

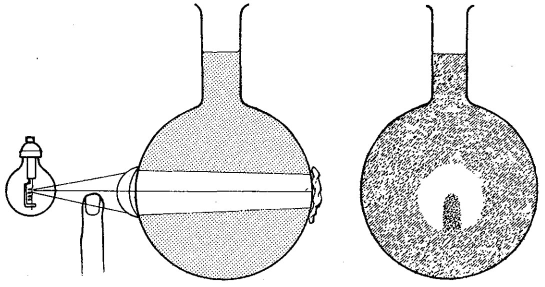
The pupil holding the lens places his finger pointing upwards, just in front of the lens—like the pin just in front of the eye. They look at the screen and see a shadow of the finger—the same way up as the finger itself.

Some pupils then transfer this result to the experiment with their own eye and realize that their brain must somehow turn the upright shadow of the pin upside down. But many will still feel puzzled. Now offer them a demonstration that will seem more realistic, with the flask model. Simply move the lamp up. It is well worth while to get the model out on a later day for this. To add this to the main demonstration of that model on the same day would be confusing.

Demonstration 27b Pin's Shadow With Model Eye

Apparatus

1 model eye kit (as for 24, but correcting spectacles will not be used)	item 144
1 compact light source	21
1 L.T. variable voltage supply	59
1 retort stand and base	503–505
1 slotted base	30
1 large card with hole 45 mm (for iris)	
1 beaker of fluorescein solution	512



Preparation

Fill the flask as before. Turn it so that the normal eye is in use. Make sure the lamp can be moved very close to the eye.

Procedure

Place a piece of wet paper on the back of the model. Move the lamp up close, say 10 cm from the front of the flask. The lamp now represents the bright pinhole close to one's eye. It will make a round patch of light on the back of the flask.

Hold a finger, upright, just in front of the flask. Pupils look at its shadow.

Spectacles Range of accommodation and the use of spectacles have already been discussed. Pupils are not expected to use $1/v$, etc., to calculate spectacle prescriptions. However they should be able to do the following: describe clearly the limitations of various eyes; say what kind of spectacles are needed; and explain clearly in terms of images how the spectacles do their job.

Optional extension: prescribing spectacles Fast pupils with a clear feeling for the use of lens powers can learn to prescribe spectacles without using a formula. (There is no need for any formula for a thick lens or for a combination of thin lenses in contact—which would be untrue of the actual combination.)

EXAMPLES:
(I) For short sight. A man of 40 has the average range of 4 D but is short-sighted. Suppose he can see things comfortably if they are anywhere between 10 cm from his eye and 16.7 cm.

His accommodation therefore covers a range of 'power' from 1/0.10 metre to 1/0.167 metre; that is, from 10 D to 6 D, the usual 4 D for his age.

He should wear spectacles that form an image of a distant mountain at his far point, 16.7 cm in front of his eyes. They must move the mountain optically from infinity (real object) to 16.7 cm (virtual image).

The 'calculation'. The farthest object that his eyes can focus sends fans of rays of power 1/0.167 metre or 6 D.

With his glasses he wants to look at the mountain at infinity which sends fans of rays of power 1/(infinity) or 0 D.

Therefore (6 D) + (power of glasses) must make 0 D.

Therefore he needs glasses of power -6 D.

He can still keep his glasses on to read a book if he likes. Fans of rays from the book held at $\frac{1}{4}$ metre have power 4 D. His eyes at their strongest can focus a fan of rays of power 1/0.10 metre or 10 D. And with his glasses he can just focus a fan of power 10 D + (-6 D) or 4 D.

(II) For long sight. Suppose a long-sighted man has a near point $\frac{1}{2}$ metre away. To read a book held at $\frac{1}{4}$ metre he needs spectacles that will give him a virtual image at $\frac{1}{2}$ metre to look at.

His eyes alone can focus a fan of rays of power 2 D, but the book sends fans of power 4 D.

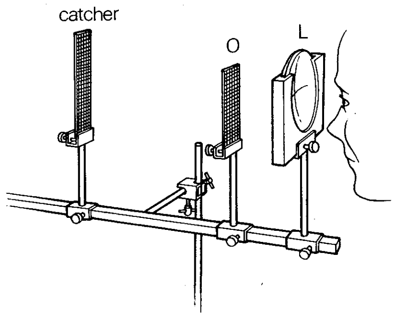
Therefore he needs lenses +2 D to help him.

Magnifying Glass and Microscope

Class Expt 28 Magnifying glass: Magnification *(ADVANCED)*

Apparatus

16 telescope mounts	item 115
16 plano-convex lenses (+14 D)	113/1
32 pieces of graph paper (1 mm or 2 mm squares)	
32 wooden strips (tongue depressors)	53F
16 lamps from ray optics kit	94A
16 retort stands and bosses	503–505
16 supports for lamps	



Preparation

Paste coarse graph paper (or a mm scale) on each of the 32 wood strips.

Arrange lamps to illuminate the object scales strongly. It will hurt this rather difficult experiment if the mount has to be lowered below eye-level because the lamp is so low. The lamp should be raised on a box or supported by a separate retort stand.

Procedure

Pupils put the +14 D lens in a holder on the telescope mount. If it is a meniscus or plano-convex lens, the less bulgy face should be towards the observer.

The object, O, and the image-catcher, C, are wooden strips with translucent graph paper (or mm scales) stuck on. Pupils fix these, each vertical, in holders on the mount. The top of C should be higher than the lens. The top of O should be level with or just below the top of the lens. The object must be very well lit by a lamp close to it.

Pupils follow these instructions:

* * * * *

Fix the lens, L, at the end nearest you. Place your eye close to the lens.

Since you want to look at a virtual image at a comfortable distance, fix one scale as an 'image-catcher', C, at the average eye's comfortable distance of $\frac{1}{4}$ metre. (Remember C is NOT an image: it is a trap, put there to catch the image!)

Now install the other scale just behind your lens. That is the object, O. Shine plenty of light on O. Move O until you see its image clearly.

Keep both eyes open. Look through the magnifying glass, L, with one eye; look at the catcher, C, with the other, naked, eye. *Concentrate on the naked eye; insist on its keeping the catcher in focus.* Meanwhile, move the object O nearer and farther until you see its image clearly in focus, sitting on the catcher.

* * * * *

Faster pupils should be encouraged to estimate the magnification. ('If you like, make an estimate of the magnification that your lens gives when it is used like this. How many centimetres on the catcher does one centimetre of the image cover?')

Others may be content with seeing that the image is back at the image-catcher and obviously considerably bigger.

As an alternative method, which is neither so easy nor such good teaching of the meaning of images, some pupils may be helped by trying the 'method of no-parallax'. Keeping both eyes open (*and concentrating attention on the naked eye*) the pupil moves his head to and fro laterally, moving the object until image and catcher seem to stay together.

There is a poorer method, only to be recommended where a pupil has uneven eyes, or can use only one eye well. The pupil moves his head *up and down* rapidly, first looking *through the lens* at the virtual image, then *over the lens* at the catcher, then through the lens at the image again, and so on. During this rapid alternation of glimpses of image and catcher, the pupil moves the object until both image and catcher seem equally in focus.

Compound microscope Pupils should make a large model of a compound microscope, as an aid to using a commercial microscope with comfort and success.

Tell pupils that in a microscope the first lens (objective) forms a magnified real image of the object. The second lens (eyepiece) is used as a magnifying glass to look at that real image.

Setting up this model is easy for teachers, who know how to place the object for a magnification of about 3. But for pupils this is puzzling. If the image is just formed in mid-air they will have trouble in keeping track of it as they move the object to get a suitable magnification. However, if the object is so bright that its real image can be caught on a scrap of paper, the experiment becomes easy and pleasant.

Therefore the object should be *translucent* so that it can be illuminated brightly by a lamp behind it for the initial adjustment. Since some pupils will want to estimate the overall magnification, the object should be marked with a scale. Then when a rough adjustment has been made the object can be illuminated from in front and the eyepiece adjusted to make the final, virtual image fall on the object—as in professional microscopy.

Class Expt 29 Large Model of a Microscope

Apparatus

16 telescope mounts	item 115
16 plano-convex lenses +14 D	113/1
16 plano-convex lenses +7 D	112
32 retort stands and bosses	503–505
16 lamps, holders, and stands	94A
16 clamps for lamps	506
16 graph paper 'objects'‡	

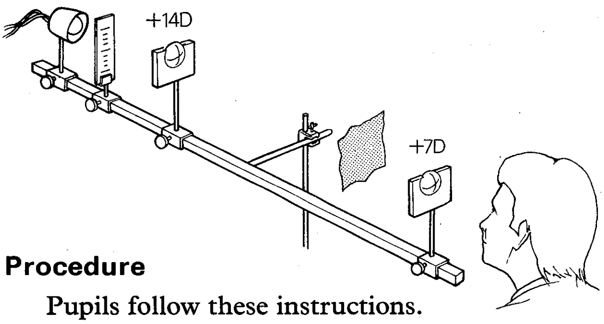
‡ The object should be a translucent millimetre scale. This may be a transparent scale backed by kitchen greaseproof paper (or any thin paper treated with oil); or it may be black-ruled millimetre graph paper, treated with oil. Adhesive peel-off graph paper and adhesive tape with a millimetre scale are now available.

Preparation

The object should be carried on a lens holder which slides on the mount. The way to attach it depends on the particular make of apparatus.

The lamp may be a ray-streak lamp clamped to a retort stand so that it can be raised to a suitable height, first to illuminate the object from behind, later to shine on the object from one side in front.

It is even more important with the microscope than with the telescope for the mount to be raised so that the lenses are at eye level when the pupil stands up straight. The optical comfort of looking straight ahead will repay the trouble of arranging the supports.



Procedure

Pupils follow these instructions.

* * * * *

Set up the bar to carry lenses at head height for comfort.

Place the +14 D objective lens about 15 cm from the far end of your bar.

Place the object marked in millimetres about 10 cm beyond the lens.

Put a bright lamp behind the object to begin with. Hunt for the real image with a scrap of paper about 30 cm from the lens on your side. Move the object slightly until you catch its image on the scrap of paper. Then fix the object at that place.

Place the +7 D eyepiece near the scrap of paper so that it acts as a magnifying glass for the scrap which you are still holding at the real image.

Take away the scrap of paper. Move the eyepiece a little forward and back until you see the final virtual image clearly in focus.

Move the lamp round to the front of the object. Take the lamp away from the back of the object. Let it shine light on the object from in front.

Keep both eyes open. Look through the microscope lens with one eye while you look directly at the original object with the other, naked eye.

Concentrate on the naked eye and move the eyepiece until you see the final image also clearly in focus. The image should be back at the object, sitting on the object.

If you like make an estimate of the overall magnification made by your large model microscope. Keep both eyes open and look at one magnified scale-space of the final virtual image. How many scale-spaces of the original object does that cover? A rough estimate will do.

Then let your partner have a try. He should start from the beginning and arrange the lens himself. Let him make his estimate of magnification and compare it with yours.

* * * * *

Commercial microscope Now that pupils understand where the final virtual image *should* be placed and have some skill in placing it, they should use professional microscopes if those can possibly be made available. It is sad to hear students—and older adults—in other sciences say 'The microscope strains my eyes.' No wonder, if they mistakenly place the image only a few centimetres away!

Pupils will need microscopes later in the year to look at the Brownian motion of smoke specks—unless they remember that really well from an earlier year—so practice now will be useful. However, if this involves long queues to snatch a brief look it may do more harm than good. Pupils should have enough time to enjoy focusing. One microscope for every group of four is a minimum.

Class Expt 30 Using a Commercial Microscope

Apparatus

Microscopes (at least 8 per class)	item 23
Lamps (one per microscope); e.g. item 94A	
Plain slides (one per pupil)	97A

The microscope should have a low power objective (between 15 and 30 mm—the usual 18 mm is suitable) and a standard eyepiece.

Procedure

Each pupil should have his own slide and place some object on it; a hair, a scrap of paper, a smear of blood . . . Each in turn should place his slide on the microscope and follow these instructions:

* * * * *

Squat down till the stage is at eye level and bring the objective down *almost* to the slide. Then look through the microscope and *raise* the tube until you see the object roughly in focus.

To focus properly *keep both eyes open.* Place a page of print on the table. Look through the microscope with one eye. Look at the print with the other, naked, eye.

Concentrate on looking at the print with the naked eye. Change focusing slowly till you see the virtual image through the microscope sharply in focus on the paper. KEEP BOTH EYES WIDE OPEN.

* * * * *

(Some pupils may have a microscope at home. Many of the small models now available have a small aperture but offer great magnification. Teachers may need to explain, without hurting an owner's pride, that most 'small' microscopes have great depth of focus, so that focusing the large model in the lab needs new skill—which nevertheless will help with the one at home.)

A Return to Ray Streaks

Now that pupils have focused their own telescope and made a model microscope they should look at models of those instruments with ray streaks. In fact one of the main purposes of the ray-streak equipment is to provide realistic models of instruments.

Pupils should now make ray-streak models of telescope and microscope (if they did not do them before in the earlier ray-streak series).

See the note on page 90 about the 'three-ray trick' to simplify these more difficult patterns.

A little later still the ray-streak apparatus will be used to make a spectrum.

Class Expt 31a Ray-Streak Model of Telescope, with Two Lamps

Apparatus

As for earlier ray-streak experiments with kit for ray optics (item 94):

3 transformers	item 27
16 (or more) lamps, holders, and stands	94A
8 pairs housing shields	94B
16 combs	94E
16 holders for combs	94F
16 plano-cylindrical lenses +7 D	94H
16 plano-cylindrical lenses +17 D	94J
32 barriers	94G
(16 metal plates with three slits)	(94D)
pale colour filters for lamps (e.g., Rank-Strand Cinemoid No. 38)	

Pupils work in pairs, but they will probably have to form groups of four when they need two lamps.

Procedure

One lamp. Pupils place the lamp 1 metre or more away. They raise it as far as possible without making the streaks too short, so that the streaks are bright enough to see easily.

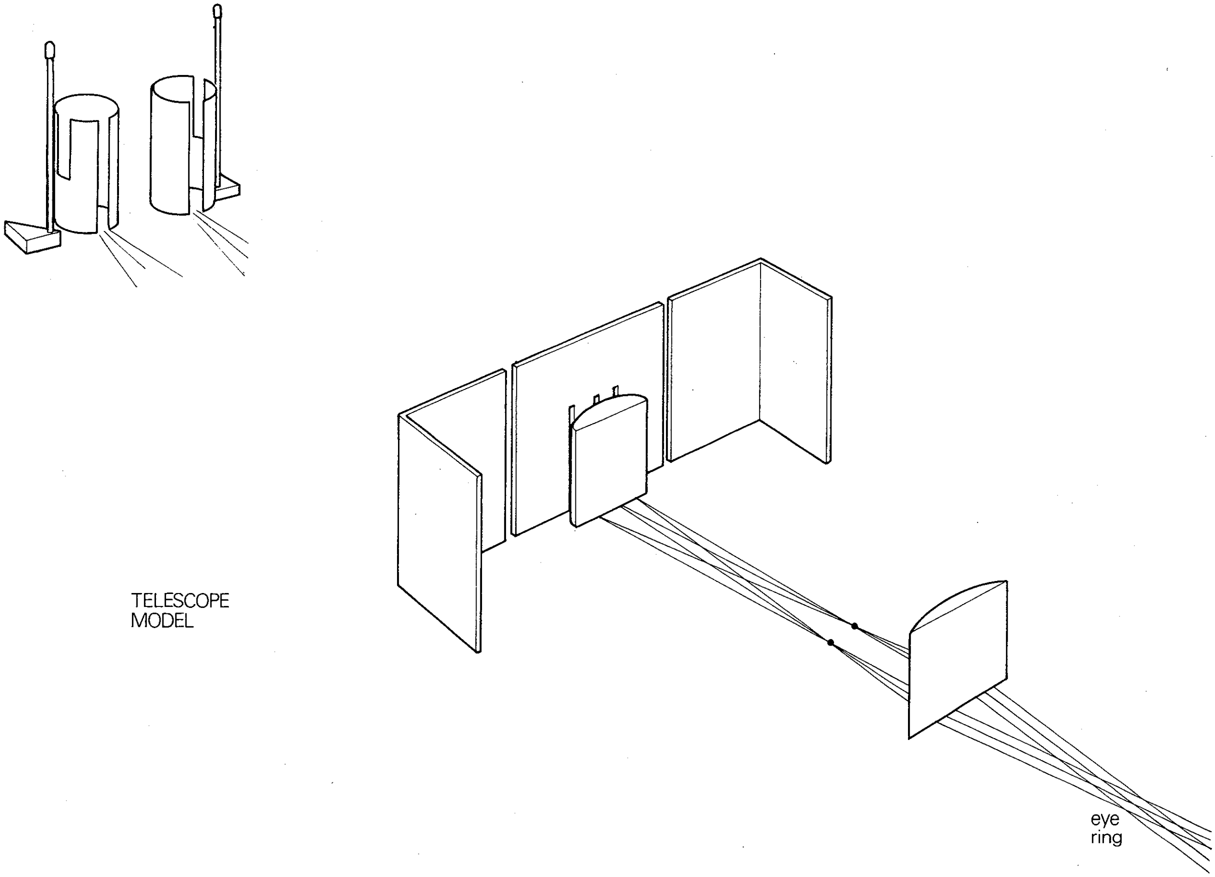
They use the weakest lens +7 D as telescope objective and place the comb a small distance before it.

For less aberration the curved face of the lens should be towards the object lamp. It would be a pity to tell pupils that. Instead, help slower pupils with a question:

> 'Which way should the lens face? If you don't remember, how can you find out which way makes a better image?'

Pupils use the strongest positive lens +17 D as eyepiece. In this case tell them it is better to place it with the light meeting the curved face.

Some pupils will not be sure where to place the eyepiece. Rather than let confusion grow, help them to arrange it so that rays emerge in an almost parallel beam. Other pupils will consider they



know by now and will enjoy placing their eyepiece and seeing what it does to rays of light.

If aberrations spoil the simplicity of the picture, pupils should, of their own accord, move in barriers to reduce the aperture.

With faster pupils, suggest also making a model with rays diverging from a virtual image that is nearer—say $\frac{1}{4}$ metre away—with the object lamp still at 1 metre.

When visiting pupils, show them how to move the lamp sideways and watch the ray streaks emerging from the eyepiece to see how direction of the virtual image changes. With care and a little acquired skill, pupils can thus see the magnification clearly.

Two lamps. However, the magnification is shown better if pupils have two lamps, representing 'head and feet' of the distant object. Unless there are spares, one pair of pupils should borrow the lamp belonging to a neighbouring pair and all four of them make a model telescope as follows: the two lamps are placed very close together a metre or more away from the objective lens. (If, by good luck, one lamp is brighter than the other, rays from these two object points will be easily distinguishable. Better still, a pale colour filter should be placed in front of one lamp.) The objective must be carefully placed so that the rays from both lamps make only small angles with its axis and the eyepiece must be shifted until it treats the two sheaves of rays equally.

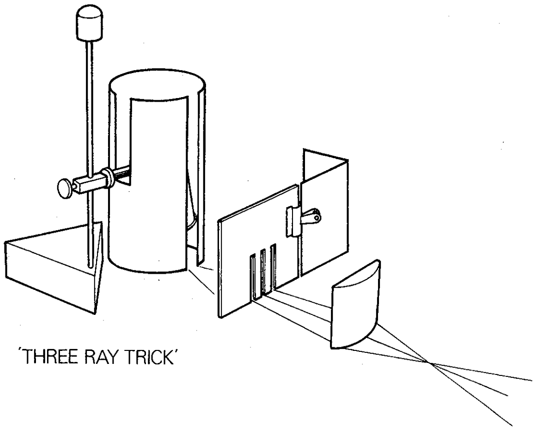
Pupils will see the two real images formed by the objective lens clearly; but the rays emerging from the eyepiece now form a rather complicated picture—except that the 'eye-ring' will be clearly visible as a place where the two sheaves of rays cross, making a narrow region where an observing eye receives everything.

Here it may be wise to change from the comb to the screen with three splits, placed *at* the objective lens. (See the note below.)

Also let pupils try the model without any comb or screen.

Aberrations and the three-ray trick The aberrations of lenses are real and they are there for pupils to see in the ray-streak experiments. To those who are interested we can point out the marvel of successful design of wide-angle camera lenses, large aperture camera lenses, microscope objectives, cataract spectacles, and even the simpler lenses of projectors which form such sharp images.

But spherical aberration is so obtrusive in some experiments that some pupils find it difficult to see the essence of the (approximate) imaging. This is particularly likely when there are two lamps and two lenses. Then aberrations will confuse the picture, unless things are arranged with great care for symmetry.



'THREE RAY TRICK'

In such cases teachers may like to use just three rays instead of many. If the screen with three slits is placed *at* the objective lens, the rays from both lamps that emerge from the central slit can be made to meet the objective lens near its optical centre and these will represent undeviated rays from two object points. The rays through the outer slits will hit the objective lens near each edge. Although the bending of those rays will be greater than it should be for perfect imaging (the symptom of spherical aberration) that trouble will not be noticeable—because there are only three rays—provided the slits and objective lens are arranged to make the pattern as symmetrical as possible. Teachers who have once done that for themselves will find it easy to show pupils how to do it.

Then, both with a moving lamp and with a pair of lamps, the whole behaviour of the telescope will look very close to the formal optical diagrams that one draws for such an instrument.

This is of course cheating; but it is a useful trick for showing simple diagrams of the working of optical instruments with ray streaks. In the more complicated models this dishonest trick provides a simplification that is almost essential *for a first look*; and we suggest teachers should occasionally show pupils how to use it, with a warning that it only covers up the symptom without curing it. (This untruthful simplification is, of course, used all the time in traditional optical diagrams—usually without any warning to pupils, and it is this lack of warning that we deplore.)

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

Class Expt 31b Ray-Streak Model of Telescope with Field Lens *(BUFFER OPTION FOR FAST PUPILS)*

A fast group, or a specially keen pupil, may like to try adding an extra, fairly weak, positive lens *at* the real image formed by the objective of an astronomical telescope.

Apparatus

For each pair of pupils:
As for telescope model:

2 lamps, holders, and stands	item 94A
1 pair housing shields	94B
1 comb	94E
(1 plate with 3 slits)	(94D)
1 holder for comb	94F
2 barriers	94G
1 plano-cylindrical lens +7 D	94H
1 plano-cylindrical lens +17 D	94J
transformer	27
For field lens	
1 plano-cylindrical lens +7 D or +10 D	94H or 94I

Procedure

Pupils set up the telescope model with two lamps as before. Then they place an extra lens (+7 or +10) at the real image formed by the objective lens. They should look at the effect of this on the light meeting the eyepiece and on the eye-ring.

Explanation. If a converging lens is placed exactly at the image, it does not alter the convergence or divergence of the fan of rays that passes through the image. To pupils who question that:

> 'If you stick your thumb on the glass of a magnifying glass and look at your thumb through the glass does it look anywhere else except just behind the lens?'

(If the distance from object to lens is zero, the distance of image from lens is also zero and the magnification is 1.)

However, this extra lens does do something: it tilts the whole fan of rays so that they emerge pointing in a different direction (except for a ray which happens to hit the extra lens just in the middle). When we make a ray-streak model of a telescope with two lamps the fans of rays through their two real images cannot both pass through the centre of the eyepiece. Then, although the extra lens does not alter the angle between rays within a fan, it does tilt the two fans to pass through a more central region of the eyepiece.

Advantages? Ask the fast pupils who try the experiment what advantages they see. The advantages are: a larger field of view, less aberration, an eye-ring that is not so far outside the eyepiece. The enlarged field of view is the important thing. We should not tell a fast pupil any of those; but we might coax him into thinking of them.

Model microscope with ray streaks This is a more difficult model to arrange but it is very valuable in helping pupils to understand the microscope.

All pupils should try it just before or after they make a model microscope with spherical lenses.

Trials have shown that a good small model is impossible with the usual ray-streak lamp. With two lamps as close together as they can be, their real images are still too far apart for rays to meet the eyepiece; and even if the model is made much longer aberrations are serious.

However by using a special lamp with two filaments close together pupils can make an excellent ray-streak model microscope. The model is so important that we hope schools will assemble a set of mounted lamps as part of their ray-streak equipment. Failing that, a single lamp can be used to make a demonstration, but that would be an unfortunate change in the ray-streak series.

Class Expt 31c Ray-Streak Model of Microscope with Special Lamp

Apparatus

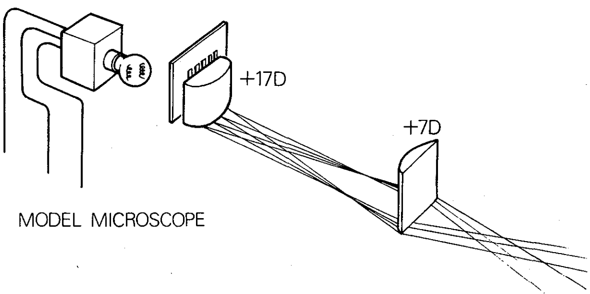
From ray-optics kit, 16 sets of:	item 94
plano-cylindrical lenses +17 D	94J
plano-cylindrical lenses +7 D	94H
metal combs	94E
barriers	94G
holders	94F
16 special lamps (see note ‡ below)	230/1 (= 94L)*
16 wood bases for lamps (see note ‡)	230/2 (= 94M)*
3 or more transformers	27
[16 rheostats (for the 21 W filaments)‡‡]	[541/1]

‡ The special lamp is a standard car lamp for tail light and stop light operating at 12 volts. The two filaments, one at 21 W and the other at 6 W, are straight and about 7 mm apart. The lamp fits in a special base but that is not worth the expense. A wood block with a hole into which the lamp can be pushed does well instead.

Solder two wires to the contacts on the lamp and a third wire to the cap of the lamp, and pull the lamp into the hole. The axis of the lamp must be horizontal, with the filaments vertical.

For streaks of approximately equal brightness, the 21 W filament should be run at 6 V; and the 6 W filament at 12 V. Then the streaks are clear in half or three-quarters blackout.

‡‡ If the transformers have a 6-volt tapping, that should be used for the 21 W filament; and rheostats will not be needed.



MODEL MICROSCOPE

* The lamp and base are new Nuffield items, added to the ray-optics kit.

Procedure

Pupils place the lamp about 6 cm from the plane surface of the +17 D objective lens. That will makes images of the filaments about 16 cm from the lens, and nearly 2 cm apart.

It is better to use the comb than a screen with 3 slits; but pupils will need to narrow the aperture of the objective with barriers until they obtain good images.

Pupils place the +7 D eyepiece at such a distance beyond the images that the final emergent rays seem to come from a vertical image back at the lamp.

This will give an overall magnification of about 7.

It is helpful, in setting up, occasionally to switch off one of the filaments.

Expts 31d Further Experiments with Ray Streaks as buffer options

Teachers and pupils may enjoy devising other ray-streak experiments in the lab or at home:

illustrating a Galilean telescope;

illustrating a terrestrial telescope (using a *pair* of extra lenses);

showing curvature of field and distortion of field (with 4 or more lamps in a transverse row as objects);

a model eye with spectacles (a small cylindrical crystallizing dish filled with water will be useful but extra lenses will be needed).

CHAPTER 3

LIGHT AND COLOUR

Experiments and theories

This chapter moves on from fans of rays to the bending of a single ray, spectrum of colour, wave and particle models for light.

The section on colour offers simple interesting work. The section on theories—entirely optional now—is demanding, but some pupils will find the experiments memorable.

Bending of Rays: Reflection and Refraction

{We have built up a knowledge of optics that uses the properties of images. Classical optics teaching started with Laws of Reflection and Refraction—either announced as starting points for deductive geometry or extracted from precarious experiments with pins—and it arrived much later at instruments.}

{We might feel tempted to give our pupils those laws at this later stage in our programme; but what use would be made of them? By the time a long excursion into geometry had become productive, most pupils would consider it had complicated their clear knowledge. So we do not advise a study of laws now, still less their use for deduction.

{Nevertheless when pupils come to compare theories of light, now or in Year 5, they will need clear acquaintance with the phenomena of reflection and refraction.}

We suggest pupils should then be reminded of the simple 'angle story' of reflection which they saw with ray streaks and do a qualitative class experiment on refraction. They should not see demonstrations instead because they will find discussions of theory easier if they have a strong feeling of personal knowledge.

And, after so many ray-streak experiments, they can take a second look at reflection (if necessary) and then arrange their own experiments to see rays being refracted, all in a short time.

Reflection

If pupils do not remember what they found (or if they missed it) they might repeat Expt 19j now. If any are specially interested in continuing to measurements they might try an optional experiment (32) with a protractor—but not with pins, or there will be diversion into delays and boredom.

A Law of Reflection? We would like every pupil to be able to say, as a result of his own observations: 'When a ray of light is reflected, the two angles are equal.' That contains the information of one Law though the wording is informal.

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

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

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

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

Examinations will ask for well-understood knowledge of behaviour and *not* require the formal statements.

With very able future scientists the usual formal statements might be given; but they will not need them till after O-Level.

Class Expt 32 (= 19j) Flat Mirror and a Ray

This is the ray-streak experiment on reflection, only to be repeated now by a pupil who feels uncertain, or who missed that part of the series.

Apparatus and Procedure

See Expt 19j in the ray-streak series.

Class Expt 32X Law of Reflection
(OPTIONAL)

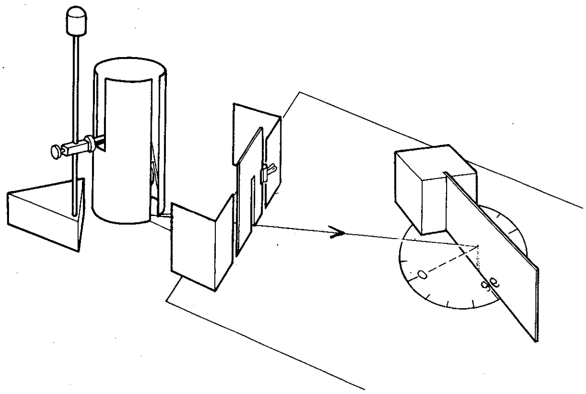
(This may be offered to all the class, or only to some, or to none, according to abilities and interests. Therefore the list here shows the apparatus needed for *each pupil or pair of pupils* wishing to try the measurements.)

Apparatus

1 protractor‡	item 550
1 lamp for ray streaks, with holder, stand, and shield	94A, B
1 single slit and holder	94C, F
1 plane mirror	116
1 holder for mirror	117
1 transformer	27
white paper	

‡ The protractors should be of paper or card with the full circle of 360°, reading both clockwise and anti-clockwise.

(If time is very short this might be replaced by a demonstration with a device like a 'Hartl disc' which has a protractor and a scheme for showing the behaviour of a single ray. However, this should not turn into a demonstration with a special 'ray box' on a vertical white screen, because that would seem to pupils a quick repetition of their own ray-streak experiments, 'to put things right at last'. Then there would be serious danger of a ray-box experiment spoiling the earlier class experiments in retrospect and, in the course of years, even threatening to replace them.)



Procedure

Pupils follow these instructions.

* * * * *

Place the mirror along the 90° line.

Shoot a ray in to the place on the mirror which sits on the centre of the protractor's circle.

Now look at the angles.

* * * * *

NOTE. Teachers who have tried asking pupils to make pencil lines to mark the paths of rays on a sheet of paper find that the experiment is rather tedious and the measurements not very accurate. So we suggest a simpler, quicker look at reflection angles, by noting where the ray streaks cross the angle scale.

We hope that the usual class experiment with a plane mirror in which pupils trace rays by pairs of pins will be omitted, as it takes considerable time and it diverts attention from the great, precise law to the difficulties of manipulation.

This is meant to be an enjoyable finding of a simple rule just by *looking* at the protractor readings.

Refraction

Pupils should see refraction of rays *qualitatively*. *Measurements* in a class experiment with a ray streak and a block of glass (or a tank of water) would seem tedious and puzzling to pupils who have been making optical instruments work.

{Careful measurements with pins and a rectangular block of glass are likely to be still more tedious; and, though they are pleasing to some pupils with neat fingers, they are likely to obscure the essential investigation with their details of aligning and drawing and measuring. So we urge teachers not to use pins and blocks in this scheme of teaching optics. Instead we suggest that pupils will do better with their own qualitative experiment to observe refraction of rays.}

{The mathematical form of the law is *not* essential to the discussion of the 'crucial' experiment to distinguish between waves and bullets. So pupils will not need to extract a quantitative law or be given one.}

General acquaintance will suffice: of rays bending as they pass from air to water or glass, bending more if they impinge more obliquely, always being partially reflected as well; and when rays pass from a dense medium to air, the reverse behaviour; and then in that case total reflection beyond a certain obliquity.

(If time is short, a qualitative *demonstration* of refraction, e.g. with a Hartl disk, could replace the class experiment; but we hope that will not be necessary.)

Pupils use ray-streak equipment with a transparent plastic box filled with water. Plastic lunch boxes, about 20 cm × 8 cm × 7 or 8 cm deep are suitable.*

Class Expt 33 Refraction of Rays with a Box of Water

Apparatus

8 rectangular plastic tanks	item 100/1
From the ray optics kit:	94
8 lamps, holders, and stands	94A
8 metal combs	94E
8 holders for combs	94F
8 transformers	27

Preparation

Clear, clean water must be available.

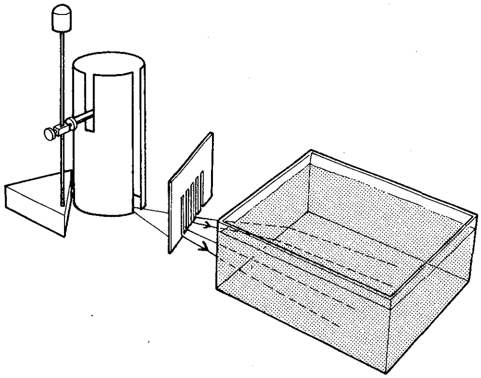
Whereas the streaks will show on white paper on the table in air, they will not show in water unless the *inside* surface of the bottom of the box is painted with flat white paint.

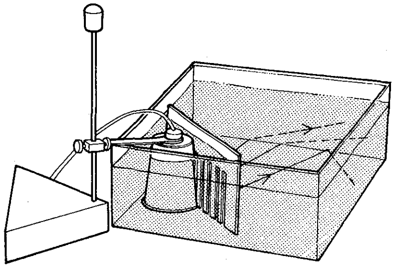
Procedure

(i) Air to Water. Pupils fill the plastic box with clean water and direct ray streaks at its side. They look at the bending of the rays where they strike the water surface at the side of the box. But they should *not* make measurements of angles.

(ii) Water to Air. Then pupils place the lamp and comb carefully inside the tank, under water. They will see what happens when the streaks meet the water/air surface at the side of the box.

Pupils will certainly see refraction as the streaks emerge into air. We hope they will also see total reflection without any prompting. If not, give a hint.





(The rays can be made visible in water by another method, by adding a little milk or a very little fluorescein; but the white painted bottom seems to be much better.)

Make sure that pupils notice that, when a beam of light is refracted at an interface, some of it is *reflected*. We see that when we look at a picture mounted in glass. It bears on the conservation of energy.

{**A Law of Refraction?** Looking for a law of refraction, whether as a class experiment or a demonstration, is not likely to appeal to pupils. They do not feel an urgent need for such a Law. They do not know the long line of search from the Greek philosophers to Descartes, Kepler, and Snell. So an experiment with measurements of refraction should only be offered to a few very fast pupils with special interests. A demonstration with measurements would be an unwelcome diversion.}

{Furthermore, the apparatus used for simple measurements seems artificial to most pupils. To avoid having to entangle the refraction that is measured with a second refraction at a parallel surface, use a semicircular sample instead of a rectangular block. If every ray passes through the centre of the semicircle—because we cover the boundary-diameter with a screen and make a slit at the centre—each travels along a radius and is not refracted at the curved surface. This is a further reason for restricting this experiment to fast groups who can see the reason behind the artificial apparatus.}

* Very good, strong, clear boxes are obtainable from suppliers of metric teaching apparatus.

Expt 33X Law of Refraction *(OPTIONAL BUFFER EXPERIMENT, outside the normal scope of the programme)*

Apparatus

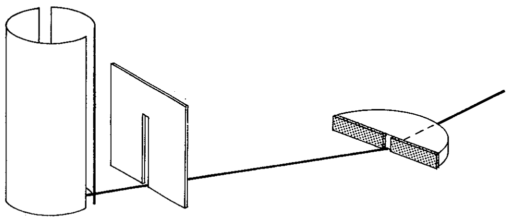
Since few pupils, if any, are likely to do this, the following list shows the apparatus needed *for each pupil or pair of pupils.*

1 semicircular block	
1 lamp, holder, and stand	item 94A
1 housing shield	94B
1 metal plate with single slit	94C
1 holder	94F
1 transformer	27
white paper	
protractor, or card with angles printed on it	550
scissors	
adhesive	

Semicircular blocks of glass (and of plastic) have long been available in schools. But we do *not* advise any school to buy them for this Nuffield programme. If semicircular boxes of thin transparent plastic are available (such as are sometimes used for small cheeses), these can be filled with water and used.

Preparation

Stick strips of card to the flat face of the semicircular slab (or box) so that only a vertical slit is exposed at the middle of the flat face.



Make sure the base of the slab is frosted or painted with white paint. Otherwise, total reflection at the base will prevent the path of the ray inside the slab being visible.

Procedure

Pupils place the slab on a circular protractor card, on a sheet of paper. They direct a ray streak to the slit; and measure the angles.

Pupils may also direct the ray streaks in through the curved face—taking care to aim them straight at the central slit. Then they observe refraction and total internal reflection.

Qualitative Experiments on Refraction

Pupils will learn more about refraction if they do their own *qualitative* experiments such as those below. These might be done as quick demonstrations; but pupils should be encouraged to do them for themselves at home.

Expts 34 Examples of Refraction

(These are experiments that pupils might well try at home or they could be given as demonstrations to small groups.) The instructions to pupils and the questions that go with them are given in *Pupils' Text*, thus:

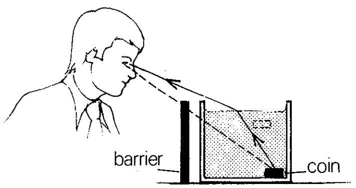
* * * * *

34a Coin in Water

Place a coin on the bottom of an empty jam jar or wide tumbler, near the far side. Stand away so that you cannot see the coin through the open top. (Cover the side of the jar with paper if you like; then you cannot see the coin at all.)

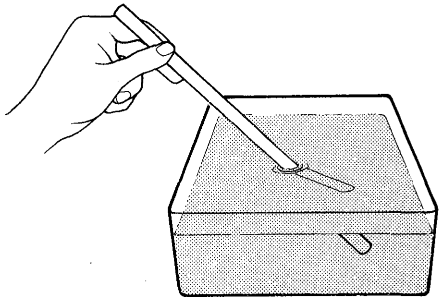
Ask someone to fill the jar with water. The coin will appear.

Can you explain that by a sketch showing rays of light from the coin being refracted as they go from water to air?



34b The Bent Stick

Dip a straight stick or pencil into a sink or large bowl full of water. Tilt the stick at about 45°. Stand and look down at the stick. *Does it look bent? If so can you sketch rays being refracted to explain that?*

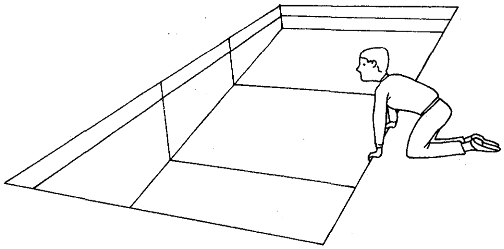


34c Is a Pond as shallow as it looks?

Look at objects at the bottom of a pond or a clear river. The water looks shallower than it really is. That is something fishermen have to learn.

Lie in a warm bath with the water just covering your feet. Look at one foot while you raise it out of the water.

Kneel at one *side* of a swimming bath and see how deep the water looks as you glance from your side across to the far side.



Does the bottom look flat and level? Or does it look curved? If it looks curved, how could you make sure it is not really curved (without having the water all emptied out, and without diving in)?

Does it look shallower or deeper than it really is?

Can you sketch rays being refracted to explain the mistaken impression?

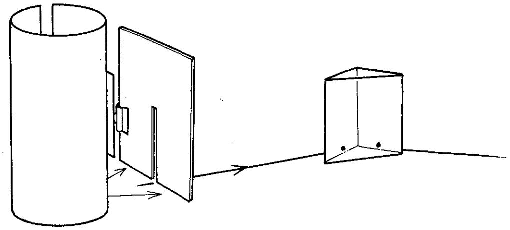
* * * * *

Class Expt 35 Single Ray passing through a Prism of Glass (Qualitative, with a Ray Streak)

Pupils set up the lamp and single slit on a sheet of white paper, as in other ray-streak experiments. They place a 60° prism in the streak and look at the effects of refraction. They try rotating the prism.

Pupils might look back *along* the emergent ray, from the far end, to see whether its bending then shows.

It is better not to suggest looking for dispersion into colours until the next experiment; but those who notice it deserve immediate praise.



SPECTRUM AND COLOUR

Pupils should see dispersion making a spectrum now or in Year 5. Since some may miss Year 5 of the programme, it is better to have a quick class experiment with ray streaks now. Whatever arrangement is adopted, it should be as simple as possible, without complicated optics. Better spectra can be produced by more sophisticated means, but here simplicity is essential.

Class Expt 36 The Spectrum (Band of Colours)

Apparatus

From the ray optics kit:	item 94
16 lamps, holders, and stands	94A
16 housing shields	94B
16 metal plates with single slits	94C
16 metal combs	94E
16 60° prisms	111
8 transformers	27
16 sets of colour filters: red, green, cyan, magenta, yellow	205

Preparation

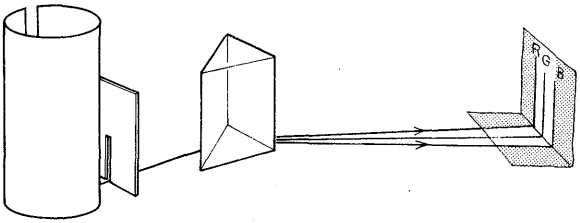
Examine the filaments of the lamps and replace any whose filaments are not straight and vertical. A crooked filament will make the little spectrum hopelessly impure.

Procedure

36a Colours with a Single Ray Streak

Pupils direct a single streak at a prism; and look at the emerging ray carefully. They should also catch it on a vertical scrap of paper.

They try twisting the prism.



36b Spectrum with a Fan of Rays

Pupils direct a fan of rays (from lamp and comb) at a lens (+7 D) so that the emerging rays pass through an image 40 to 60 cm away. They place the prism just beyond the lens and look at the effect.

A small piece of paper or card held upright to catch the rays above the table will show the spectrum clearly.

To make the spectrum as pure as possible, there are two conditions to be met:

(i) The screen should be at the same optical distance from the lens as the image was before the prism was inserted.

(ii) The prism should be turned to minimum deviation. However turning the prism to a greater deviation will make a wider spectrum.

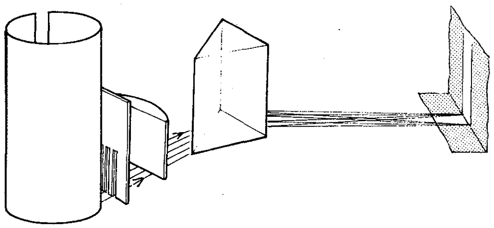
To make the spectrum much broader, the paper screen should be turned to catch the spectrum very obliquely.

36c Effect of Coloured Plastic or Glass

Pupils should try placing a sheet of transparent red plastic (or glass) in the path of the light. Ask: 'What do you see now in your spectrum?'

Then offer them a piece of green plastic or glass.

Other colour filters might be provided; but as the spectrum available in this class experiment is either narrow or faint, further investigations with filters are better postponed to Experiments 37.



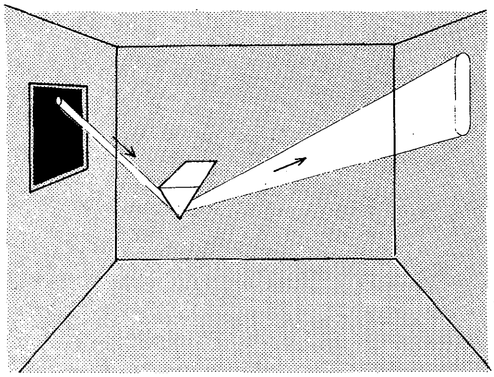
Spectrum Demonstrations

Newton was delighted, and his contemporaries were amazed, when he analysed a beam of sunlight with a glass prism. We should let pupils share those feelings, when they see a large, bright spectrum.

Without any complicated optical system, let a beam of light, *preferably sunlight,* fall on a prism, and then travel to a distant wall.

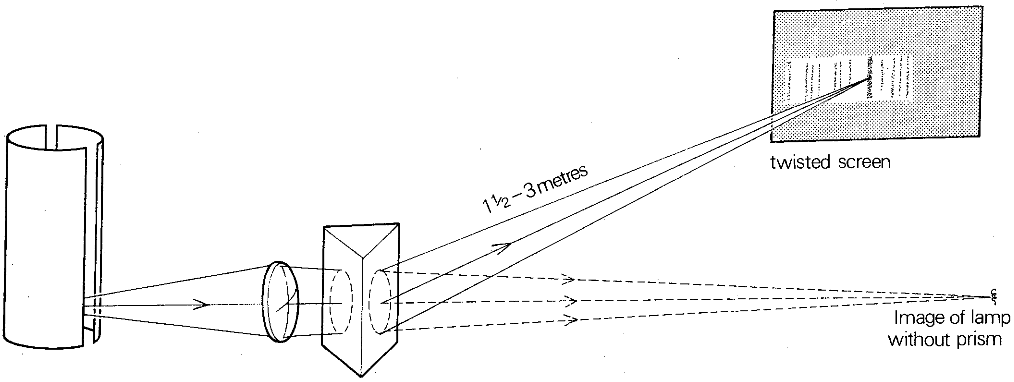
The Sun's disk subtends an angle of $\frac{1}{2}°$. Therefore each colour of the spectrum will make at least a $\frac{1}{2}°$ patch in the spectrum at any distance. If the prism is of common low-dispersion glass the spectrum will then be disappointingly impure. A high-dispersion prism should be bought for this.

Then ask pupils, as a surprise problem, what

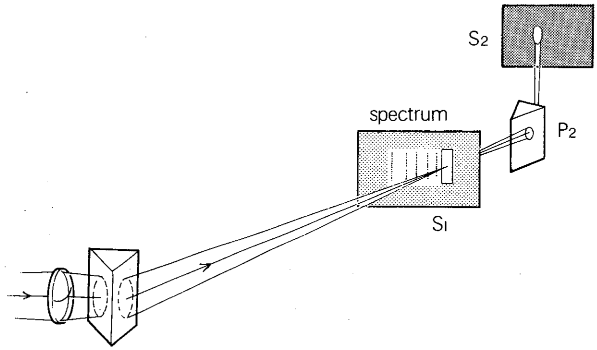


they think Sir Isaac Newton, a very good scientist, did as his second experiment.

{The splitting of light into colours by that prism was a fine sight and it must have been noted



by many, though they did not think about it as Newton did. But it was an act of scientific genius to pierce a hole in the card which caught the spectrum, and try a second prism with the light of one colour that came through the hole. The result: no further production of a new range of colours. That is *not only* sensible new experimenting but it gives a strong hint about the original experiment: the colours were *already there* in a mixture in white light, waiting to be sorted out once-and-for-all.}



Demonstration 37 Spectrum*

Apparatus

1 line filament lamp	item	94A
1 L.T. variable voltage supply		59
1 lens +7 D		112
1 large 60° prism (preferably high dispersion)		69
white screen or wall		

Procedure

37a Wide Spectrum

Direct light from a strong compact source to a lens (+7 D) which forms a large real image of the source on a distant screen $1\frac{1}{2}$ to 3 metres away. Twist the receiving screen so that the light falls on it *obliquely* making a much wider spectrum than with normal incidence.

Place the prism (preferably of high-dispersion glass) just beyond the lens, so that it swings the image of the source round to a new position at the same distance. The spectrum formed there is a band of coloured images of the source.

No slit is needed if the source is compact, or if it is a line filament parallel to the prism's edge; and this avoids optical complications. For a brighter spectrum, *over-run the 12-volt lamp at 16 volts.*

37b Trial with Second Prism (Newton's test)

Cut a small slit in the screen S_1 on which the spectrum falls and place another lens and prism P_2 to receive the light of one chosen colour that goes through that slit. Let the lens form an image of that slit on another distant screen S_2. When the prism P_2 is interposed, ask pupils to look to see whether the new spectrum shows a new set of different colours or not.

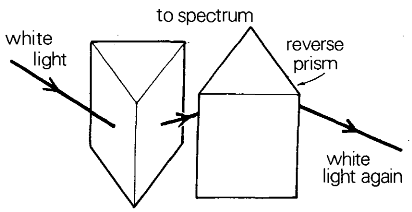
The demonstration is sufficiently convincing without the lens as in the sketch. Light passing the slit then forms a patch on the final screen S_2; but the patch is sufficiently uniform in colour to prove the point.

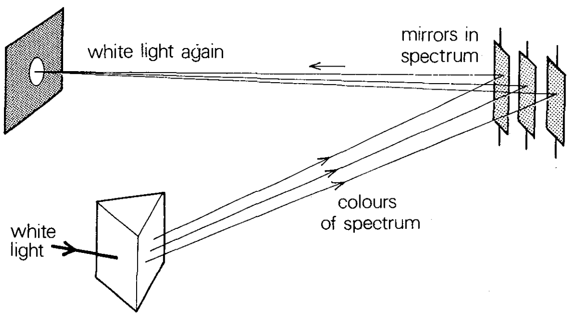
* Teachers may also like to give a demonstration of energy flow in the spectrum. That is in Year 2 and in Nuffield Combined Science (Section Ten, Expt 1m) and it appears again in Year 5.

Teachers who did not show it at the beginning of this Year may wish pupils to see it now. (Details are given in Expt 1h in Chapter 1.)

Colours in white light Nowadays we take Newton's view for granted, that the colours are already there in white light, so that a prism (or a grating) just sorts them out—and does not manufacture them from 'pulses' of white light. We need not give tests or 'proofs' of that unless pupils ask. But if pupils are interested teachers might show the following:

Demonstrations 37X From Colours back to White Light *(OPTIONAL)*





a. The Reverse Prism. If the lab has a second prism with the same dispersion as the one used for the spectrum demonstration, place it in the demonstration arrangement, next to the first prism but the other way round.

b. Reassembly by Mirrors. Form a spectrum. Place strips of plane mirror in the spectrum: one to catch the red, one to catch orange, . . . etc. Twist each mirror so that all the reflected beams fall at the same place on a white screen.

There is a very elegant form of this demonstration (originally by Zeiss) which uses strips of small-angle prism instead of mirrors.

[*c. Additive Colour Mixing.* Demonstration 39 with three projection lanterns gives support, though it is not directly relevant to the prism's action.]

Colours and Light

In the classes of Year 3, some pupils will enjoy the descriptive physics of colour more than other more formal topics; so we suggest a group of experiments involving a prism spectrum, colour filters,* and small projection lanterns. These are optional now.

Pupils will have seen the colours of a spectrum first in their own Class Experiment 36, then in the larger Demonstration Spectrum 37. They probably tried holding a red filter and then a green one, in the white light.

Now they should see what happens with six different filters—three 'physical primaries' and three 'secondaries'—one filter at a time; then two at a time.

One is tempted to give a demonstration, interposing each filter in turn in white light on its way to the spectrum; but that will give pupils much less lasting knowledge than a class experiment with filters in pupils' own hands. Since the coloured sheets are *filters*, each pupil can just as well hold one to his eye and look through it at the demonstration spectrum of white light.

(Each pupil should have his own set of six filters. If a set is shared by two pupils, the time needed will be doubled and the chances of confusion quadrupled.)

* Filters of plastic 'Cinemoid' are available from stage lighting suppliers, Rank Strand Electric, P.O. Box 51, Great West Road, Brentford, Middlesex TW8 9HR.

The dyes used in either kind of stage-lighting filter for the spectral regions from green to violet also transmit a little unwanted red. This is not a serious drawback in most experiments. If pupils notice the red, they easily understand if we explain it is due to an imperfection of the dye. Optical filters which eliminate the extra red are far more expensive, and their cost is not justifiable.

Class Expts. 38 Colours *(OPTIONAL NOW)*

Apparatus

As for Demonstration Spectrum:

	item
1 compact light source	21
1 L.T. variable voltage supply	59
1 lens +7 D	112
1 large 60° prism (preferably high dispersion)	69
white screen or wall	
32 pieces of each of the following Cinemoid plastic colour filters (item 205):	
Primary red (No. 6)	
Primary green (No. 39)	
Primary blue (No. 20)	
'Cyan' (blue-green) (No. 16)	
'Magenta' (purple) (No. 13)	
Yellow (No. 1)	
1 translucent screen	46/1
1 lamp to go behind screen	46/2
2 Bunsen burners with sodium bicarbonate (or salt)	508
samples of brightly coloured cloth	
1 small projector to provide large patch of coloured light	557
1 set of colour filters (6 cm × 6 cm) for projector	205

The number given after each colour filter is its number in the Rank-Strand Electric catalogue. It is easier for pupils to look with both eyes—also it lessens confusion in handling if each pupil has large pieces. We suggest pieces about $15\frac{1}{2}$ cm × $7\frac{1}{2}$ cm. The filters are only sold in full sheets or half sheets. A *half* sheet will make 36 of those, at less than 2p each.

To help pupils to choose the right filter, label each beforehand with grease pencil or felt-tipped pen or biro R, G, B, C, M, or Y.

It will save time and trouble if each set of six different filters is put in an envelope ready to be issued to a pupil. A useful key list could be printed on the envelopes: e.g.,
R is RED
M is MAGENTA (RED + BLUE) etc.

Preparation

Set up the demonstration spectrum. Arrange it so that the screen faces the class normally, but the spectrum falls on it very obliquely so that pupils see a long spectrum.

Set up a low wattage lamp behind the translucent screen, as a background for pupils to view the 'colour' of a filter. Place this far away from the spectrum screen.

The rest of the room should be as dark as possible for parts b, c and d.

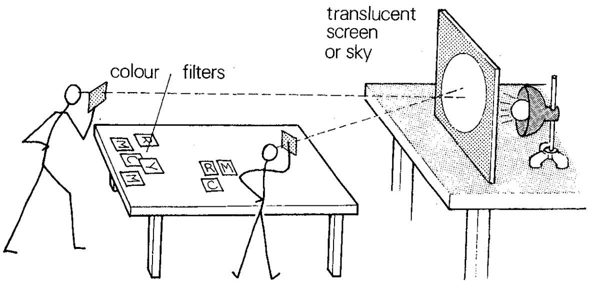
Procedure

38a Examining Colour Filters

Issue a set of filters to each pupil. With the lab well-lighted, pupils examine their filters, looking through each in turn at the lighted translucent screen or a bright sky.

They should use one filter at a time first; but the temptation to try two or more in series is great and experiments will go better if pupils are free to do that—even at this early stage—*but explanations* should wait till the spectrum has revealed the story.

Show, in full daylight, a piece of red cloth. Ask pupils to look at it through a red filter; then through a green filter. Then offer green material. (Knitting wool shops stock a green wool which is the best pure green for this. Take red, green, and blue filters to the shop to choose it.)

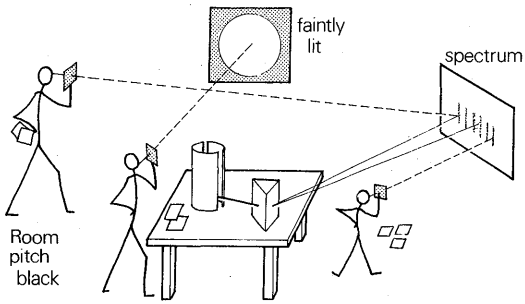


38b Primary Filters and Spectrum

Darken the room as much as possible, but keep a small lamp running behind the translucent screen. Then pupils can turn to it and select the filter they want.

Make the spectrum. Pupils look at it through a red filter; then green; then blue.

Ask what each filter does to the various coloured lights. Does a red filter blot out (absorb) parts of the spectrum or does it paint the spectrum red? Does it manufacture more red light or just leave red light that was already there?



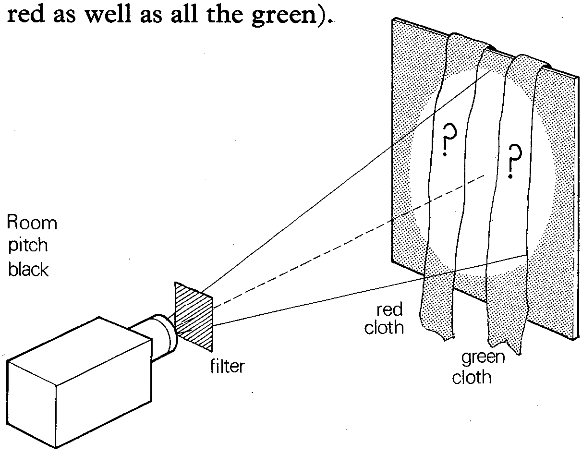
38c Secondary Filters and Spectrum

Pupils look at the spectrum through a cyan (blue-green) filter. Then through magenta.

Pupils try a yellow filter. This is surprising because it transmits red and green, as well as a little true yellow. Almost all the yellows we see are mainly red + green, '*subjective* yellow'. True yellow is such a narrow band that adding it to the mixture of red and green makes little difference.*

38d Seeing the Colours of Things

With a small projector throw a large patch of red light on the wall by hanging a red filter on the front of the projection lens. Show pieces of coloured cloth in that red light—with no other light in the room. Then change to green light (unfortunately the green filter transmits a little red as well as all the green).



Discussion Ask:

How do filters make coloured light? Think about your red filter. Some red dye has been melted into it. Does that dye change all parts of the spectrum to red, or does it just cut out other colours and leave the red that was always there in the white light? Is the dye a colour-*adder* or a colour-*subtractor*?

Pupils should have found from their own observations that filters transmit their own colour, selected from the spectrum, and absorb the rest—they do not, as children are apt to think, dye all the light with their colour. Explain that the dye in a piece of coloured cloth is a selective filter.

If you have a piece of red cloth it can only return red light to our eyes and look red if it receives some red light.

If you offer it white light or magenta light you see its red colour because each of those contains red light. But if you offer only green light, the cloth looks black because it receives no red light to return to you.

38e Painting and Printing: Subtractive Colour Mixing

Return to full daylight. Pupils try looking at the bright screen or sky through pairs of filters.

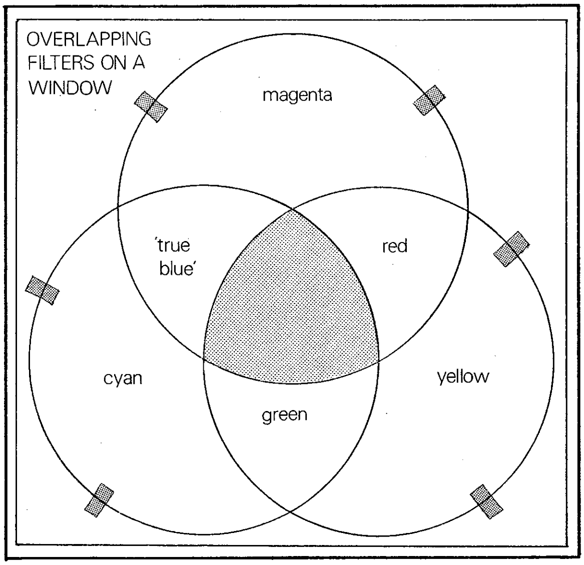
RED and GREEN filters 'in series': BLACK
('One lets through only Red; the other lets through only Green. What can get through both?')

MAGENTA AND CYAN: TRUE BLUE† gets through
CYAN and COMMON YELLOW: GREEN gets through
MAGENTA and COMMON YELLOW: RED gets through.

So it is Magenta, Cyan, and Yellow that are best for colour printing, technicolour films, and water-colour paints. All those operate by subtractive colour mixing.

Expt 38eX 'Poster' of Subtractive Filtering

Take three large pieces of filter, magenta, cyan and yellow, and tape them on a window pane, overlapping, so that they can act as a reminder.



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* If the lab has a piece of didymium glass, hold it together with a yellow filter in front of the white screen. Then interpose them in the light going to the spectrum. The combination looks yellow but transmits only red and green, 'subjective yellow'.

† 'True Blue' is surprising because the 'Blue' of children's paintboxes really transmits Blue + some Green; so most pupils have learnt to call Cyan 'Blue'. Hence the paint-mixing story:

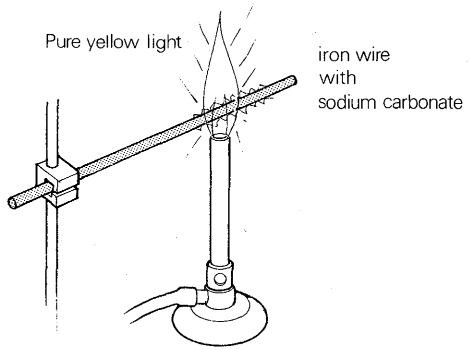
'Blue and Yellow make Green'

which is nonsense for subtractive or additive mixing if 'Blue' means true blue.

38f True Yellow: Sodium Light

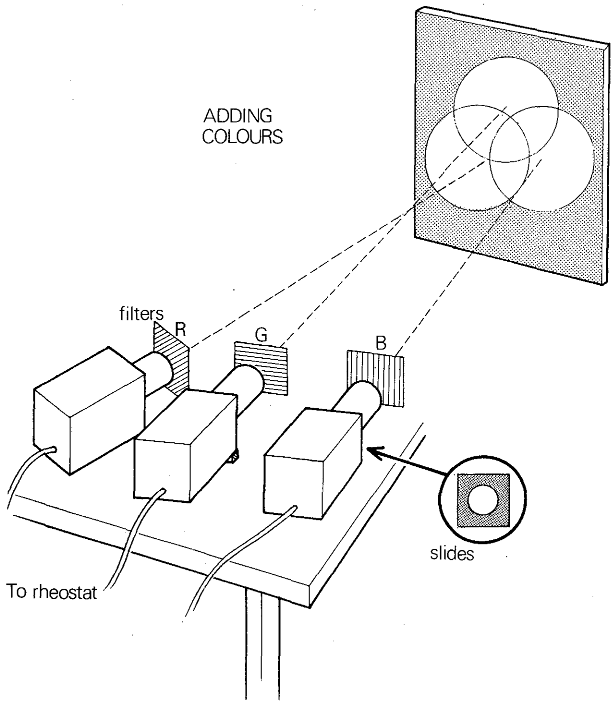
Darken the room completely and light two or more salted Bunsen flames. (A sodium vapour lamp is expensive and quite unnecessary.) Pupils look at each other's faces and clothes by this light.

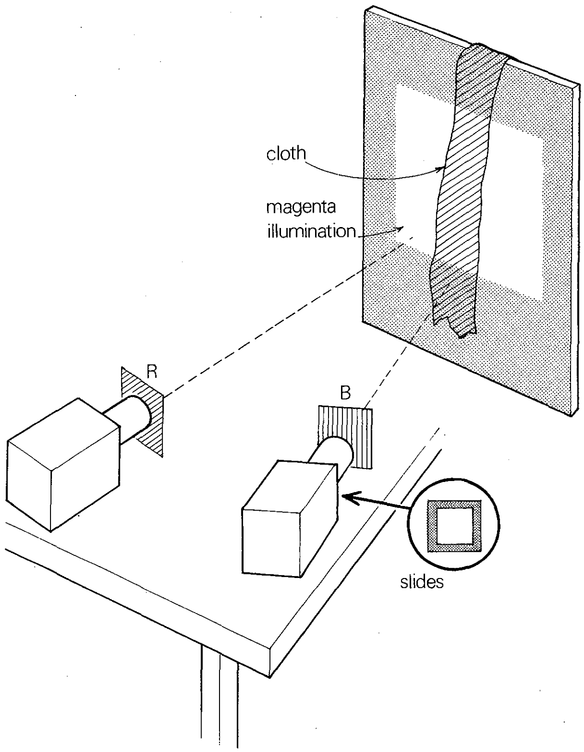
Moral: a coloured object such as cloth can only return its characteristic colour to one's eyes *if it is offered that colour*. If we offer pure yellow alone the only possibilities are yellow, grey, black.



Demonstration 39 Additive Colour Mixing
(OPTIONAL NOW)

Although this may be postponed to Year 5 (and even then will depend on three projectors being available), it is delightful and important for general knowledge so we hope pupils in Year 3 will see it.





Apparatus

3 small projection lanterns (35 mm slide projectors) item 557
3 slides† for projectors
3 small pieces (6 cm × 6 cm) of colour filter: a red, 1 green, 1 true blue 205
1 or 2 shielded rheostats (541/2) or variacs (78) for projectors‡
white screen or wall

† The slides are squares of card or metal with a hole about $2\frac{1}{2}$ cm diameter.

‡ Some method of changing the brightness of one or two of the patches is necessary. Instead of a rheostat or variac in the supply to a projector, a finger or piece of card held in front of the projection lens to reduce its aperture will suffice instead—*it will change the brightness of the patch uniformly.*

Preparation

Place the slides in the projectors and focus each to make a round patch of light on the screen. Hang one filter in the front of the projection lens of each. (If the projectors are not equally bright, hang the blue filter on the brightest.)

Arrange the projectors so that their three patches of coloured light overlap with a central 'triangle' illuminated by all three.

Darken the room completely. Run the 'blue' projector at full voltage. Adjust the other two projectors (with rheostats or variacs) till the central triangle looks *white*.

Procedure

a. Adding Two Colours. Turn on the red and blue projectors. Pupils see magenta where the patches of red and blue overlap.

Similarly, try blue and green; and finally red and green. Comment again on subjective yellow.

b. Three Colours to make White. Then turn on all three. Wave a hand in front of the white patch, making coloured shadows.

c. Adding and Subtracting. Turn on the red and blue projectors to make a large patch of magenta. Hold pieces of coloured cloth in that light: first magenta cloth, then red cloth, then green cloth. Ask for explanations.

NOTE. There is a simple 'algebra' of the colours of white light that makes adding, subtracting, and complementary colours easy to deal with—see *Pupils' Text 3.*

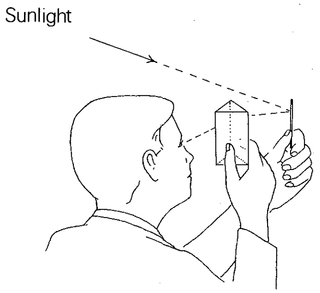
Class Expt 40 Poor Man's Spectrum of Sunlight with Sewing Needle as 'Slit' *(OPTIONAL)*

Give each pupil a bright sewing needle and a prism. He holds the needle at arm's length in one hand and the prism in the other hand, close to his eye. He twists the prism until he can see the needle by refraction through the prism.

The needle must be in bright sunshine parallel to the edge of the prism. It forms a bright, narrow line image of the Sun, and that serves as a slit. The eye viewing the needle from some distance provides the only lens system that is needed. The needle when viewed through the prism appears drawn out into a bright spectrum.

The higher the dispersive power of the prism material, the better, but the experiment is worth while with ordinary moulded prisms. Pupils will see a good spectrum and may even see a hint of absorption lines.

This experiment is so simple and beautiful that we hope teachers will take the risk of lending prisms for it to be taken home.*



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

CONTINUATION EXPERIMENTS

The material just ahead extends into a brief comparison of theories of light and experiments on interference that pupils will meet in Year 5—and probably in simple form in O-Level Examinations. Those experiments are labelled here 'OPTIONAL NOW' as buffer extensions for fast pupils or for any class with special interests in this direction.

Theories

{As children grow up, they can develop more and more of a taste for theory, if we present it lightly to them by saying it is a hunch that detectives get from their clues and employ—with some clever guessing added—to help their hunt.}

{It is simply not true—though some researchers assert it dogmatically—that children below a certain age (which is in the range of our programme) cannot carry out reasoning and understand complex abstract concepts. Educational research too often examines the OUTPUT—the 'results'—without enough attention to the INPUT—the choice and history of the experimental group. Children brought up in formal schooling from early years may fail to welcome or to understand discussions that go well in Nuffield science classes. So we trust teachers will not be discouraged, by pronouncements based on a different framework, from trying imaginative reasoning which 'Nuffield pupils' have shown can be welcome at this age, and earlier.}

{In fact we would say *far* earlier if we watched very young children's growth in vocabulary of words . . . abstract phrases and ideas . . .poetry . . . delight in all the arts. Watch a baby's skill in arguing for something he really wants; watch the enthusiasm and skill of an older child making a collection of something he prizes as an expert. It is *interest* as much as mental machinery that determines what a child can do or understand. Trying to coax physical laws out of a dutiful child who has no interest in them will indeed lead to discouraging statements of age-stages.}

{But it would be careless and dangerous to regard such findings as immutable and apply them as criteria to a programme where young people have interest and pride in their experimenting and thinking.}

{Young pupils are ready to enjoy the romance of theoretical thinking. It is the adult non-scientist who is apt to condemn theory as difficult and no good. We may be able to improve that aspect of the reputation of science in the adult world if we make some interesting uses of theory in our teaching.}

In Year 3 it would be good to look briefly at theories of light if time permits. And there is a short encounter with a theory of magnetism at the end of the year.

Theories of Light

A bullet theory Ask whether reflection of light and the way in which the white light travels in straight lines both fit well with the idea that light is a stream of speedy bullets.

Class Expt 41 'Reflection' of a Particle

Apparatus

Rubber ball(s)

Procedure

The path of an ordinary rubber ball (tennis ball, squash ball, or toy) bounced obliquely on a wall or floor will show something like equality of angles.

Pupils should try to compare the angles the ball's path makes with the wall before and after collision. However, that is difficult in a demonstration: personal experience is better. Fortunately, many pupils know the answer already: others should be asked to go and try.

(A superball is unsuitable. It is apt to suffer strange changes of motion! A spinning or rolling ball is unsuitable. Otherwise it would be simple for each pupil to roll a marble along the table to hit a glass block obliquely; but the rolling motion upsets the angle relationship.)

Discussion of Refraction

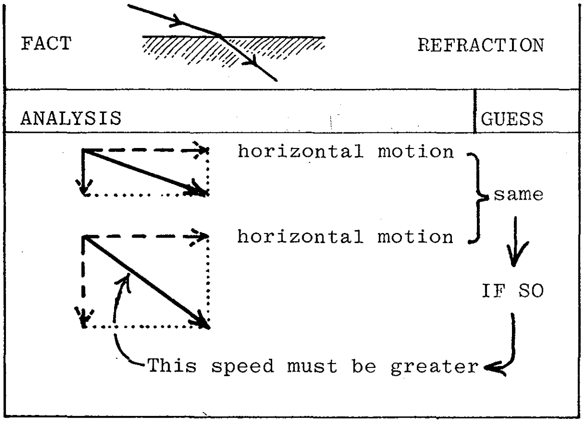
Ask about the bullet's path:

But what about refraction? What do you think a fast bullet would do if you shot it into water? Yes, a real bullet in real water would go slower and slower, yet it would continue to travel in the same direction, except for gravity.

But you can see that 'light-bullets' bend their path as they enter the water and then follow a new straight path. Newton thought about that and decided that the water would have to do something special to the bullet just as it approached.

What do you think the water must do? Stop the bullet? Repel the bullet? Attract the bullet? Twist the bullet? Which of these would make it bend to a steeper path?

Yes, *ATTRACTION* would do it. But if the water attracts the bullet, what happens to the speed of the bullet? (Remember these 'light-bullets' travel on and on once they are in the water, so the water does not seem to act on them with any friction.) . . . Yes, the bullet must move faster in water than in air.



Class Expt 42 Particle Model of Refraction *(OPTIONAL NOW)*

Apparatus

1 kit for particle model of refraction.

Contents:	item 96
8 hinged hardboard platforms	96A
8 launching ramps	96B
8 steel balls (22 mm)	96C

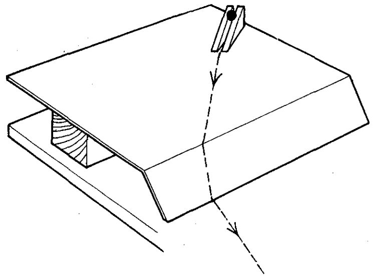
This should be a quick, qualitative experiment, just to watch what happens.

Procedure

The two pieces of hardboard have a hinge underneath. Pupils raise the larger piece on a wooden block or books. They launch the ball again and again down the ramp. Its path is refracted, as it speeds up in descending from the upper platform to the bench-top. Pupils should try different angles of incidence.

Fast pupils may also try launching the ball on the lower surface to see 'refraction away from the normal' as the ball slows on going up the ramp. For this the height of the upper board must be reduced to about $\frac{1}{2}$ cm. It is also possible to see 'total internal reflection'.

(Measurements are not of great value here; but if pupils want to make them they should use thin carbon paper over white paper. They place white paper on the platform and on the bench top, with edges accurately parallel to the edge of the ramp. They place carbon paper, face down, on each sheet.)



{Thus—as Newton knew—a bullet theory accounts for the behaviour of light quite well, and makes straight rays of light and sharp shadows seem much more reasonable than a wave theory would. There are two serious difficulties ahead: the fact that some of the light is reflected and some of it refracted at the boundary—how can bullets split their work like that?—and the phenomena of interference and diffraction. (It is probably wiser not to raise the former difficulty with pupils.)}

{The two difficulties together forced Newton to suggest his strange scheme that endowed the surface with alternating 'fits' of easy reflecting and easy transmission. He knew very well that his theory implied some periodic activity connected with the moving bullets, so that one could assign a wavelength—yet he did not change to a wave theory, because he considered sharp shadows and straight rays too difficult to reconcile with waves.}

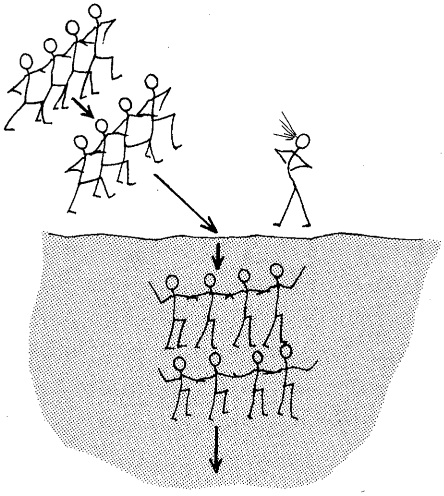
{Long after Newton's time, the speed of light in water was measured and compared with the speed in air. Light travels *slower* in water.}

{That is generally considered to be a crucial experiment which decided clearly against the bullet theory. Yet most crucial experiments, if not all, are only crucial—leading to an inescapable decision—if one sticks to the full details of the theories being tested. Newton's prediction assumed that the MASS of a 'light-bullet' remains constant, so that its momentum perpendicular to the interface must be increased as it passes from air to water—increased by some attractive force. If instead one assumes that the bullet's KINETIC ENERGY remains the same, but not its mass, the prediction can be reversed!}

Model of refraction of a bullet In thinking of light as bullets and endowing those bullets with properties that make their behaviour agree with the facts of refraction, we say that water or glass must attract the bullets at a boundary with air, to make them move faster in the denser medium. Pupils can illustrate that with a model in which a ball speeds up as it rolls down hill from one level field to another.

If possible, try a model with pupils marching. Here is an experiment which teachers will read about, smile, and almost certainly not do. This is unfortunate, for those who try it will find the reward great. It will make a lasting impression on the pupils.

Class Expt 42X Marching Model of Refraction *(OPTIONAL)*



Equipment

hard road with straight boundary adjoining soft grass, (alternatively, areas of asphalt marked with chalk can be used)
small army of pupils
discipline

Procedure

a. Align the army in fours or sixes. They must first learn to march in step with a uniform pace. Then teach them to march on the grass *with the same frequency*, but with shorter 'wavelengths' by taking steps half as long.

Then let them march on the road meeting the boundary obliquely: 'refraction' will occur.

b. Try the experiment again with pupils marching from the grass to the road: 'refraction' will occur the opposite way.

c. If carefully drilled the army can discover total reflection, to everyone's surprise. (It may be better to have each line of four link elbows loosely.)

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

Refraction of waves If pupils looked at refraction of ripples in their class experiments with ripple tanks, ask what happened, and if necessary bring out a tank for a quick look.† If

† A strong plea: no films. At this stage teachers may feel tempted to show a film; but we still make a very strong plea: that no films of ripples be shown this Year.

Teachers in schools which carry the programme through to the O-level examination have endorsed this plea almost unanimously. In Year 5 a film may be useful to revive memories of interference; but a film now would hurt the pride that pupils have developed in their knowledge of ripples and their success with the apparatus.

(If a film seems necessary now, that is probably a sign that it would be better to postpone this whole section to Year 5.)

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

they postponed that part of the ripple-tank series, they should now try it. Although it is difficult, personal trial in groups of four with plenty of help will give the sense of genuine experience that is needed.

Class Expt 43 Refraction of Ripples

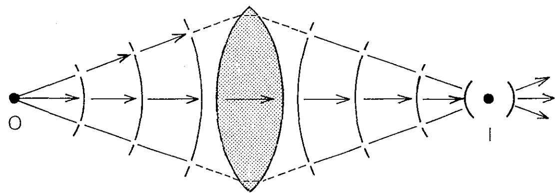
See Expt 4t in Chapter 1 for Apparatus and Procedure.

Recapitulate the results:

(i) Ripples travel slower in shallow water than in deep water.

(ii) If ripples strike the boundary between deep water and shallow at a slant, they are bent. Their 'guide-lines' of travel, or 'rays', bend.

Illustrate the second fact with a sketch. Then compare that sketch with the bending of rays of light when they pass from air to water.*



Lead to the conclusion: *if* light consists of waves, the refraction of light shows that it must travel *slower* in water than in air—the opposite of the story for bullets.

Then we can ask for a 'crucial experiment'; a comparison of the speeds of light in air and water. Unfortunately light travels so fast that we cannot give a demonstration—as we could for sound, with an oscilloscope. We must simply tell pupils the result: slower in water, only $\frac{3}{4}$ as fast.

Waves versus Bullets

Pupils have seen that a bullet theory of light ('a thinking-model') fits with straight-line rays, sharp shadows, reflection, and *(if light travels faster in water and glass than in air)* with refraction.

* Alternative appeal. Avoiding rays and considering wave-fronts, show waves diverging from an object point to a positive lens, then converging to an image point. Ask what must happen to the part of the wave that meets the middle part of the lens, of thick glass. The 'nose' of the wave is clearly delayed by the glass. Then, as regards speed . . .

But we have also told pupils that some scientists developed a wave theory; and we asked for a choice between the two views. At first that was just a matter for guessing, or for accepting some assertion. But now wave theory predicts '*slower in water than in air*' and the 'crucial experiment' seems to decide definitely in favour of waves.

{Yet we should announce the decision with a little hesitation. A 'crucial experiment' provides a *fact* but the *interpretation* of it can usually be twisted. So we encourage pupils to see some more experiments before making up their minds—though it will not be till Year 5 that still more experiments force us to the view that light has properties of bullets *and* waves.}

First pupils do some wave experiments with water ripples (*unless they remember them fully*); then some experiments with light to see corresponding effects: diffraction and interference.

Class Expts 44 Special Ripple-Tank Experiments for Comparison with Light *(ALL OPTIONAL NOW)*

44a Straight Ripples pass through a Gateway

This is the diffraction experiment in the ripple-tank series. For Apparatus and Procedure see Experiment 4q in Chapter 1.

44b Two Sources makes Ripples

This is the interference experiment in the ripple-tank series. For Apparatus and Procedure see Experiment 4p in Chapter 1.

44c Double Gateways *(OPTIONAL, more difficult)*

This is the interference experiment in Young's double-slit form. For Apparatus and Procedure see Experiment 4s in Chapter 1.

'Special experiments with light, for comparison with water waves' Then let pupils see diffraction and interference of light for themselves, clearly and *without any lenses*. (See special notes on equipment.)

Details for Apparatus for Diffraction and Interference

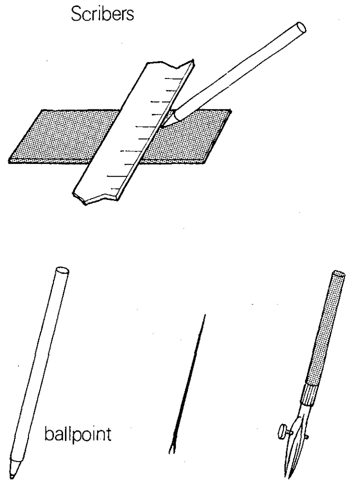
MATERIAL FOR DOUBLE SLITS. The slits are scratched in a soft black film on glass. Paint microscope slides quickly with Aquadag (colloidal graphite), using a soft brush. Allow the slides to dry.

Before the slits are ruled, hold each slide up to a bright light and make sure it is thoroughly opaque.

RULING THE SLITS. Each pupil should do this. There are several good ways of ruling slits on the coated slides, ranging from simple hand scribing to the use of a special device.*

(1) *Rough ruling by hand.* Drag a blunt pin along a metal ruler. To make the second slit, hold the ruler there but tilt the scriber a little and drag it again. A biro as a scriber is even better, but it must be the very fine kind.

This is the method that we recommend strongly for Year 3 pupils.



* The ruling of double slits—like measurements of g and the monkey-and-hunter demonstration—will often attract the ingenuity of physicists. There are many good schemes and devices. For our qualitative class experiment now there are two dangers:
(i) If the method of ruling strikes pupils as both necessary and *special,* some may even think the phenomenon arises from special ruling.
(ii) More generally, if the ruling is complicated, some pupils may miss the wood for the trees and remember ruling rather than seeing fringes.
(An example of both dangers together is the use of the traditional 'bucket-and-cylinder' device for Archimedes' Principle where the logic obscures the real issue for young pupils.)
Therefore we recommend a simple direct method with a ruler and a blunt pin or needle.
We also mention special devices that may be better in Year 5. These would help teachers to make good slits quickly for a private stock to help very discouraged pupils.

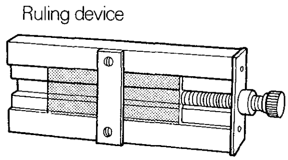
(2) *The eye of a darning needle,* broken across, can be used as a miniature pitchfork to rule double slits.

(3) *The old fashioned ruling pen* used by draughtsmen rules parallel double slits very well. The separation of the slits is easily adjusted by the knurled knob that moves the two blades closer or farther apart. Make that adjustment by trial, then run the pen along a ruler. If the width of each slit should be greater, grind the tips of the blades a little.

This is probably the best method for the teacher's private reserve of ready-made slits.

(4) *Special ruling device.* Insert the glass slide in the ruling device and rule one slit in the Aquadag with a blunt needle or pin held up against the cross-piece. (The edge of a small screwdriver could be used. A fine biro works well in practised hands.)

To rule a double slit: rule one slit; then displace the slide slightly by turning the thumbscrew on the end of the device; then rule the second slit.



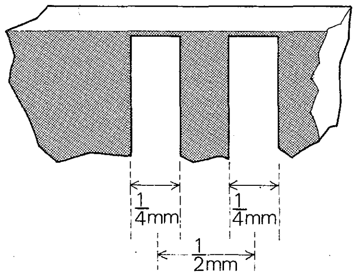
SIZE AND SEPARATION OF SLITS FOR YOUNG'S FRINGES. In a large lab, slits $\frac{1}{2}$ mm apart, centre to centre, will give fringes that are wide enough for pupils to see easily, *provided the screen is several metres from the double slits.*

If each of the two slits is itself about $\frac{1}{4}$ mm wide, only two or three bright fringes will be visible—because such a wide slit does not spread the light over a broad diffraction pattern. However, those fringes will be brightly illuminated.

If each slit is only about $\frac{1}{8}$ mm wide (and the slits are still $\frac{1}{2}$ mm apart) the pattern of fringes will be just as coarse; but more fringes will be visible; *and the pattern will look much less bright.*

In a small room, it may be necessary to rule the two slits closer together to make the fringes far enough apart to be seen easily.

There is no need to make the rulings conform to some special values. The suggestions above are merely general guides.



PRE-TESTING SLITS. When pupils have ruled several pairs of slits they should bring them for inspection before they use them.

The best test would be to set up the slits as in the actual experiment and look at the fringes; but that would bring the teacher into the pupils' main observation. Instead, the teacher should make a quick test (in which practice will give skill) as follows.

Hold the slits just in front of one eye and look at a distant line-filament lamp. Then the eye acts as a 'telescope' focused more or less for infinity. One sees Young's fringes and can judge them for brightness and separation. *This arrangement should be a teacher's test: it should not be used by pupils,* because the use of the observer's eye in this way is very confusing and likely to spoil the essential message of the experiment.

After some experience in testing slits, teachers may prefer a simpler test, which pupils will appreciate: judging by eye. Have a small translucent screen at hand, brightly illuminated from behind; and hold the slide with slits in front of it. (One could have a specimen 'recommended' slit already hung on the screen for comparison—though that might not seem good Nuffield teaching.)

HOLDERS FOR DOUBLE SLITS. When a pupil has ruled a 'good' pair of slits, he must clamp his glass slide where it will intercept a beam of light. Ordinary clamps will be awkward for the pupil—who must adjust the slits to make them vertical—so we suggest using a comb holder from the ray-streak kit to hold the slide. If its jaws let the slide slip, line them with plastic tape. The comb holder should itself be held by a clamp on the retort stand.

VIEWING SCREEN. The screen at which pupils view diffraction patterns or interference fringes must be a translucent one that scatters light through a *small* angle. Each pupil in turn stands immediately behind the screen and receives the light that comes almost straight through it to him.

Kitchen greaseproof paper, waxed paper, oiled tissue, are all good for this. (So is translucent plastic sheet, but that is unnecessarily expensive.)

One might expect a screen that scatters the transmitted light through a *large* angle to enable other pupils standing at one side to view the pattern; but the pattern would then be far too faint. (Architects' tracing linen scatters through a *large* angle—that is what makes it so useful for an illuminated screen placed behind apparatus to show it in silhouette to a widespread audience in front. But that is not what we need. Here, tracing linen is unsuitable.)

LIGHT SOURCES

For all diffraction demonstrations, the compact light source is essential for brightness. And its small filament area is near enough to a point source for some of the effects to be seen.

For clearer patterns, and especially for the shadow of a disk or ball, the source must be still smaller. Place a metal screen with a 1 or $1\frac{1}{2}$ mm hole in front of the compact light source.

For class experiments on Young's Fringes, use ray-streak lamps, perhaps run at higher voltage. They must have very straight vertical filaments. Bulbs of 36-watt would be better than 24-watt ones.

Surround each ray-streak lamp by its shield, with the long wide opening in the shield serving as doorway for the light beams. A few centimetres from the doorway, place a home-made 'limiting screen'—tailored to fit the arrangement of the lab.

LIMITING SCREENS. Eight groups of pupils will need 8 beams of light traversing the room but it is not necessary to set up 8 lamps. One lamp can provide 3 or 4 beams if a limiting screen is set up in front of it.

Such screens are necessary to cut off stray light in the dark room. The visibility of the pattern on the distant translucent screen is easily spoiled by stray light or by light reflected from shiny bench tops.

If a lamp is to serve three groups, the limiting screen should be about $7\frac{1}{2}$ cm square with three coarse slits in it, to let out three beams of light. Those can be rough slits cut in a piece of tin plate with snips. No precision is necessary—these are light shields, not combs for ray streaks. If the screen is placed 5 cm from the lamp filament the slits should each be 2 to 3 millimetres wide, spaced about 14 mm apart. Then each of the three beams will cover a slide with double slits 1 or $1\frac{1}{2}$ metres away.

GLARE. Unless the lamps are high up, there is danger of light on its way across the room being reflected by polished table tops—reflection is copious at very oblique incidence. So black cloth should be laid on table tops, or extra screens placed to stop reflected light from reaching the viewing screens.

Spacing and Size of Slits for Young's Fringes: Discussion of Theory

The amount of light reaching the fringe pattern is determined by the width of each slit of the pair. The wider each slit is, the more light.

But the width of the patch over which the fringe pattern is spread (by diffraction from each slit) varies inversely as the width of the individual slits. Therefore, wide individual slits give more light concentrated into a narrower region, making the fringes much brighter. On the other hand, the narrower that bright patch formed by diffraction, the fewer fringes there are visible—and pupils need to see several dark and bright fringes to be convinced.

The closer the two slits are together centre-to-centre, the greater the spacing from fringe to fringe, and the easier the fringes are for pupils to see.

Therefore, we should aim at using a double slit with the two slits each as wide as possible and with as small a separation between them as possible. Those two conditions would lead to two slits overlapping and merging into a single slit if we pushed them too far! The widest slits allowable for a reasonable picture of fringes seem to be slits of width x whose centres are a distance $2x$ apart. That is, two slits of width x with an opaque region of width x between them. That arrangement will give three bright fringes with two dark fringes between them, and little illumination in regions beyond that.

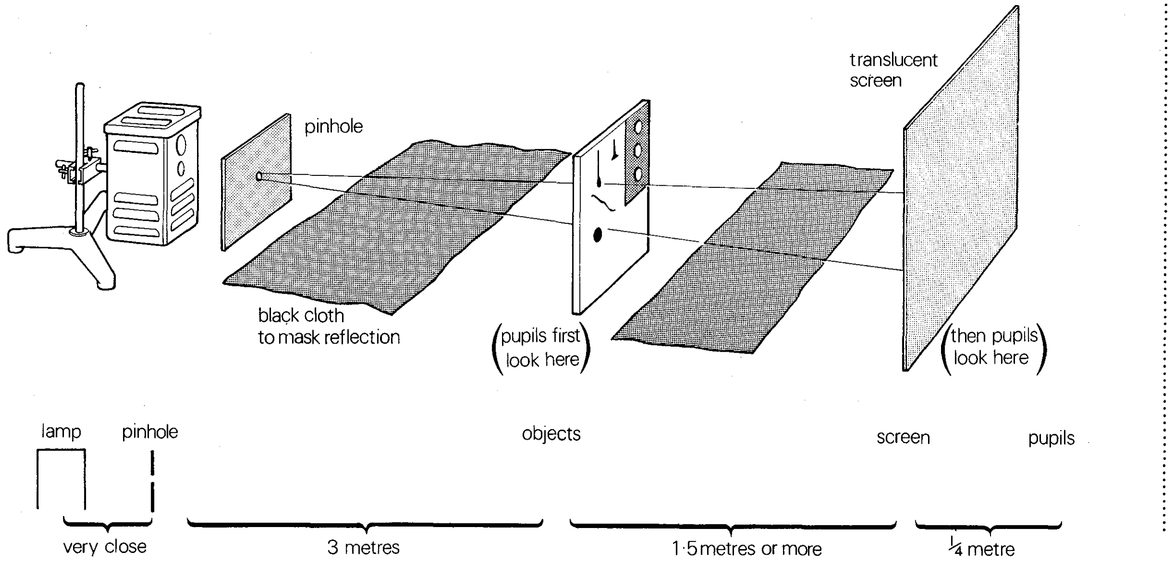
If the slits made are too far apart or themselves too wide, the central maxima of the diffraction patterns may not overlap and no fringes will be seen.

Very thin slits are ideal for making a broad display of many fringes: but that display would have to be observed with a magnifying glass or photographed, because the fringes are both fine and faint—then the cogent simplicity is lost.

Diffraction

A quick look Let pupils see an entirely different property of light. They probably expect to see sharp shadows cast by light from a point source, in *all* circumstances. ('*Light travels in straight lines*' is learnt only too thoroughly, with never a thought about the philosophical assumption in 'travels' still less any doubt about 'straight lines'. And talk of 'bullets' as a model for light will have reinforced that.) Pupils will be surprised to see the failure of sharp shadows.

Diffraction should not bulk large and take much time from the interference experiment that follows; but pupils should take a quick look, for surprise. And seeing diffraction of light passing through a narrow slit helps to prepare the ground for Young's fringes.



Class Viewing 45a Sharp Shadows? Diffraction *(OPTIONAL NOW)*

Apparatus

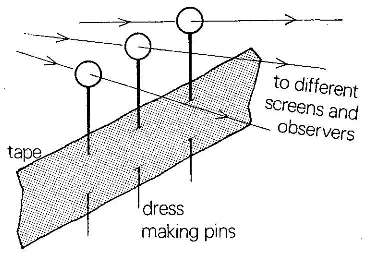
1 compact light source	item 21
1 L.T. voltage supply, variable	59
1 translucent screen of greaseproof paper	
3 retort stands, bosses, and clamps	503–6
1 piece of plate glass to hold objects for casting shadows	
hard wax to attach objects to plate	
1 or more dressmaking pins (with ball heads)	
1 metal plate with $1\frac{1}{2}$ mm hole	
wax	

Avoid inserting lenses, or the magic will be lost.

Preparation

Place the compact light source at one end of the lab, with the $1\frac{1}{2}$ mm pinhole just in front. Place the translucent screen near the other end of the room. In the middle between them place the objects to cast shadows. The objects should be far from the lamp, at least 3 metres, preferably 5 metres. The screen should be at least $1\frac{1}{2}$ metres beyond the objects.

A sewing needle, a pin, a sheet of metal or card with small holes drilled in it, and a small disk or steel ball (maximum diam. 5 mm) all make good shadow-casting objects. Stick them with wax on a piece of plate glass. Perhaps because it is natural, a human hair seems to do best of all.



A dressmaking pin, with spherical glass head (diam. about 4 mm) is best of all for showing the 'white spot'. It can be held separately in mid air. Or several can be used with one source, to cast shadows on several screens.

Procedure

Darken the room as much as possible.

Pupils should stand near the collection of objects and look at them. If they hold a piece of paper just beyond the objects, they may catch sharp shadows.

The diffraction effects. Then pupils move to the translucent screen, *go round behind it*, and look at the shadows there. Remind pupils to hold their heads $\frac{1}{4}$ metre or more behind the screen—'as in reading a book'.

The shadow of a disk. To a physicist, the strangest shadow of all is that of a small ball or disk: there is a white spot in the centre of the shadow. One can just see that, in a long, very dark room, if one expects it: but our source is too large and pupils will probably miss it unless the source is made smaller. *Place a metal plate with a hole 1 mm diameter just in front of the lamp.* Then ask pupils what they see.*

Diffraction by a slit If time permits, change to a set of three prepared slits: wide, medium, and very narrow. Suitable slit widths are 1 or 2 mm, $\frac{1}{4}$ to $\frac{1}{2}$ mm, 1 to 3 hundredths of a mm. The narrowest slit needs no microscope to check its width; judge it by its diffraction spread which should be 2 or 3 cm on a screen at 1 metre. These could be ruled on a coated glass slide, the narrowest with a razor blade.

(Avoid a V-shaped slit or a variable slit. Those belong in A-Level and would be confusing now.)

After that, ask a very able pupil what the moral is for pinhole cameras.

After pupils have looked at diffraction effects, we should comment only briefly:

'Light *does* do those things. But they are only noticeable when the objects are small and the distances are great. They are signs that something connected with light is extremely small.'

* When Fresnel as a young man submitted his paper on the wave theory of light to the French Academy, Poisson read it and objected at first that it must be wrong because he saw that it would predict that white spot. Fortunately the spot was observed, and later photographed. In an earlier age it might have led to an accusation of witchcraft.

Then let pupils proceed immediately to their own experiment to see interference of light from two sources.

Interference

Young's fringes When two streams of light arrive at a screen (from a single source) pupils probably expect to see a brighter patch where the streams overlap. (One lot of bullets + another lot of bullets should make still more bullets.) Now let them find another strange property of light by their own observations in a class experiment.

They let light from a line filament lamp shine through a pair of slits. The two streams that emerge continue to a screen far away, and make bands of light and dark—'interference'.

At this stage pupils will get so much more from doing the experiment themselves that the trouble of arranging a class experiment is well worth while.

The outcome we hope for is a pupil's boast, 'I have seen light waves interfering: light + light making black as well as bright.'
(Better still if he can add, 'and I can take it home and make it work there'.)*

Therefore we hope that the only difficult bit of manipulation, ruling the slits, will be done by each pupil but will be made as simple as possible—with help given if necessary. If pupils make the double slits themselves, they know there will be two streams of light.

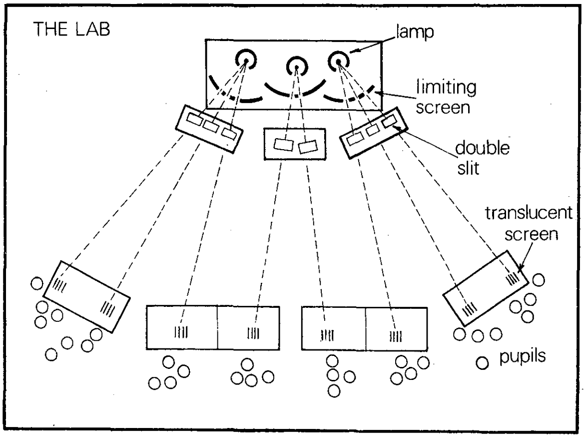
A strong plea: no lenses There should be no lenses, or the important message will get confused. (Young's fringes are traditionally shown with an eyepiece to observe them. That would spoil the simple cogency of the experiment for young pupils. They know that lenses can introduce peculiarities—particularly if the observer is not sure where the observing eye is being focused. So we plead strongly for a clear experiment without lenses. But that needs a bright source and large distances.)

An important experience We hope teachers will not regard this as a difficult experiment to prepare and run. It can be a highlight in Year 3; and it will be essential with measurements in Year 5. A first look now will be helpful then; and, for pupils who do not continue to Year 5, this glimpse should be a memorable experience.

Class Expt 45b Light from a Pair of Slits: 'Young's Fringes' *(OPTIONAL NOW)*

AIM. For pupils to see disturbing evidence, in their own experiment.

Outline. Light from a ray-streaks lamp meets two slits, very close together, in a black screen 1 or 2 metres from the lamp. The light passes through the slits, and continues, spreading a little, to a translucent screen several metres farther on. Pupils standing *behind* that screen see interference bands where the two patches of light overlap. There are no lenses, so the wave property of light seems inescapable.



Apparatus

From double slits kit:	item 97
4 dozen microscope slides	97A
1 bottle of Aquadag	97B
1 soft paintbrush $2\frac{1}{2}$ cm wide	
32 short metal rulers, or plain microscope slides	
32 pins	
1 reel masking tape	94
From ray-streak apparatus:	94
2 to 4 lamps, holders, and shields	94A
16 holders for combs	94F
2 to 4 transformers	27
16 retort stands, bosses, and clamps	503–506
8 screens of greaseproof paper about 30 cm × 30 cm	
plastic tape (to line bulldog clips)	
2 to 4 home-made 'limiting screens' of cardboard or wood	

* The J. Willmer fund will pay for loss or damage.

Pupils share lamp and translucent screen in groups of 4. (There is enough apparatus for pairs, but more than 8 beams of light traversing the room may make the running of the experiment difficult. On the other hand, there should not be fewer light-beams and larger groups: there would be confusion of waiting; and pupils' independence would be lost.)

Each pupil should make, and use, his own pair of slits.

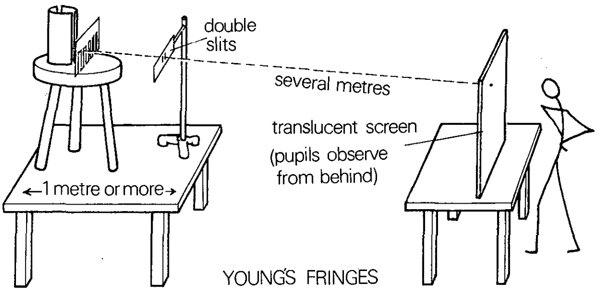
Preparation

Arrangement of the lab. With eight groups, each using lamp and slit-holder and translucent screen, time and trouble can be saved—and confusion avoided—by careful planning.

The actual arrangement must depend on the shape and size of the room and the positions of benches, etc. The suggestions below are offered as hints.

Suppose the lab is about $7\frac{1}{2}$ metres by $12\frac{1}{2}$ metres. To keep the groups apart from each other, place the lamps near the centre of one long wall. And place the translucent screens for observers all along the opposite wall, continuing round the corners to part of each end.

Those translucent screens should be spaced at least a metre apart so that they are separated enough for each to have a quartet of pupils round it.



Preparing the lab. If possible, arrange the lamps beforehand.

If the lamps are high up, the double slits and the translucent screens can be raised to pupils' shoulder level, making adjusting easier and observing more comfortable. That also lessens the danger of table-top reflections. *So it is best to place the lamps (with limiting screens) on stools standing on a bench.*

If the translucent screens can be set up beforehand, that will help the running of the experiment. Turn on the lamps and install 'limiting screens' to cut off stray light. Follow the emergent beams of light across the room to translucent screens 4 to 6 metres from the lamp. There must be space for four pupils *behind* each screen.

That in turn will define the placing of the double slits. Pupils will clamp their pair of slits on a stand at least 1 metre (better, $1\frac{1}{2}$) from the lamp. If those stands are arranged beforehand, set the clamp on each at the right position to intercept the light on its way to the translucent screen.

Make sure that light does not reach the screen by reflection from table-tops on the way.

Preparing slides for slits. These need time to dry, so the coating should be done beforehand. Make one Aquadag-painted slide for each pupil, plus 50% for spares.

Each pupil should rule his own slits.

A few pupils may become seriously discouraged. For them, after a few attempts, the teacher may decide an offer of ready-made slits will provide comfort and ensure success. So, when the slides have been painted a few should have 'good' pairs of slits ruled on them—to be kept in secret reserve.

Procedure

Keep the room lit while each pupil makes several pairs of slits.

Then darken the room fully and help pupils to orient their double slits parallel to the lamp filament.

Pupils follow these instructions:

* * * * *

Use a ray-streak lamp as source of light, near one end of the room. Make sure its filament is straight and vertical.

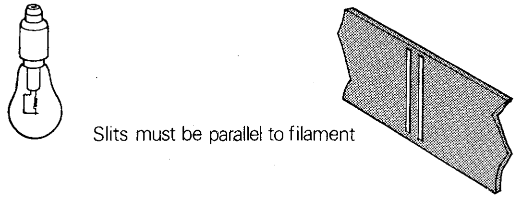
Ask for a small sheet of glass coated with black paint. You can scratch two slits in the paint very close together. Then, if light shines on the black sheet, two lots of light will get through the slits and make two patches of illumination on a screen at the far end of the room. If the slits are thin and close together the light from each slit will spread and the two patches will overlap. What will you see there?

To make the slits, hold a ruler across the glass sheet and scratch the black paint away by dragging a blunt pin along the ruler. To make the second slit, hold the ruler there, but tilt the pen and drag it again. The slits need to be *very* close, about $\frac{1}{2}$ millimetre apart, or even less.

(You may be offered a special machine to hold the glass and guide for the making of slits, but simple ruling is quicker.)

Make several pairs of slits. Then ask your teacher to look at them and choose a pair that will behave well.

Place the slits in a clamp, one or two metres from your lamp. Make sure the slits are vertical, parallel to the lamp filament.



When the room is dark, hold a piece of paper just beyond your pair of slits and see the light that comes streaming through and spreading out a little.

Then go as far away as possible—it must be several metres—and hold a translucent screen of greaseproof paper there. Place the paper to catch the light that has come through the pair of slits.

Go round behind the screen and look at the bright patch where the two lots of light overlap.

What do you see? What do you think that tells you about light?

* * * * *

Each pupil looks at the pattern with his naked eyes. Explain that the pattern is made by the two overlapping patches of light—it is called Young's fringes after Sir Thomas Young who claimed it as a test for light waves.

(This is not the time for measurements. A fuller understanding and measurements come in Year 5; but some pupils who will not continue till then will enjoy seeing the strange and important pattern now.)

Discussion Then, after pupils have made Young's fringes themselves, hold a general discussion. One might say:

Extraordinary. Bands of black and white, like a zebra. If light is a stream of bullets, could you have:

LIGHT + LIGHT, making LIGHT, in some places; and LIGHT + LIGHT, making darkness, in other places?

You could have:
BULLETS + BULLETS, making MORE BULLETS;
but could you have . . .?

'Have you seen anything in physics where two lots of something arrived and made a *big* result in some places and made *nothing* (cancelled out) in others?'

Geometrical demonstration in teaching interference The idea of waves adding when they are in phase to give a large wave and 'interfering destructively' when they are in opposite phase, is easy for adult physicists but strange to many pupils. It is easy for pupils too, once they have grasped the essential idea: but that seems to need some extra demonstration of the difference of phase that arises from different paths.

The demonstration with plastic wave strips does that.

Demonstration 46 Plastic Wave Model for Interference *(OPTIONAL NOW)*

Apparatus

2 wave strips	item 126
2 retort stands	503–504
4 bosses	505
2 small G-clamps	44/1

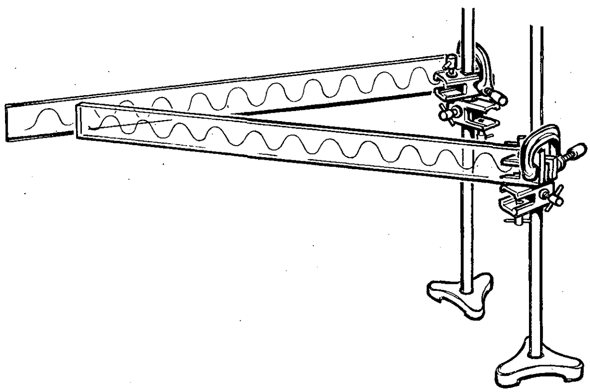
Preparation

Support the wave strips with two retort stands as in the diagram. One boss is fixed on a stand, another boss is slipped on the stand to rest on the first boss and turn freely. One end of a wave strip is attached to the free boss with a G-clamp.

Each strip extends out horizontally, but its face with the pattern is vertical. Place the two stands 3 or 4 wave-lengths apart.

Procedure

Hold the free end of each strip and make them cross. Swing them to show what happens at various cross-over points.



Some words are helpful too:

'This wave arrives and makes things go

FLIP-FLAP, FLIP-FLAP . . .

then the two waves added together make things go

FLIP-FLAP, FLIP-FLAP . . .

But when we move to another place where one wave has travelled half a wavelength farther than the other, they arrive out of step. The first wave makes things go

FLIP-FLAP, FLIP-FLAP . . .

and the other wave makes things go

FLIP-FLAP, FLAP-FLIP . . .

and then the total of the two is . . .?'

Simple model of wave addition Instead of the 'waves' engraved on strips, pupils use thin strips cut from a piece of corrugated cardboard. This works better if pupils have already been shown by a demonstration what they are going to do. Then, as well as using it in class, pupils might take it home and explain interference patterns—not very amusing alone, but a magnificent chance for pride if the real Young's fringes experiment can be borrowed as well.

Class Expt and Home Expt 47 Model of Wave Interference, with Corrugated Cardboard *(OPTIONAL)*

Apparatus

16 drawing boards	item 551
48 ordinary pins	
corrugated cardboard	

Preparation

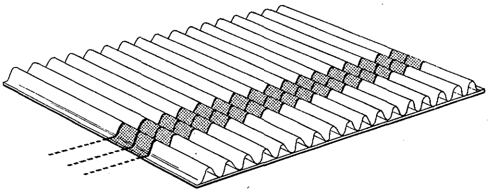
Cut the corrugated cardboard in narrow strips, each about 20 cm long by $\frac{1}{4}$ cm wide, two strips per pair of pupils. Have spares available for taking home.

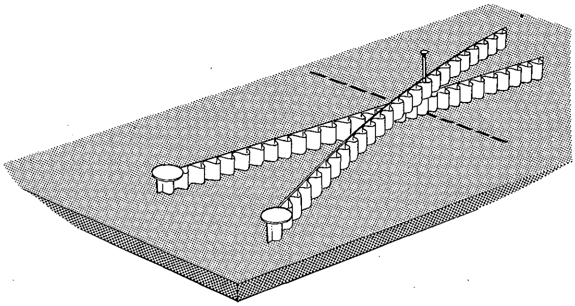
Procedure

The pupil places two strips *on their sides* on a drawing board. He pins each strip to the board by a pin through a wave-hump near one end. These ends, anchored, a few centimetres apart, represent two 'sources'.

The pupil pulls the strips taut and uses them to predict 'bright' and 'dark' at a 'screen' marked as a line near the end of the board.

At that screen, he sticks a single pin through two wave-humps, one hump of each strip, to find a place where the waves add up to 'bright'.

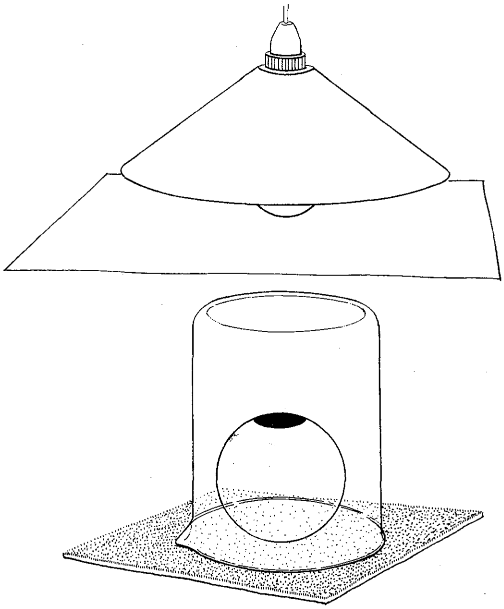




Interference Patterns made by Thin Films

As a final look at light waves making patterns because they 'interfere', pupils should see patterns made by light reflected from two surfaces of a thin film.

A soap bubble shows irregular patterns, because the thickness is irregular; but its colours remind us—as Young's fringes should have shown—that wavelengths are different for different colours.



Demonstration 48 Soap Film *(OPTIONAL NOW)*

AIM. Pleasure in seeing a beautiful experiment and in extending scientific knowledge to a childhood toy.

Apparatus

1 beaker (400 cm^3)	item 512/2
A large beaker (1000 cm^3)	513
1 copper wire frame	
fresh soap solution (from toyshops, or detergent)	
glycerine	

Preparation

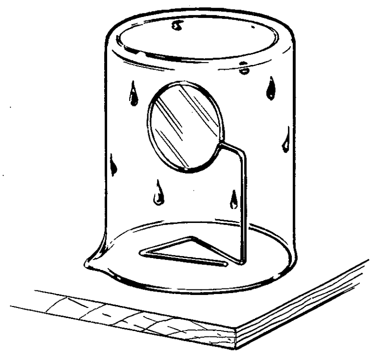
For (a), bend a frame of copper wire, 16 or 18 SWG, as shown. The vertical circle at the top should have a diameter at least 5 cm, preferably 7 cm or more.

Put soap solution in the 400 cm^3 beaker. Soap-bubble liquid from toyshops does very well. Or make a mixture of Stergene and water. (A dilution of Stergene of 1 in 10 gives a rather streaky pattern but the film is strong. 1 in 1000 gives a film with closely spaced fringes but the film is weak. A dilution of 1 in 100 is probably best. Add glycerine to make the film stronger—but the colours will be poorer.)

Procedure

a. Dip the frame in soap solution to make a film. Use this film as a mirror to reflect light from the sky to pupils. As the film drains it thins, and interference bands appear.

The film will last a long time, even when thinned, if evaporation is discouraged. Place a large beaker, wet inside, over the frame carrying the film as it stands on the bench-top



b. Blow a soap bubble and catch it on a small piece of carpet made of synthetic fibre. Place a big beaker over the resting bubble. Arrange a bright white screen behind the beaker (or a lamp and large white lampshade above).

Just before the film breaks, the thinnest region becomes invisible. That 'black spot' is spectacular. A slight draught makes the experiment more convincing and dispels any idea that the black region is a hole in the film. The most convincing test is to poke the black region with a piece of blackboard chalk—a good way of breaking any soap film.

Pupils would expect the light-waves from two surfaces very close together to reinforce, not annul Here we must say frankly to pupils, 'There is a good reason for the black spot but it is too difficult to explain'.

Avoid saying 'The film is too thin for light waves to show it'—a thin film of absorbing material *would* be visible.

Class Expt 49 A Thin Film of Air—Interference with Air Wedge *(OPTIONAL NOW)*

(This simple experiment should be done by each pupil holding a pair of plates individually. A demonstration for pupils just to look at would not be worth while at this early stage.)

Apparatus

2 Bunsen burners	item 508
16 pairs of plate-glass plates	129
32 bulldog clips to hold glass plates	564
1 translucent screen	46/1
1 lamp (behind screen)	46/2
sodium bicarbonate or common salt	
iron wire to hold salt in flame	
16 pieces of red and green colour filter	205
scraps of tissue paper	

Although a sodium lamp is the easiest source of monochromatic light for this experiment, a Bunsen burner fed with common salt or, better, sodium bicarbonate, on an iron wire, provides a good simple source.

Preparation

Clean the pieces of plate glass carefully beforehand. To test them for reasonable flatness, press them together and examine the fringes by monochromatic light.

An air wedge is formed by spacing the plates apart at one end with a scrap of tissue paper.

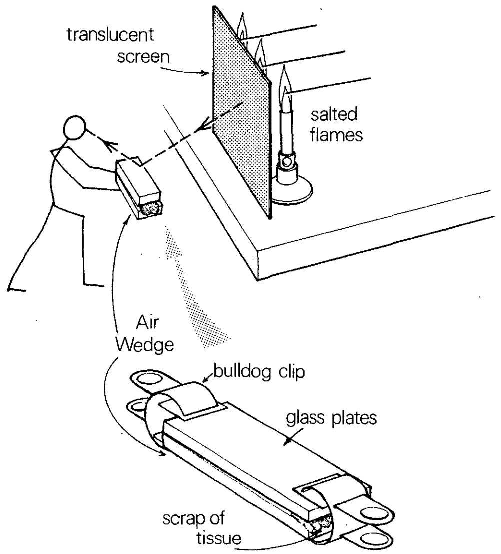
Arrange the Bunsens behind a translucent screen (or in front of white screens) to make an extended source.

Procedure

The pupil holds his sandwich of plates and tilts it until he sees the yellow sodium light reflected brightly. Then he follows these instructions:

*   *   *   *   *

Press the sheets of flat glass tightly together like this, so that the two inner reflecting surfaces are very close indeed. Hold the plates as if they were a book that you are trying to read by the yellow light.



You may see the black spot that you saw in a soap film if you squeeze the plates together tightly.

Now open the plates and prop them apart *at one end* with a scrap of very thin paper. Hold them tightly clamped together with a bulldog clip at each end.

Look for the zebra stripes. If you knew the wavelength of light, what could you estimate by counting the stripes?

Focus your eyes directly on the surface of the glass plates, not on the reflection image of the light source farther behind.

Optional Extension. If red and green colour filters are available, use a white light source with each filter in turn to illuminate the sandwich. Make a quick change between red and green and think about the difference that you see. What does that tell you about the waves of those two colours?

*   *   *   *   *

NOTE. The fringes will be difficult to see if they are very close together—that is why the tissue must be thin and the bulldog clips must hold the plates tightly together.

Air wedge Pupils should look at an air film sandwiched between two plates and illuminated by sodium light (or by a mercury arc with a green filter). They will see fringes caused by 'interference' of light reflected from the two *inner* faces of the glass sheets—the outer faces of the sheets are too far apart to show any noticeable consistent pattern by their reflections.

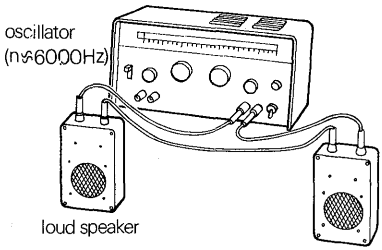
Home Expt H49 Air Wedge

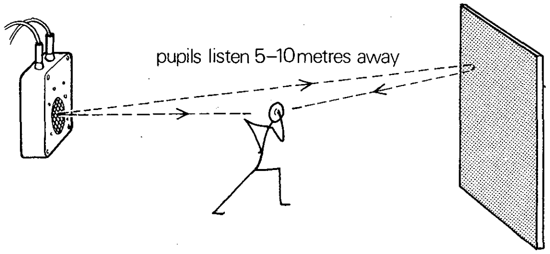
If pupils live near a street with sodium lamps, suggest they should try looking at a sandwich made with any small plates of glass.

The fringes may be far from straight, but they will be visible by reflection if the plates are held firmly together with thumbs and fingers.

The standard metre Tell pupils that counting fringes like these is the basis of the modern way of specifying the standard metre. Here counting fringes would only tell us the thickness of the scrap of tissue; but the method can be extended.

Interference with sound waves Pupils use their own ears as detectors for sound waves of wavelength a few centimetres. It is necessary to work out of doors so that wall reflections do not spoil the simple pattern.





Class Expt 49X Interference using Sound Waves *(OPTIONAL. This is a luxury experiment, outside the normal scope of our programme. If the apparatus is ALREADY available, this offers a good demonstration of interference—particularly in the form of Young's fringes. But we do not suggest that any school should buy the apparatus for this use in Nuffield O-Level teaching.)*

Apparatus

1 signal generator (audio oscillator) Optional item 182
2 small loudspeakers Optional item 183
large metal sheet (or smooth hard wall)

Procedure

a. 'Young's Fringes'. The best demonstration is with two loudspeakers driven *in series* by the oscillator. Set up the speakers several wavelengths apart, out of doors, far away from any walls.

The frequency should be high, say 6000 Hz (wavelength about 6 cm) with the speakers about 30 cm apart.

Pupils move about and listen. They will 'hear Young's fringes'.

b. Standing Waves. Direct a beam of sound waves, from a single loudspeaker, normally at a large sheet of metal or any other reflecting wall. In the region in front of the wall, incident and reflected waves may interfere to form standing waves.

Even if he stops up one ear, a pupil will need to move at least 1 head-span to appreciate the change from maximum to minimum. That requires a wavelength at least $4 \times (15\text{ cm})$, a frequency at most 550 Hz, preferably about 400 Hz.

Demonstration 49XX Interference using Centimetre Radio Waves *(OPTIONAL. This is a luxury experiment, outside the normal scope of the programme. If centimetre radio-wave apparatus is ALREADY available, this offers a good demonstration of thin film interference. But we do not suggest that any school should buy apparatus for this in Nuffield O-Level teaching.)*

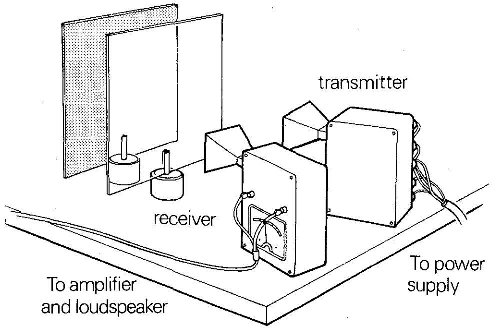
Apparatus

1 centimetre wave transmitter Optional item 184/1
1 centimetre wave receiver Optional item 184/2
1 amplifier Optional item 181
2 glass plates, about $\frac{1}{4}$ metre square (or 1 Perspex plate and 1 metal plate)

Procedure

(1) Show that centimetre waves are partially reflected and partially transmitted by the glass plate.

(2) Set up the transmitter, receiver, and plates as in the diagram. Demonstrate the interference between the waves reflected by the first plate and those reflected by the second plate. Show the effect of reducing the thickness of the 'film', which is the space between the plates.



CHAPTER 4

MOTION AND FORCE

Informal preparation for Newtonian dynamics

We now make a complete change, and embark on an informal study of motion (preparing for more formal work with Newton's Laws in Year 4). That is followed by some simple Kinetic Theory; and then a return to class experiments with electric currents, using the Westminster electromagnetic kit.

EXPERIMENTS ON MOTION

Introduction In constructing the original programme, we wanted young pupils to gain a feeling for acceleration, force, and mass by doing their own experimenting. That seemed better 'teaching for understanding' than expounding formal Laws and giving practice in artificial calculations. We offer this revised programme with the same view.

Time, Speed, and Acceleration

Our aim for Year 3 is to give some general ideas, partly by letting pupils do experiments, and partly by asking questions.

Pupils should make their own simple measurements of motion. Formal experiments on Newton's Laws of Motion are left until Year 4; so the treatment now should be a quick light introduction to pose some questions and let pupils enjoy using the apparatus.

Passengers have a better journey if they know where they are going. It is a peculiarity of the teaching of Newton's Laws that we ourselves are so well aware of the importance of these Laws that we are apt to forget to tell pupils where they are going.

Start by asking some questions as sign posts and stimulants.

(The questions printed below—and in the Pupils' Text—are only offered as specimens of the kind of question that might be asked to arouse interest or start discussion. We do not suggest asking all these. Nor is it necessary to give full answers: that is not the point of these questions—their point is to start some thinking. Teachers may wish to use a few of these, perhaps with some simpler ones.)

(1) How does an Earth satellite keep going without using up fuel?

(2) What does a space ship do, far out in space? Does it travel slower and slower or keep the same speed as time goes on? Does it travel in a circle or in a straight line or how?

(3) When a policeman starting out on a motor cycle speeds up to 30, 40, 50, . . . kilometres per hour, it takes him some time, and some petrol, to reach 70 kilometres per hour. What is it that prevents him reaching that speed *at once*? Is it air resistance, or road friction, or something else? (Try starting to run carrying your younger brother on your back; try again without him.)

(4) Suppose a rocket has a downward blast of hot gases that is just strong enough to keep it hovering a short distance above the ground (without rising or falling). What will that rocket do *with the same blast* if it is aimed horizontally? What will the force-measuring machine on a test-bench show, if the same rocket is fired horizontally but is kept at rest, tied up to the machine?

(5) Can a rocket go faster and faster in a vacuum?

(6) Does a railway diesel engine need friction on the rails?

(7) If a diesel engine pulling *ten* carriages takes 30 seconds to speed up to 50 kilometres per hour, how long will the same engine take if it is pulling *twenty* carriages?

(8) Is there any force pulling or pushing the Moon as a whole?

(9) Some radioactive atoms shoot out a small particle—a chip of their central core, their nucleus. In some cases that is an 'alpha-particle', which turns out to be a helium nucleus itself. Then the remainder of the original atom is quite a different atom with different chemical properties. When an atom at rest shoots out a high-speed alpha-particle like that, does the rest of the atom recoil (bounce backwards) faster than the alpha-particle, or slower? Or does it not recoil at all?

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

Speed, Velocity, and Acceleration

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

Acceleration as something measured is also difficult, the more so because to most children a unit which has the form of 'metres/second per second' is somewhat ludicrous. And the compact form 'metres per second^2' recommended by

* This comparison of scientists with detectives appears from time to time in our programme. We hope that teachers will use it, because we think it offers useful insight to young pupils; but the wording needs to be changed to fit the taste and age of each group.

It is significant that the suggestion of this comparison was brought to the Project at an early stage of its development by an extremely able lawyer who has unusual insight into the problem of conveying a good understanding of science to laymen.

mathematicians and many a mature physicist, is more puzzling still. And 'm s^{-2}' will certainly maintain an unwanted sense of mystery at this stage.

With beginners, we should certainly measure acceleration at first in *mixed units*, such as 'kilometres/hour per minute'.

The meaning is not obvious to a beginner when we say an electric train has an acceleration of '1.5 metres/second per second'; but '100 *kilometres/hour per minute*' has a more satisfactory ring. That last form is easier still if worded as '100 *kilometres/hour in each minute*'.

{It is important to distinguish between an implicit understanding possessed by a child and an explicit understanding. Very often, a pupil has an implicit understanding of a concept long before he can make it explicit. Our purpose now is to foster the process of acquiring implicit understanding; explicit understanding can come later. Sometimes a carefully framed, gentle question for homework will help that development. 'Suppose your neighbour, who sits at the next desk, missed the lessons (or experiments) on ... what would you tell him to explain what happened? Give him some help in your own words.'}

The development of Nuffield apparatus for dynamics When the Project was being developed, team members tried various carts and trolleys for class experiments on motion. Here is a short history:

The ancestor of our Nuffield trolleys was the long 'Fletcher's Trolley', which had a vibrating blade with a brush that drew a wavy line on the trolley itself to mark time-intervals. This was a demonstration device, and pupils found the analysis of its record difficult to understand—few could see readily the relationship between the obvious wavy trace and a speed.

A large 'Playground Trolley' which could be loaded with pupils was suggested in Education Pamphlet 38, H.M.S.O., 1960. This was a noble innovation: an intermediate stage between formal demonstrations and the present Nuffield pupils' experiments with small trolleys. *A school should NOT buy a large trolley now, when equipment for class experiments is so much more important.*

Some manufacturers developed a demonstration trolley system, which employs an electric stop-clock; but this appears complicated to pupils. We should not obscure natural behaviour by expensive ingenuity.

Small trolleys for individual work by pupils were designed by the Physical Science Study Committee in USA. At first these were just roller skates loaded with building bricks; but the commercial form was a block of wood with three wheels of roller-skate type, with extra devices such as a spring piston to make an 'explosion' between two trolleys.

The Nuffield Physics Group encouraged the production of similar equipment in England.

Nuffield teams also devised equipment for measuring speeds of trolleys and the forces pulling them: speedometers; a dynamo and millivoltmeter; photocell and capacitor; and a damped spring balance of low mass, to be carried by a trolley. Although delightfully ingenious, these threatened to move work with trolleys away from pupils' activity into demonstrations again. So we do not recommend them.

The Nuffield choice So, for class experiments we decided to follow the PSSC example and give pupils simple trolleys with a small vibrator to mark time-intervals on a paper tape; and let them measure the pulling force by rubber bands or elastic threads kept at a constant stretch.

For later experiments on momentum-conservation, etc., we suggest two modifications for demonstrations:

(1) The same small trolley carries a long card which intercepts a beam of light on its way to a photo-transistor; the time-of-transit is measured by a scaler arranged to count milliseconds—an easy precise scheme for measuring speed.

(2) Instead of trolleys, we use metal rings sliding on a level sheet of glass with practically no friction because they are supported by gas, like hovercraft.* Some of the rings are magnets arranged to repel each other and make

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* Another 'hovercraft' type of apparatus, the 'linear air track', is available. This is a long hollow straight beam pierced with many holes from which streams of air emerge to provide a frictionless air-bearing for saddles that ride on the beam and demonstrate collisions, etc.

The air track is a fascinating marvel to watch in action and all who see it are tempted to buy one. However, they are expensive, they require very careful adjustment, they are easily damaged, their air supply is noisy, and they give demonstrations in only one dimension. Also they usually require special devices for timing, so that the demonstrations look complicated.

All those are minor objections compared with the major one for our programme: that such a device provides for more *demonstrations*, where we want to emphasize *class experiments*, or at least experiments in which pupils participate.

Furthermore, many teachers who have bought linear air tracks find that the initial delight wanes fairly soon: they are tempted to return to simpler machinery.

The two-dimensional 'air table' is much more likely to increase in use. The table has a large number of tiny holes fed by compressed air so that pucks ride on it almost without friction. The noise is distracting—the air jets hiss and the vibrating walls buzz—but the table makes a fine large model for some demonstrations of collisions; also a model of gas molecules.

elastic collisions; others are of brass, to pile on additional mass.

Some form of these 'pucks' is essential for demonstrations of Conservation of Momentum in two dimensions—and without an understanding of that principle pupils would miss a lot in modern physics.

In measuring the motion of pucks, we must leave them quite free, so for Year 4 we suggest a photographic method: 'multi-flash' pictures. We take a series of photos at regular time intervals on the same piece of film. The multi-flash picture is developed and projected on a screen for study; or, better still, large prints are quickly made from it for pupils to analyse.

The evenly timed flashes of light for the photo are provided by a spinning disk with a slit in it. The disk interrupts light from a lamp that illuminates the experiment. It stops the light either as it starts from the lamp or just as it reaches the camera.

Details of Nuffield trolley apparatus

Our aim is to give pupils *personal* experience in experimenting with force and motion rather than show them results.

QUANTITY. Pupils should work in pairs if possible; at the very most, four pupils to a runway. This equipment plays an important part now and a very important part in Year 4, so we hope it will be provided in full quantity. If many pupils stand round a trolley and its runway we are in danger of having poor demonstrations instead of good class experiments.

Problems of cost, storage, and laboratory space will tempt a school to suggest the economy of working with still more pupils to a runway. That would be very unwise economy: it would miss the aim of this work.

TROLLEYS. Good small trolleys are available from several makers. In choosing them, teachers should test the friction of the wheels and consider their durability. Will the bearings wear well, and will the wheels stay reasonably aligned?

RUNWAY FOR TROLLEYS. Good trolleys need a runway that is smoother and nearer to a plane than most laboratory tables. Also, the trolley is to run down an inclined plane in some cases. So there must be a long board, with a fence at each edge, as a runway for trolleys.

We suggest a plank of 25 mm plywood or chipboard, about 30 cm wide by $2\frac{1}{2}$ metres long with a border of slotted angle along each side. If the size of the laboratory, or its storage arrangement, makes a shorter runway necessary, 2 metres will do; but the disadvantage is considerable, because the accelerated motions which the pupils will study cover large distances in the later experiments.

It is better to have 8 long runways in the lab than more short ones.

A plank of ordinary wood is likely to prove false economy. Using narrower boards, or replacing the metal edges by wooden ones, will almost certainly prove false economy.

The storage of runways raises problems. We hope they can be stored safely; and we suggest they should not be used for other purposes, such as a large seesaw, which might damage them and reduce their value for use with trolleys.

'TICKER-TAPE' TIMER. The moving trolley drags after it a streamer of thin paper tape which serves as a measure to show the distance travelled. The tape travels under the hammer of a tuned vibrator (somewhat like an electric bell without the bell) running on a.c.

The ticker-timer's blade hits a small piece of carbon paper just above the tape, driving the carbon paper down on the tape as it passes over a firm anvil. This makes a mark on the tape at regular time-intervals, one every period of the timer, one every 'tick'. (The a.c. ticker-timer has proved preferable to ones running on d.c. with unknown frequency.)

A piece of carbon paper held in position would soon wear out under repeated impacts and fail to make good marks. To prevent this, the carbon paper is a small disk anchored by a drawing pin through its centre. The tape runs under the carbon paper disk, out near one edge of the disk; and as it runs it makes the disk rotate, thus providing a fresh surface.

This device seems obvious to pupils. They can hear the vibrator running at a uniform rate. But the teacher needs to remind them at intervals that the timer makes marks at equal *times* apart—not necessarily at equal *distances* along the tape.

TAPE. Narrow tape for the timer is supplied in two forms, plain and gummed. The gummed form makes the construction of tape-charts easier; most teachers prefer it.

FRICTION-COMPENSATED RUNWAY. In some experiments pupils pull a trolley along a level runway with an elastic thread. We would like the motion to have no contribution from gravity and none from friction. But with a truly level runway which would avoid the effect of gravity there will be friction which will make complications. Therefore teachers should develop, in conference with pupils, the idea of a 'friction-compensated runway' with a suitable, very slight tilt. (With good trolleys, it may be as low as a few degrees.)

To test for friction-compensation, pupils place a few exercise books under the starting end of the runway, start a trolley with a small push, and then examine the tape record. They change the tilt until the trolley runs with constant speed, once it is started.

It is essential to make this friction-compensation with the tape and timer in action, because they contribute to the effective friction.

When the trolley is loaded with extra mass one might expect the same friction-compensation to hold but in practice it is better to check the friction-compensation again.

Since friction-compensation takes time and confuses the simplicity, it is better to omit it in rough experiments where friction does not matter enough. And of course it is unnecessary for measurements on a trolley accelerating down a slope, because friction only takes away a constant fraction of gravity's constant contribution.

PULLING FORCE. In our whole programme, we suggest teachers should take FORCE as a basic well-understood quantity in dynamics. We describe FORCE as a push or a pull and expect pupils to accept the measurement of force by spring balances or stretched elastic threads. This differs from the professional convention that takes MASS as basic and understood *a priori*, and defines force as:

MASS × ACCELERATION

For O-Level pupils, we consider that force is something they can feel and we know that mass is an unfamiliar difficult concept. Indeed, we hope that by the end of the O-Level programme pupils will have gained a feeling for mass which will make it easier for them to understand space travel, atomic physics, nuclear energy, . . .

Therefore we provide a simple method of applying forces which we hope will seem obvious. The pupil pulls the trolley (on a friction-compensated runway) with a piece of elastic thread stretched by a standard amount.

The easiest method is to have a ring on each end of the elastic. Then the pupil puts one ring on a peg at the rear end of the trolley and pulls the other ring until it is level with the front of the trolley. He moves with the trolley, keeping the front ring there, so that the elastic is at constant stretch. Pupils achieve skill with this after a little practice.

To apply double force, the pupil uses two elastics (tested for equality) in parallel; and more elastics for greater forces.

{**Assumptions** In our method of applying a 'known' force, we are assuming, axiomatically, that the pulls of equal elastics in parallel simply add up; whereas, in the professional approach, physicists assume, axiomatically, that masses simply add up. Although one feels that one can test both those assumptions experimentally, careful logical examination will show that one cannot do so. We have to choose one of those assumptions as an axiom in building our theory of dynamics. Then the property in the other assumption emerges from experiment. Of course, none of this philosophical worry should appear in our O-Level teaching. It is only mentioned here as a piece of background which we should consider in forming our own view of teaching dynamics.}

Note on introductory experiments with timers Because the tape and ticker-timer techniques (and our use of stroboscopes) are new to many teachers, we offer detailed suggestions for explaining them to pupils and giving practice in their use. Teachers should not infer from this that we regard these as very important innovations. They are merely useful devices for quick, clear teaching, especially in class experiments. Such 'training experiments' should not bulk too large or take too long.

Starting the Study of Motion

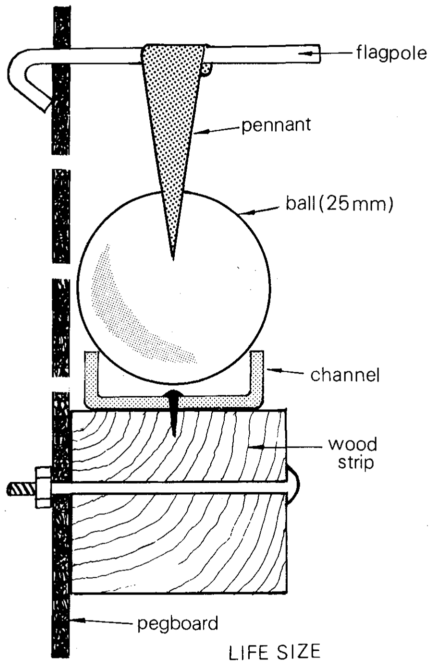
To give the idea of accelerated motion an informal start, keep a long inclined track available at the side of the classroom and let pupils roll marbles down it. This is Galileo's plank. The rolling ball makes audible signals by hitting metal 'pennants' hung above the track.

It would be good to have this available for a week or two before work on motion starts; and it should remain available for some weeks after.

Galileo's Plank: Details of Equipment

TRACK. The best form for the 'plank' is a plastic channel of rectangular U section screwed to a long strip of wood. The channel is stocked in 2-metre lengths by do-it-yourself shops for use with sliding doors. For a $2\frac{1}{2}$ cm ball, the channel should be about 20 mm wide with sides about 6 mm high. Attach it with screws or glue to a long strip of wood, say $2\frac{1}{2}$ cm × $2\frac{1}{2}$ cm × 2 metres or more.

(A long wooden plank, 3 or 4 cm × 10 cm with its narrow edge upward can be used instead. Either cut a groove in that edge or nail grooved moulding on it. Metal channel is less suitable because it adds confusing noise.)



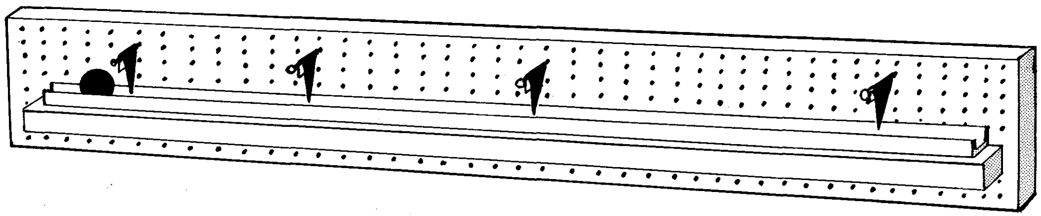
PENNANTS TO ACT AS TIME-MARKERS. These are narrow triangles cut from thin sheet metal. Bend each over at the top to hang down loosely on a peg as axle. Cut off the point so that the rolling ball makes a more 'massive' hit.

FLAGPOLES. The pennants hang on horizontal pegs which pupils can move along the runway.

A long strip of pegboard behind the runway provides an easy means of supporting the movable pegs and pennants. (The pegboard limits the moves to integral hole-spacings; but this is an advantage—it makes approximate success easier.)

Screw or glue the channel's wood base to the pegboard with spacers. Support the pegboard by two retort stands (or, better, two slotted bases).

It is best of all to bolt the whole assembly to the wall.



Class Demonstration 50 Motion of a Ball rolling Downhill

AIM. An experiment to visit and play with.

Apparatus

track of mounted channel or long plank (at least 2 metres)	item 225/1
supply of *large* marbles ($2\frac{1}{2}$ cm)	225/2
14 small metal pennants	225/3
14 pegs (axles for pennants)	225/4
pegboard support for pennants (20 cm × length of runway)	225/5
2 retort stands and 4 bosses	503–505
(or, 2 slotted bases and wood block)	30

Preparation

Set up the track, inclined so that pupils can let marbles roll down it. A slope of 1 in 8 is suitable.

Arrange the small metal pennants, swinging loosely on pegs as axles, so that when a marble hits one there is a 'clink'. Push the axles into holes in the pegboard. Make sure the line of holes in the pegboard is parallel to the track.

Procedure

Letting a marble roll from the top all the way down should be legitimate play.

a. Pupils try placing the pennants at regular intervals: every 8 or 10 holes from the starting place at the top of the plank.

b. Listening to accelerated motion. Then pupils try to place them so that the clinks seem to come at *equal intervals of time.* They hang the first pennant at the same place again; but they must hunt for the other positions.

If slower pupils do only the first part of the experiment and do not think of rearranging the pennants, leave the problem unfinished.

{For now, that experiment is a matter of trial and error. Pupils will have had no chance to extract a guiding rule from their trolley experiments. That comes much later. Of course, *we* know that the pennants should be placed in a quadratic spacing, in proportions 1 : 4 : 9 . . . from the start. But it is far better teaching to leave pupils to wrestle with the problem. Give praise for success but do not give away the answer.}

Home Expt H50 Ball rolling Downhill

That is also something that a pupil may enjoy setting up at home. Once the regular series of clinks has been heard, there is delight.

Go back to Year 1 and ask pupils to measure the time taken by a pupil to run 100 metres. *Each should make his own measurements.*

Class Expt 51 Measuring Each Pupil's own Speed

AIMS. (i) To let pupils try a first stage in measuring short times with some precision.

(ii) To look at the work of a class group statistically.

Apparatus

16 stop-watches or stop-clocks	item 507
(Also a large clock on the wall with a large 'seconds' hand, or pupils' watches)	
1 statistics frame *(Optional)*	48
metre rules	501
several magnifying glasses (+14 D will suffice)	113/1

Preparation

Mark out roughly a distance of 100 metres; or post up a notice saying how many laps of the classroom's length are needed for that run.

Procedure

Pupils time one pupil running 100 metres. The runner should be allowed a start.

a. Rough measurements. Pupils use the clock on the classroom wall or their own watches if those have large hands that go round once a minute. Or, if they have watches with a small 'seconds hand', they may use them with magnifying glasses. Quartz watches should be allowed to run.

b. Precise measurements. Pupils use a stop-watch or stop-clock (at least 1 per pair).

Make a quick statistical summary of the measurements by all pupils for the *same* run by the *same* runner. If the statistics board (Year 1) is available, show the summary on that. Otherwise, a tally on the blackboard will suffice.

Timing accelerated motion Explain that we shall not just measure things moving at constant speed but shall make measurements of things like a car that is speeding up or coming to rest with its brakes on. For that we need very careful measurements of short time-intervals—a few tenths of a second.

As a preliminary example for pupils to discover the need for tape and timer, give pupils a trolley and a long sloping runway and ask them to make measurements of the trolley's motion.

Class Expt 52 Timing a Coasting Cart. First Attempt

Apparatus

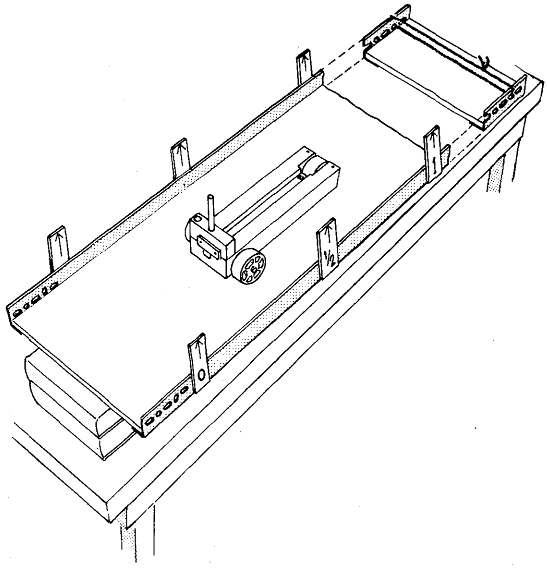
8 to 12 runways	item 107
(see special note on trolleys and runways)	
8 to 12 dynamics trolleys	106/1
16 stop-watches or stop-clocks	507

Pupils may have to use runways and trolleys in groups of four. More than four to a runway would take away most of the value of the experiment. Although three or four may have to share a runway, each *pair* should have a stop-watch, so that every pupil can make his own measurements without much waiting.

Preparation

Support one end of each runway to make it slant about 1 in 20; so that the trolley runs down with obvious acceleration.

Tie string or a rubber band across the runway at the lower end to act as a stopping buffer, or depute one of the team to act as keeper.



Procedure

Ask pupils if they can measure the time the trolley takes for the first $\frac{1}{2}$ metre it travels, and the next $\frac{1}{2}$ metre, and the next, etc.

Pupils let the trolley start from rest and try to time it.

No record need be made of the measured times because the experiment will only show that the times to cover successive $\frac{1}{2}$-metre distances decrease rapidly. Pupils will see what the difficulties in timing motion are like.

Discussion

After that attempt, hold a discussion of difficulties. The distances involved in trolley experiments are easily measured but the time intervals—some of them only a few tenths of a second—require some special technique.

Could better measurements be made with a clock that ticks 50 times a second? Pupils may say there are still difficulties of hand and eye.

Then offer a vibrating timer and ticker-tape. The timer will make a mark every $\frac{1}{50}$ second on the tape. The faster the tape is pulled through the farther apart the marks.

Class Expt 53 Trying the Ticker-timer and Tape

Apparatus

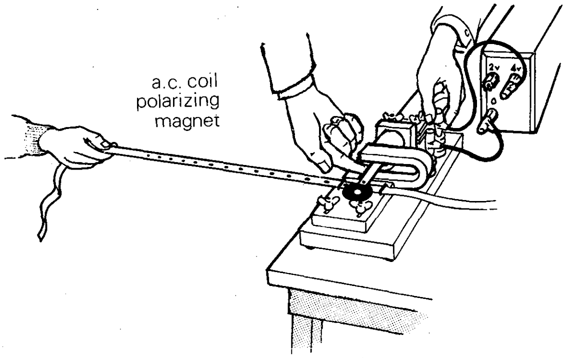
16 ticker-tape timers	item 108/1
16 rolls of tape	108/4
8 transformers	27

There should be one timer and tape for every two pupils although when trolleys and runways are used limitations of space may reduce that to one set for every four pupils. With 16 timers 8 transformers will suffice, each supplying two timers in parallel.

Procedure

Let pupils examine their timer, at rest and then running. Let them put a short piece of tape under the carbon paper disk and pull it through with the timer running.

This device seems obvious to pupils. They can hear it vibrating at a uniform rate. If pupils are very uncertain, discuss the meaning of the record *very briefly*; but most pupils will learn very well from their own experiments which follow.



Before pupils use ticker-timers and tape to measure the motion of trolleys, they should practise with simple uses: timing the interval between two hand-claps, recording the motion of a running pupil, making a rough calibration of the timer by pulling tape through for 2 seconds by the clock (Expts 56, 57, 58). But before that practice, or just after, it is good to consolidate pupils' understanding of the vibrating timer by showing a giant model and letting them try various ways of timing the motion.

Giant vibrator It is probably best to save time by making this a quick demonstration* with pupils participating. Pupils estimate the time of one vibration by counting 10 of them and timing with a stop-watch (one per pair). Then with the frequency made greater, they try a hand stroboscope (one per pupil).

* If a full class experiment is preferred, provide a hacksaw blade for each pair. Pupils clamp it firmly between metal plates, with a small G-clamp. They clamp that G-clamp to the bench with a large G-clamp.

Class Expt 54 Giant Model of Ticker-timer

AIM. To give a quick, light-hearted, introduction to timers.

If pupils are amused by timing the giant vibrating blade, well and good. If this becomes a period of drill in studying timers, we shall have missed the point and may indeed have spoiled the beginning of important dynamics experiments. Therefore we urge teachers to make this experiment very short and light or else omit it.

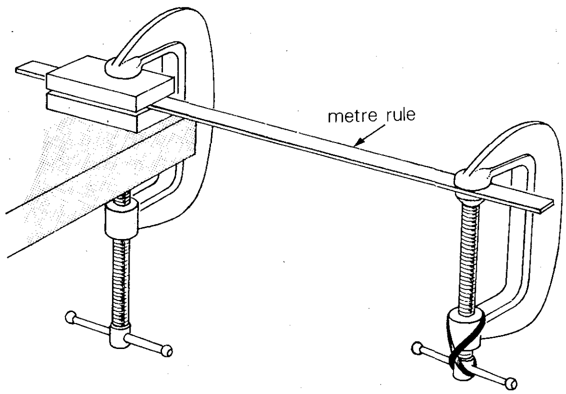
Apparatus

1 metre rule (or a kitchen palette knife)	item 501
2 small wood or metal blocks for jaws	121
2 large G-clamps	44/1
16 stop-watches or stop-clocks (1 per pair)	507
32 hand stroboscopes (1 per pupil)	105/1
4 reels of masking tape	105/2

Preparation

The model is a metre rule with one end firmly fixed and the other free to vibrate. The free end of the blade projects out over the edge of the table.

In clamping any vibrating blade it is important to have the jaws of the clamp holding tightly and symmetrically just where the blade emerges. Loose clamping, or one-sided clamping, leads to annoying change of frequency with amplitude and a disastrous waste of energy at the clamp.



To make sure of firm clamping, place the blade between two small plates of metal which are held tightly in the clamp. A G-clamp is better for this than a lab clamp. Anchor that G-clamp in turn to the table by a second G-clamp.

Procedure

a. Watching a Giant Timer.

(i) Pupils see if they can count the vibrations. These are too fast; so the motion is slowed by attaching another small G-clamp as a load on the outer end of the blade. (A rubber band wound on the handle of this clamp will stop it from rattling.)

Pupils measure the time for 10 complete oscillations.

(ii) Move the clamp inward, so that the vibrations speed up. When the loading clamp is removed from the blade, the frequency can be increased further by reducing the length of blade protruding from the jaws.

b. Watching a Giant Timer with Stroboscopes (OPTIONAL).

When the vibrations are too fast to count, offer stroboscopes. Each pupil holds his strobe disk so that the slit through which he looks is parallel to the timer's length.

Each pupil holds the disk in front of his eye and turns it very slowly, changing the speed until he can 'freeze' the motion. This is best done with a disk with one slit (all the other slits being closed with black tape).

For high frequencies it may be necessary to remove one tape from the disk, so that there are two slits, 180° apart.

A partner measures the time taken for 10 revolutions of the disk.

Class Expt 55 Watching a Small Ticker-timer with Stroboscopes *(OPTIONAL)*

Then each pupil might try to use the stroboscope to observe the real timer—the ticker-tape vibrator. (It will not work with an added load so it cannot be slowed.) The timer's frequency is so great (50 cycles a second) that pupils will have to 'freeze' a sub multiple of that frequency.

This makes a set of experiments of increasing difficulty, both in technique and in reasoning.* It is *not* essential for every pupil to follow the whole series—these are only intended to offer some practice. Here is a case where the teacher should give considerable help to those who need it.

Making experiments with timer and tape Explain that these experiments are to make the kind of measurements an engineer would make if he wanted to know about a car speeding up or its brakes working or even about a rocket accelerating up to its orbit. We start with some simple games to see how the tape and timer work.

The timer and tape are going to be put to many uses in Year 4; so this year's work should introduce them briefly and give pupils a little practice in interesting uses. Then next year the technique of handling them will not delay some important difficult experiments. However, since some pupils will not continue to next year, we should be careful to see that this year's work is not just preparation but is in itself interesting experimenting.

We should offer plenty of time for class experiments with this apparatus. However we should not labour experiments on $F = ma$.

Class Expt 56 Using the Timer as a Clock: Practice in using Ticker-timer and Tape

Ask pupils to measure the time between two signals. Their unit of measurement will be one 'tick', the time from one dot on the tape to the next.

Apparatus

16 ticker-tape timers	item 108/1
16 rolls of tape	108/4
8 transformers	27

(In this and subsequent experiments with ticker-tape timers there should be one timer and roll of tape for every two pupils if possible; but when trolleys and runways are used, difficulties of space may reduce that to one set for every four pupils. Where 16 timers are used, 8 transformers will suffice, each of them supplying two timers in parallel.)

Procedure

Explain that the number of spaces from dot to dot made on the tape while the timer is switched on will show the time interval in 'ticks'.

Pupils may pull the tape through at any speed sufficient to separate the dots.

Pupils work in pairs. One partner pulls the tape through while the other starts and stops the timer with a finger pressing on its blade from above.

For the interval to be timed, give two sharp hand-claps one or two seconds apart. (Remember: even 2 seconds will give 101 dots to count!)

This experiment needs a rehearsal. Then, after the main measurement collect the results. Each result will be in 'ticks' and results will disagree. Ask why.

How many ticks in every second? Proceed at once to another practice experiment which needs some cooperation among partners.

* Because our use of stroboscopes and the ticker-tape technique are new to many teachers, we offer a number of suggestions for explaining them to pupils and giving practice in their use. But teachers should not infer from that that we regard these as very important innovations; they are merely useful devices for quick clear teaching, especially in class experiments.

We hope teachers will not let these training experiments bulk too large or take too long.

Class Expt 57 How long *is* one Tick? How many Ticks in 3 Seconds?

Apparatus

16 ticker-tape timers	item 108/1
16 rolls of tape	108/4
16 stop-watches or stop-clocks (or a big clock on the wall)	507
8 transformers	27

Procedure

Pupils run their timer as in the previous experiment, except that a clock or watch gives the time interval. (An audible system of signals every second would do as a substitute: e.g. the Rugby time signals.)

(If one or two pupils operate each timer, a run of 3 seconds will give them all the dots they want to count. If three or four pupils work on one timer, a 10-second run will not hurt, because the pupils can cut their tape in quarters and count the dots.)

If polarized a.c. timers are used, we can trust them to make 50 dots per second. Disagreements between that and pupils' estimates indicate errors of human reaction.

Collect the results and survey them with the class.

Personal example Now offer a real example of using the timer and tape that is interesting to pupils: each pupil runs and makes a record of his own, quite uneven, motion.

{Although a demonstration rehearsal is usually a damaging way of preparing for a class experiment, in this case where we want to make sure that every pupil succeeds, a preliminary demonstration, done quickly, will provide the needed explanation and will save later disappointments.}

Quick Demonstration 58X Recording a Pupil's Motion

Apparatus

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

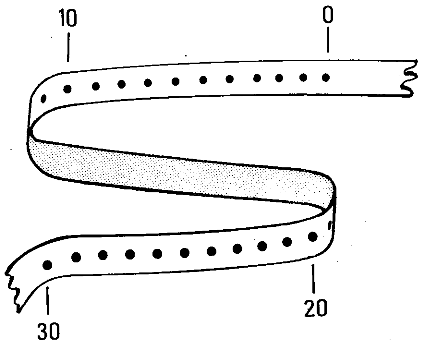
Procedure

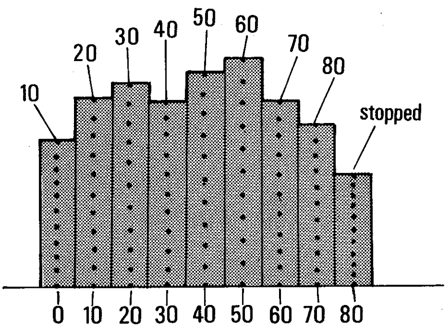
Run the timer while a pupil pulls tape through it, by walking away holding the end of the tape in his hand. After moving some distance the pupil stops.

The dots are made on the tape at *regular time intervals* but they will be close together at the start, then farther apart; then, at the end of the run, very close together.

Cut the tape into lengths containing tentick intervals. Paste these strips side by side, on a card, all with their lower ends on a horizontal base line.

It is not wise to use graph paper for this, however easy that makes the demonstration, because that is likely to encourage a rush into graph-plotting instead of the use of tapes; and that will not give such a clear understanding at this stage.





When pupils make their tape charts of their own runs, each should add this label: 'Each strip took the same time –1 tentick'

'Can you do that yourself?' All have seen the experiment done and should be ready to interpret the new chart. Ask what it tells; but, without explaining now, suggest that pupils do the same thing as a class experiment.

Class Expt 58 Analysing Pupil's own Motion

Apparatus

16 ticker-tape timers	item 108/1
16 rolls of ticker-tape	108/4
8 transformers	27

Gummed ticker-tape is more convenient for this and subsequent tape experiments. Otherwise paste will be needed.

Procedure

In this class experiment pupils work in pairs and produce their own tapes with any variations of motion they like.

Each pupil should emerge with a tape of his own motion for analysis. He should analyse his tape, cutting it up and making a chart. He should preserve his chart in his notebook and add some labels such as 'starting up', 'running faster', 'sudden stop'.

(Some pupils find it easier to stick the tentick strips on lined paper with the lines vertical, so that one edge of each tape lies along a line, even if that leaves a small interval between tapes.)

Discussion: use of tape charts We shall use the tape charts to analyse or exhibit the motion of an accelerating trolley.

The length of a strip shows how far the moving trolley went in ten ticks. It does not tell the speed in centimetres or metres per second, unless one knows the time taken by one tick. Yet the length of strip does show the speed quantitatively.

Since the tape is uniform in width, successive strips pasted side by side in contact show successive samples of speed, *taken for time intervals that are themselves spaced equal TIMES apart.* Pupils need to be reminded of that.

In helping pupils to see signs of *acceleration* in the change of strip length from one strip to the next, it may be helpful to say:

Now look at the *time-of-day* when you took the first sample (strip number 1), and the *time-of-day* when you took the second sample (strip number 2), and the time-of-day . . . The time-of-day itself gets later by ten ticks from one sample to the next.

The tape chart: speed versus time When the pasted-up chart is made, ask what the line-of-tops of strips tells us.

If it is a slanting *straight line* the trolley moved with *constant acceleration.* But at this early stage, we should not try to elicit a clear concept of acceleration. Qualitative descriptions of motion are the proper replies now.

However, we can start some thinking with questions like the following (given in *Pupils' Text 3*):

A. 'If a pupil ran along without changing his speed at all (that is at *constant* speed), what would that line of tops look like?'

Or

B. 'Can you describe the way a pupil was running if the tops of the strips on the chart make a horizontal straight line, all the same height?'

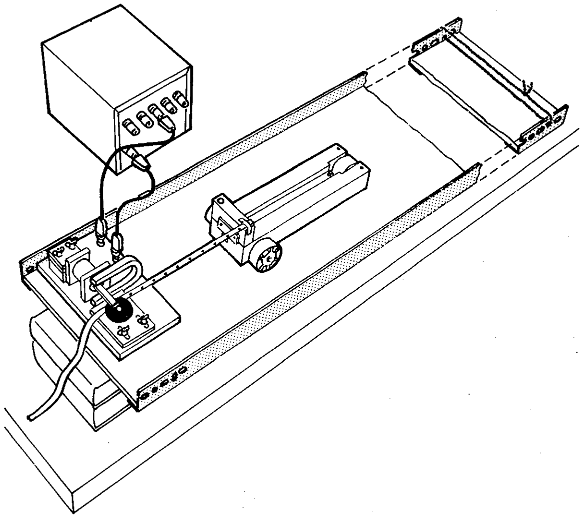
C. 'Suppose the runner is speeding up, going faster and faster and faster. What will the line-of-tops look like?' Here we hope for some mention of the slope of that line giving an informal notion of acceleration.

Meeting constant acceleration Without foretelling the result—constant acceleration—ask pupils to make and analyse a tape chart of a trolley running down a sloping runway.

This was Galileo's idea for studying free fall by using a case of 'diluted gravity'. However we should not use that description yet. Its proper place is after pupils have measured free fall—then they know what is being 'diluted' and why.

The teacher might wish to have a demonstration set of apparatus already arranged, to help pupils in setting up their runway at a reasonable slope, etc. If so, that should only serve for house-keeping hints; to make a record and start to analyse it would spoil the sense of discovery in one's own experiment.

Class Expt 59 Motion of a Cart Coasting Downhill (Trolley Running down an Inclined Runway)



Apparatus

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

Preparation

Before the work starts, make sure the wheels of the trolleys are clean. Pupils should sweep their runway clean of any small particles. The smallest irregularities have adverse effects on the results.

Raise the end of the runway about 5 cm for every metre in its length. Fix the timer at the top end.

Procedure

a. Teacher's Demonstration. Pass the tape through the timer and connect it to the trolley.

Release the trolley. It accelerates down the incline while the timer makes dots on the tape.

The purpose of this *demonstration* is merely to give pupils a start in setting up their own apparatus. Show the trace to the class but do not discuss it or analyse it. Leave the analysis to their own discoveries.

b. Class Experiment. Pupils do the experiment working in groups of 4, or in pairs if possible. Each group must take several runs so that *each pupil* emerges with his own tape, to cut up and paste into a chart which he keeps.

Each pupil cuts his tape into tentick strips. He pastes the strips side by side with their feet on a straight line, to make a tape-chart. Each should look at his chart carefully—and a general survey of a picture gallery of charts from the whole class may help some pupils to see the underlying story.

The 'result'? It would be a great pity to announce to pupils what the result should be or what the actual result means: this should be an interesting discovery for them, even though they do not know quite how to describe the result that they see.

Some pupils will see clearly that they have 'constant acceleration', in the sense that the speed increases by the same amount from each time interval to the next—from each tentick strip to the next.

To other pupils, the straight slanting lines of the tops of strips will merely mean that there is something interesting about the motion—and for them we should leave it like that.

A strong plea: no graphs Many teachers, particularly if the class is a fast group, will feel tempted to change from pasted-up tape-charts to a graph plotted from measurements of the tape. We urge teachers *not* to make that change until a a later year.

The pasted tapes have a strange virtue for beginners, of insisting on the physical nature of the chart. Graphs may look neater and take less time, but at this stage they let pupils lose contact with reality.

Class Expt 60 Trolley Running UP a Hill

(SPECIAL BUFFER OPTION. This is not a necessary experiment now or in a later year. Pupils who have not done this experiment should be at no disadvantage in a formal examination, because examiners will not expect them to have done it. Nevertheless pupils who have done this experiment may find opportunities to bring their knowledge of it into their answer to some general examination question and to gain thereby. We regard this as a very good example of a 'CONTRIBUTORY' optional experiment.)

Apparatus

(Since there may be only a few pupils doing this experiment we list the apparatus needed for each *pair*.)

1 runway	item 107
1 dynamics trolley	106/1
1 ticker-tape timer	108/1
1 roll of tape	108/4
1 transformer	27

Procedure

Ask what happens if a trolley runs uphill, after being given a push. Then pupils try that for themselves, the trolley dragging the tape behind it through the timer. They make tape-charts.

A different investigation of accelerated motion *(OPTIONAL YET NECESSARY FOR SEVERAL LATER EXPERIMENTS)*

When pupils cut their tape into successive tentick strips, those strips give the distance travelled in successive tentick periods of time. And we hope pupils will see those distances mounting up in a uniform staircase of jumps.

If we want to turn pupils' attention to the set of *total* distances, *each measured from the start,* they should make a new set of 'total strips'. These will be the distances travelled in one tentick from rest, 2 tenticks from rest, 3 tenticks from rest. . . .

If the acceleration is constant, these total strips will have lengths in proportions 1 : 4 : 9 : . . . and we hope pupils will discover that interesting relationship.

Class Expt 61 A Different Exhibit of Tapes: Total Distance versus Time *(OPTIONAL NOW)*

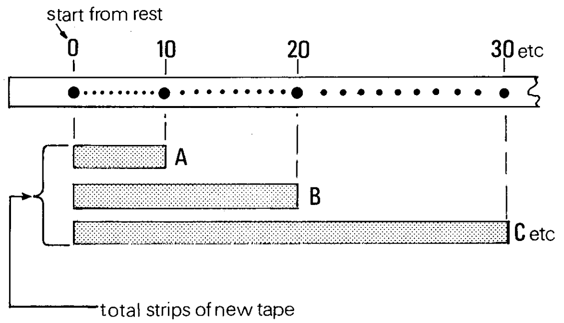
Apparatus

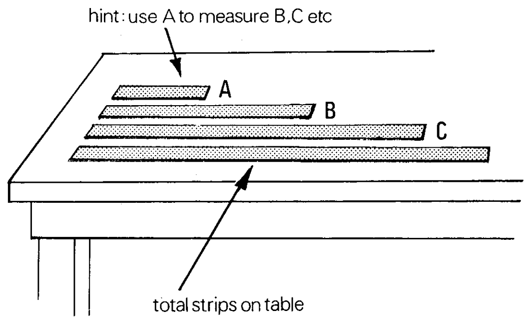
8 to 12 runways	item 107
8 to 12 dynamics trolleys	106/1
8 to 12 ticker-tape timers	108/1
8 to 12 rolls of tape	108/4
8 transformers	27

Procedure

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

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





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

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

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

The rule for 'total strips' This is a very good place for discovery; and it would be a very poor place for a dictated note of the result. Fast pupils can succeed and will enjoy it. With slower pupils the enquiry may not have much point or interest: it would be far better to omit it than try to help them through something not very interesting.

This is a difficult problem, which may be offered but should not be pushed at this stage. Its *result* will be discussed in Year 4.

Many pupils will find Galileo's answer: that the *increase of length,* from one total strip to the next, itself grows by equal jumps (e.g., 3 . . 5 . . 7 . . etc.). Few will discover on their own that the total-strip *lengths* themselves run as the squares of integers (1, 4, 9, 16 etc.).

As suggested above, it would be a pity to announce the answer. Give encouragement but do not do the planning for the bright pupils who will enjoy finding the answer. This work is a useful exercise for their ingenuity and will yield a reward for their intelligence.

Home Expt H62 Testing Free Fall by Ear

(OPTIONAL. This is intended for pupils who have discovered the 1, 4, 9 . . . rule for constant acceleration.)

Suggest to pupils who know the rule, the experiment sketched.

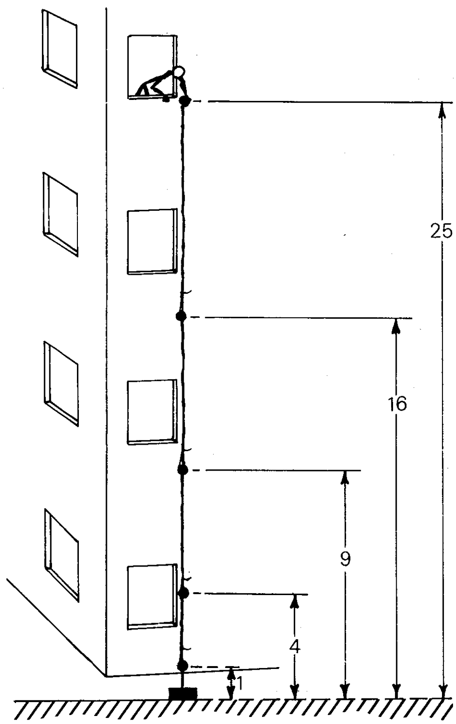
The pupil lets a string of weights or stones fall in a tall room, or better still in a tall stairwell or out of doors.

He anchors a string by a brick on the floor and holds the string taut and vertical. He lets go and nothing audible happens.

Then he attaches loads to the string at several places. The loads may be small stones or fishermen's lead weights or small coils of solder. He first spaces them evenly up the string, say $\frac{1}{2}$ metre from the floor, 1, $1\frac{1}{2}$, 2, $2\frac{1}{2}$ . . . metres. He holds the string taut, lets go, and listens.

He then attaches the loads at a different set of places: half a metre from the floor, 4 half metres from the floor, 9 half metres from the floor, etc. Again he holds the string taut, and lets go and listens. (If he finds this scheme of half metres confusing, 1, 4, 9, 16, . . . feet will do just as well.)

The loads need not be attached directly to the main string but can hang from it by short lengths of string, provided the distance from each load to the floor is correct.



Downhill-and-Uphill

A question for imaginative thinking Ask what the tape record would show for a trolley which first runs downhill, then along the level, and then runs uphill. Everyone knows the qualitative answer to that question; but what about a quantitative answer? Quite apart from records of speed and acceleration, will the trolley run up the other hill to the same height as its starting point?

Demonstration 63 Downhill-and-Uphill Motion. Galileo's Thought-Experiment done with a Rolling Ball

Apparatus

1 steel ball (or large marble)	item 131a
1 flexible curtain rail (2 to $2\frac{1}{2}$ metres)	119
2 retort stands, bosses, and clamps	503–506

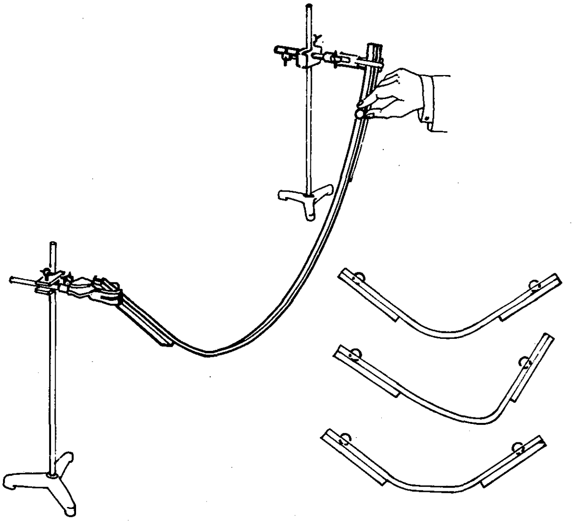
The rail must not be the unsymmetrical type. It should be at least 2 metres long, preferably $2\frac{1}{2}$. It must be flexible enough to be tilted to various slopes, both equal and unequal.

Preparation

A good method for supporting the rail is to glue or screw a $\frac{1}{2}$-metre length of wooden lath (about $1\frac{1}{4}$ cm × $1\frac{1}{4}$ cm) to the under-side of the rail, near each end. (For a $2\frac{1}{2}$ metre rail, the laths might be 1 metre long.) Hold each end firmly with a retort stand and clamp, $\frac{1}{4}$ to $\frac{1}{2}$ metre above the bench. (Do not hold the rail by hand. A hand support will take away too much energy.)

Procedure

Release the ball at the top of one end of the rail, so that it rolls down the hill and then up the other side.



Tilt the rail to various slopes. Also try a horizontal length between the two slopes.

As pupils watch the height to which the ball climbs on the ascending side, some will 'explain' the ball's failure to reach the original height as 'due to friction'. Ask them: 'How do you know?'

{Some pupils may bring an energy argument from Year 2 and point out that the potential energy that turns into kinetic energy should go back into the same amount of potential energy (except for friction) so that the ball should (or 'must') rise to the same level. That argument seems to beg the question, though it would be sound if we could be assured of the Conservation of Energy by some *other* means.}

{In fact, our belief in conservation of [P.E. + K.E.] is derived, on certain assumptions, from Newton's Laws of Motion—Laws which Newton in turn derived from Galileo's thinking and experimenting with motion on hills. That provides us with $\frac{1}{2}mv^2$ for K.E.}

{So, logically, motion on hills, Newton's Laws, and Conservation of Energy are interconnected; and we should be careful not to 'explain in a circle'. Nevertheless young people who point out any connection here deserve high praise and should not be worried with those doubts of logic.}

Galileo's stroke of genius Friction spoils our downhill-and-uphill experiment and makes it unconvincing. Galileo, three and a half centuries ago, devised an almost frictionless version of the experiment. Instead of a ball falling by rolling down a hill, he used a ball that falls by swinging down as a pendulum. Pupils should certainly see it.

Demonstration 64 Galileo's Pin-and-Pendulum Experiment

Though this would be better, if successful, as a class experiment, we suggest it should be a demonstration. The experiment needs very firm supports for the pendulum and the 'pin' that changes the pendulum's path, or the experiment will be spoilt by energy leakage.

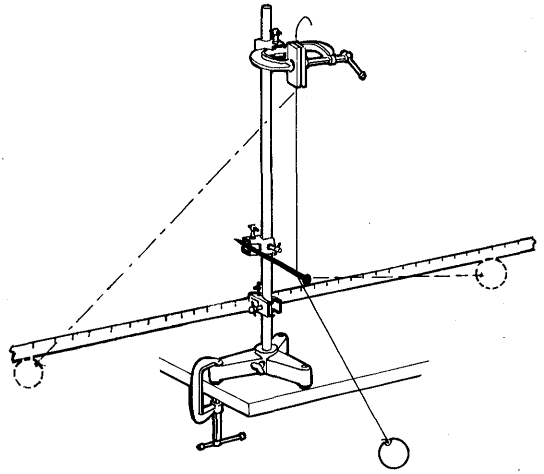
We hope this will not be shown as a set piece that is taken out of a cupboard ready made. It should be something that teacher or pupils can rig up when it is needed.

Apparatus

simple pendulum	item 527
large round nail (15 cm), or dowel rod	10H
retort stand	503/504
clamp and 2 bosses	505/506
2 metal strips and jaws	121
large G-clamp	44/2

Preparation

The best arrangement for clamping the pendulum thread firmly is to place it between two metal plates acting as jaws. For success it is essential to have a massive and very rigid support for the pendulum and for the 'pin'. Otherwise energy is lost and the demonstration 'fails' (!) visibly. Use a G-clamp to hold the retort stand firmly on the table. And tighten all other clamps fully.



Procedure

Set up the pendulum. Arrange a string or metre ruler to mark a horizontal line.

Pull the pendulum bob out to one side until it is level with that line and let it go. Pupils watch the pendulum swinging without the 'pin'. Except for the effect of air friction the bob rises to the same level again and again.

Then install the 'pin' (nail or dowel) so that it interrupts the swing. *Pupils watch to see whether the bob still rises to the level from which it started.*

Class Expt 64X Pin-and-Pendulum
(OPTIONAL)

If pupils try this as a class experiment it may not be so convincing, because loose clamps, etc., will take away energy. However, they may enjoy doing for themselves a great experiment that is more than three hundred years old.

And they will try reversing the motion so that the pendulum swings from a steep arc of small radius to a shallow arc of large radius.

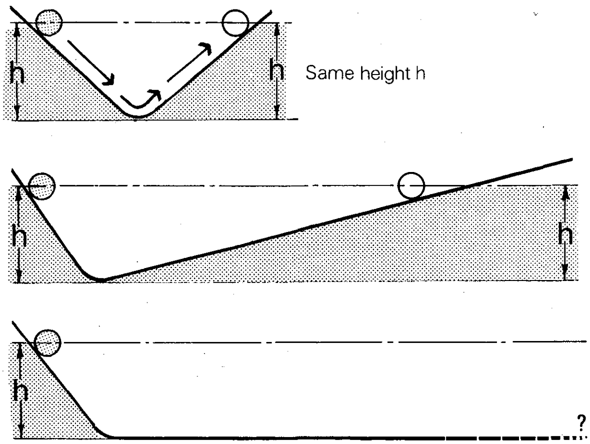
They will also have fun starting the bob too high so that it wraps the thread round the nail—harmless but not fruitful.

Discussion. Newton's First Law of Motion

Galileo's thought-experiment Galileo carried through a thought-experiment which we should describe to pupils. He was sure that a ball rolling down a hill would roll up an opposite hill to the same height—except for friction. He thought about a ball rolling down a hill and then up an opposite hill which had *no slope at all*—a horizontal road, in fact. He thought the ball would go on and on along that 'opposite hill' which was just a level plane—or perhaps a great circle round the Earth.

Some pupils will arrive at that if they are given the original problem and a little help:

Suppose a ball rolls downhill and up an opposite hill as in this picture, without friction. How high would you expect it to rise? Now suppose the opposite hill does not slant up so steeply but is like this. What would happen? . . . And now suppose . . .



Remember that the delight of making one's own theoretical discovery in a matter like this is well worth the time taken for pupils to think and guess. We hope teachers will accept the sorrow of having to leave the question unanswered for many pupils.

Introducing Newton's First Law We consider it essential for pupils to see a real experiment as an exhibit of Newton's First Law of Motion—and not just hear about one. See Demonstration 65a, b, c below.

{This is a turning-point in the development of physical science. Galileo suggested the idea of motion continuing, by his thought-experiment; and Newton stated it as a basic assumption when he began his great 'explanation' of the Solar system.}

{In Newton's use, Law I was not just a special case of Law II, but a startling denial of the general opinion that any planet—or the Moon, or a comet—must have a continuing force *along the orbit* to keep it moving.}

{Although in this age of satellites pupils may have heard about motion going on and on, it is still a strange idea to many. Blatt* puts 'the first "commonsense" law of motion' thus:

> 'A body with no force acting on it either maintains its state of rest or comes to rest very quickly if it was moving initially.'

That is just what an intelligent person would think if he watched things in ordinary life. Friction is all around us. No wonder the Greeks arrived at quite intelligent laws for motion controlled by friction.}

{Newton's First Law applies to cases where there is *no force*. That either means no force at all (including no friction)—as in the case of a moving object far away out in space—or it means motion with no *resultant* force.}

{Putting in that word 'resultant' makes Newton's First Law sound more sensible. When we have some object coasting along the level table at constant velocity, with no friction, it is not true that there are no forces acting on that body: there is its full weight (gravity pulling on it as much as ever) but that is balanced by a push up from the table. Again, we could have an object moving along a rough table with plenty of friction dragging on it and still have a case of Newton's Law if we kept pulling the object forward with a force that just balanced friction.}

{We should be careful not to give pupils the idea, now or later, that Newton's First Law of Motion is restricted to cases where there is no friction!* We know that it applies to any case where all forces balance out to zero resultant.}

{Many a physicist reverses that statement and says that when he sees motion continuing constantly he knows that there must be zero resultant force—in fact, that might be taken as a definition of zero resultant force.}

Hovercraft for Newton's First Law We can demonstrate Newton's First Law, which Galileo foreshadowed in his thought-experiment, by a 'Hovercraft' experiment with a block of solid carbon dioxide.

We consider this experiment so important, as well as so delightful, that we hope teachers and their schools will be willing to take the trouble and bear the cost of obtaining a large block of 'dry ice' or solid CO_2. (The small quantities of solid CO_2 obtained from a portable cylinder will *not* suffice for this.) A large block will be delivered to the nearest railway station if the suppliers are notified a week beforehand. It will cost several pounds and there will be some trouble of telephoning to order it and of fetching it from the station; but the demonstration is very impressive. See the list of supply depots in the apparatus appendix.

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

A fuller treatment of Newton's Laws will come in Year 4, so this demonstration can be postponed if time is short. Nevertheless, early preparation will yield good fruit in Year 4. It will enable other work in Year 4 to have the full time that it deserves. Year 4 proves to be a full year of physics.

Furthermore this is a demonstration that pupils who will finish their physics at the end of Year 3 should not miss.

* Messel, H. (ed.) (1960), *Selected Lectures in Modern Physics*, Macmillan.

* There is a danger—now that so many teaching schemes use friction-compensated trolley experiments and 'hovercraft' demonstrations to illustrate Newton's Laws I and II—that a new generation will grow up thinking that neither of those Laws applies where there is friction.

Demonstration 65a, b, c
Frictionless Motion: Hovercraft

We consider it essential for pupils to see one form, a or b or c, of this demonstration, and not just hear about it.

Demonstration 65a The Coasting Iceberg

Apparatus

1 large block of solid CO_2

From Edinburgh CO_2 kit	item 95
large glass plate	95A
4 wedges for levelling plate	95B

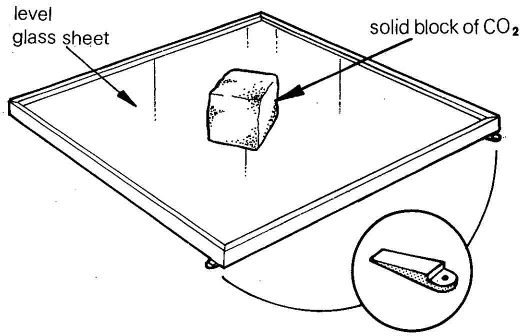
window cleaning liquid (or methylated spirits) for cleaning plate
blanket or newspaper for wrapping block
piece of thick metal plate ($\frac{1}{2}$ to 2 cm thick, preferably Al or Cu, for ironing the base of the block)
gloves

Preparation

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

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

Cut a block roughly, with a hacksaw, say 15 cm by 15 cm by 10 to 15 cm. Make one face of the block flat by sliding it on the thick metal plate. *Test the levelling of the glass sheet with the block itself.* Wrap the block in blanket or newspaper to keep it from collecting water until it is used.



Procedure

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

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

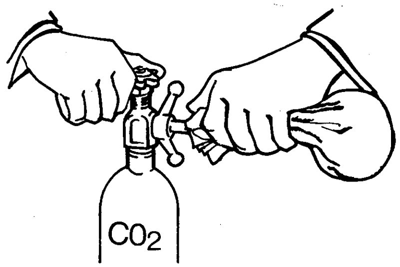
If the block rests for long at one place on the glass sheet it will cool the glass so much that moisture will soon condense there and that will make a sticky patch which will spoil motion across it.

Demonstration 65b Ring Hovercraft

If the block of solid carbon dioxide cannot be shown, this is an adequate alternative.

Apparatus

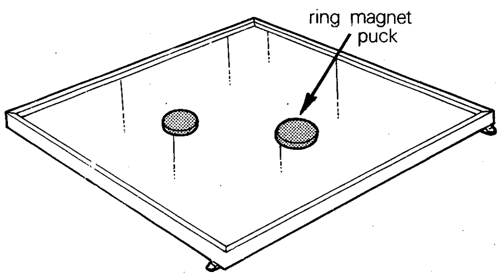
From Edinburgh CO_2 kit:	item 95
large glass plate	95A
4 wedges	95B
2 magnetic ring pucks	95C
2 brass ring pucks	95D
1 reel of magnetic strip	95G
window cleaning liquid (or methylated spirits) for cleaning plate	
CO_2 cylinder	19/1
1 dry ice attachment	19/2



Enough solid CO_2 to maintain the ring pucks can be obtained from the special CO_2 cylinder with dry ice attachment. Put the cloth that is provided, folded to double thickness, over the nozzle. A few seconds' burst of CO_2 will provide enough solid CO_2 'snow'.

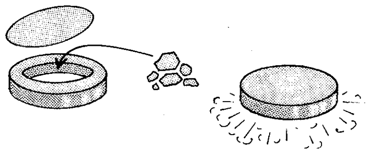
Preparation

Clean the large glass plate very carefully and level it. This is essential.



Procedure

Place a puck over a small piece of solid CO_2 (a few cm^3). The lid traps the evaporating CO_2 gas and after a moment or two a stream of gas runs out



under the edges of the ring, keeping the puck supported so that it moves with almost no friction.

Try a brass puck alone. Give it a push and let pupils watch it coasting. To show that it is not just coasting downhill, give it a push the opposite way.

Then use two brass pucks so that pupils see violent collisions. Then show two magnetic pucks making an elastic collision.

{**Photoflash pictures** In Year 4 we suggest taking photoflash pictures of two magnetic pucks colliding, so that pupils can analyse the motion and look for Conservation of Momentum. That is beyond the scope of the present year.}

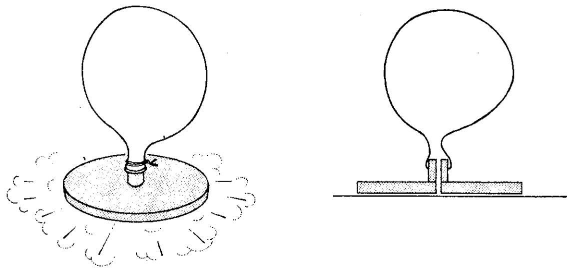
Demonstration 65c Frictionless Motion
(Economy Alternative: NOT RECOMMENDED)

The ring pucks of 54b can be supported by a thin layer of polystyrene beads spread over the glass sheet. There is little friction but the beads escape and are a great nuisance. They cling easily to hair and wool clothes and can be a hazard on the floor. Only if it proves quite impossible to show CO_2 support should this alternative be used.

Class Expt 66 Home-made Hovercraft. Poor Man's Puck *(OPTIONAL EXTRA)*

A delightful qualitative experiment for class or home can be done with an ordinary balloon supplying a simple puck.

Drill a small hole in the centre of a smooth 15-cm disc of plywood. Glue to that a short piece of tubing of any kind that the balloon's neck will fit. Inflate the balloon; attach it to the tube and place this puck on any smooth table.



Inertia

Instead of just thinking of *motion* continuing when there is no resultant force, we might concentrate on the idea of a *massive body* continuing to move when there is no resultant force. Then we think of the body as having some property in it of wanting to go on moving, and of being difficult to stop moving. It is the property that we call *inertia* —though giving it that name is little help to pupils towards understanding the idea of mass.

We can help pupils to develop a feeling for inertia by asking them about moving things:

'Can you stop a moving goods wagon that is running along a level line after being shunted? . . . Yes, but can you stop it easily or at once? Can you stop the moving object in the frictionless demonstration you saw, immediately, with no trouble?'

Pupils can gain a *practical* feeling for inertia by pushing two large tin cans, one full of sand, the other empty, hung as pendulums.

Class Demonstration 67 Feeling Inertia

Apparatus

2 tin cans
sand
string

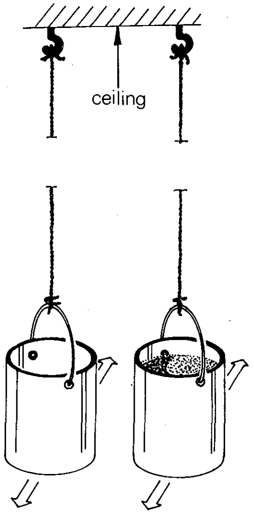
The tin cans should look identical. Treacle tins will suffice; but the larger the cans the more effective the experiment.

Preparation

Suspend the cans with strings as long as possible. Long strings from the ceiling are best of all. Leave one can empty, fill the other with sand.

Procedure

Pupils try pushing each can in turn to feel the force needed to give a can some motion. They also try stopping the cans when they are moving.

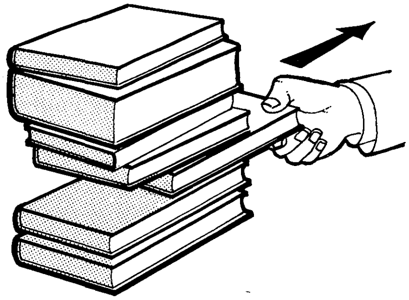


It may be good to ask why safety belts are worn in cars, and continue that by asking what happens to the non-belted passenger on the back seat when a car suddenly starts, stops, or goes round a sharp corner. That could lead later to a discussion of motion in a circle—but do not embark on that now or the class will get seriously entangled with centrifugal force.

Inertia tricks There are some traditional experiments that illustrate inertia, such as the following. To young people they are delightful tricks rather than exhibits of inertia so they are suggested now for fun with the hope that explanations will be postponed.

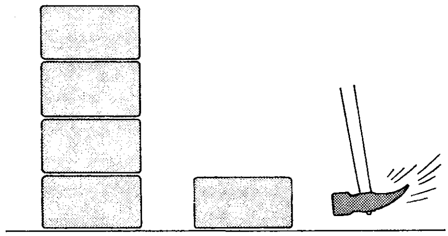
Expts 68 Tricks that Illustrate Inertia *(OPTIONAL)*

(1) *The Simplest Trick.* Pull one book out from the middle of a pile of books.



(2) *A reverse form of (1).* Push a wooden brick *in* at the bottom of a pile of similar bricks.

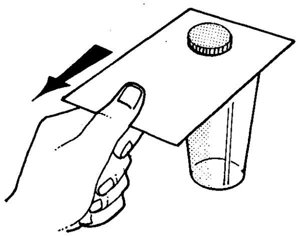
The bricks should be smooth blocks of wood, say 10 cm × $7\frac{1}{2}$ cm × 5 cm high with their edges and corners rounded. Build a pile of 4 bricks, then push a fifth brick quickly straight at the bottom brick of the pile. The fifth brick goes in and the bottom brick goes out.



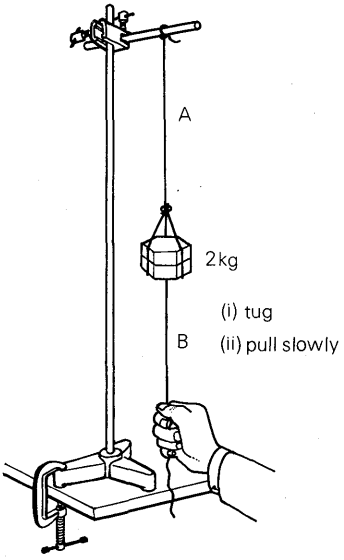
This is most dramatic if the fifth brick is projected along the table towards the pile by a 'croquet hit' from a small mallet.

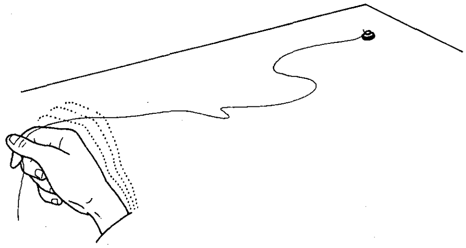
Repeat, using the ejected brick as projectile.

(3) *A Coin on a Card on a Glass.* Whip away the card and the coin falls into the glass.



(4) *Breaking Threads.* A thread is hung from the bottom of a load which is itself hung on a thread—so that a steady pull on the lower thread breaks the upper thread but a sudden snatch on the lower thread breaks the lower one. To make the underlying paradox specially clear, use the same kind of thread throughout, but have a single upper thread and two or three strands in parallel for the lower thread.





(5) *Breaking a Thread.* A very small mass (1 gram) is tied to the end of a thread and placed on the table. Although the breaking strength of that thread is many hundreds of grams and it carries only one gram loose on the end, it can be broken by a *very sudden* jerk of the other end. (Strong sewing thread needs 5 or 10 grams for this to succeed.)

{These tricks do involve a true inertial property: that if a force acts on an object for a short time, the object does not acquire much motion or move far. But some of these also involve properties of friction.}

{In (1), the book that is snatched out exerts forces by means of friction, on the books above and below it. If the operator snatches the book with sufficiently big *acceleration*, the force that would be needed to give the *same* acceleration to the books above is bigger than limiting friction; so there is slipping and the pile above does not stay with the book that is being snatched. However it does not completely fail to follow; there is friction between the surfaces in relative motion and the pile above the snatched book does get going, though not so fast as the snatched book. When the snatched book is out, clear of the books above, the latter can fall; so they follow a little farther still, while they are falling through the thickness of the snatched book.}

{If one were prepared to spoil the fun of the trick by going into details, one could point to the final position of the 'upper books'—a short distance ahead of the 'lower books'—and make this a good demonstration of inertia. Unfortunately, one cannot increase the inertia of the 'upper books' without also increasing the available friction forces, so that the critical acceleration for successful snatching is unchanged.}

{All this makes a good discussion for advanced physics but throws doubt on the use of these tricks here.}

Rocket Ship Propulsion? Ask:

'What keeps a satellite going once it is in orbit and the rocket motors are turned off?'

Here again, discuss the motion continuing and avoid any discussion of central forces. And then:

'Suppose a space ship has its rocket motor turned off *far out in space, well away from the gravitational pulls of the Earth and the Sun,* will it keep going? Why?'

Perhaps the right question to ask is 'What is there to stop it continuing in motion?' Once that leading question has been asked the First Law may seem more acceptable.

FORCE AND MOTION: INFORMAL TREATMENT

Although we are sure this is not the stage for a formal study of Newton's Laws, we do suggest a trolley experiment on force and motion. Pupils should now be ready to pull a trolley along a level runway with various forces, measure speeds with tape, and look for acceleration in their tape-charts. Accelerations should remain measured in *cm/tentick in each tentick.*

Then a careful investigation of the relationships between force, acceleration, and mass will come in Year 4.

It is important not to spoil the ground for Year 4 where there is possibly too much work with trolleys—by labouring trolleys now. Therefore we suggest only one experiment: FORCE versus ACCELERATION.*

* We suggest pupils will like to use the symbol Δ in the discussions of acceleration ahead if we tell them that Δ means 'change of' or 'increase of'. It is a Greek capital D for difference. They can use a for acceleration, v for velocity (at this stage, just speed), and t for time-of-day and write for acceleration:
$$a = \frac{\Delta v}{\Delta t}$$

Class Expt 69a Pulling a Cart with a Steady Force: Investigating Acceleration with Trolleys

Apparatus

8 to 12 runways	item 107
8 to 12 dynamics trolleys	106/1
elastic cords for pulling trolleys (3 per trolley + spares)	106/2
8 to 12 ticker-tape timers	108/1
8 to 12 rolls of tape	108/4
8 transformers	27

The elastic cords should be 15 to 20 cm long, stretched to a total length about 30 cm when in action. There should be as many runways and timers, etc., as the lab can accommodate. Ideally, pupils should work in pairs. If more than four pupils have to share a runway, the experiment loses its value in learning for understanding by doing one's own experiment—drill replaces independent working and thinking. Also the experiment drags out in time as each pupil in turn takes his tape record.

Preparation

Make sure the runways are swept clean of any small particles. The smallest irregularities have adverse effects on the results.

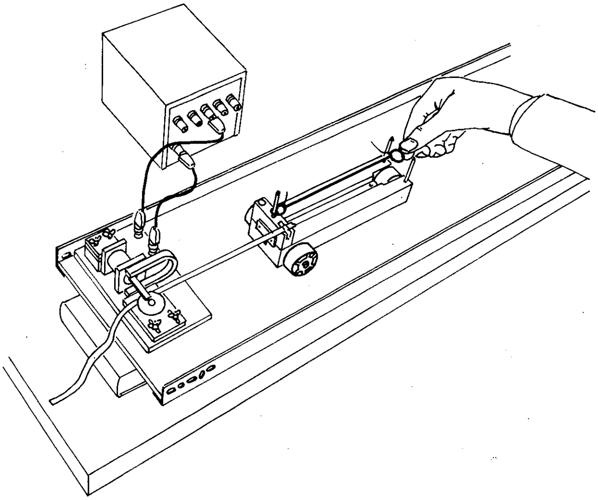
Make sure the wheels of each trolley are clean. (At the beginning of the year it is good to flush out old oil with solvent and apply a little new oil.)

The tape timer rests on the board near the top end.

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

Procedure

For this first trial, let pupils use a level runway, without discussing friction-compensation. One pupil pulls the trolley, trying to maintain a steady force, while the trolley drags the tape through the timer. To maintain a steady force the pupil attaches the elastic cord to a rod at the *back* of the trolley and stretches it so that the other end of the elastic is held level with the



leading end of the trolley. If this is maintained it serves as a constant pulling force. (In Year 4 we shall consider that a 'unit' of force.)

At first this may seem hopelessly rough, but skill is quickly acquired. Meanwhile a partner takes charge of the vibrator and tape. For the start, he holds the trolley still and gives a signal to the first pupil when he releases it.

Some prefer to put a pencil or dowel through the eyelet in the front end of the elastic and hold that level with the front pegs in the trolley, but of course not touching them.

Once the apparatus is assembled, it takes a short time for *each pupil to obtain his own tape.*

Pupils cut their tapes into tentick strips. They paste the strips side by side to make a tape-chart.

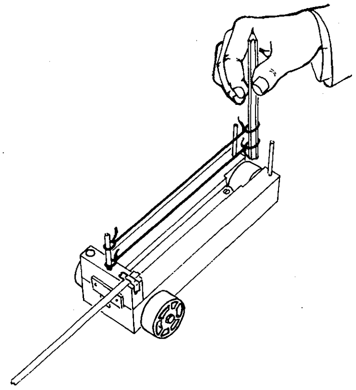
(If tentick lengths prove too long for the page when the trolley is moving fast, five-tick lengths may be used.)

In trying to see what kind of motion the trolley had *pupils should use only the part of the tape for which they consider the pulling force was kept fairly constant.* This probably means disregarding the beginning and the end sections.

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

Now suggest trying different forces acting on the trolley.

Class Expt 69b Pulling with Different Forces



Apparatus

Runways, trolleys, etc., as before (Expt 69a) with extra elastics.

Procedure

Pupils already have a tape-chart for a trolley pulled by one stretched elastic. Now they try two elastics pulling in parallel; and then three elastics. They make tape-charts and look for a relationship between acceleration (slant of tops of strips) and of pulling force.

Again, that first try with different forces should not be complicated by concern over friction. However, friction will obscure the simple proportionality to some extent. So teachers should now discuss the friction difficulty and suggest compensating by tilting the runway.

Class Expt 69c The Careful Experiment on Force and Acceleration

Pupils repeat the last experiment with *friction-compensated* runways. At most, 4 pupils per runway.

Apparatus

Runways, trolleys, etc., as for Expt 69b. Also books or wooden block to tilt the runways for friction compensation.

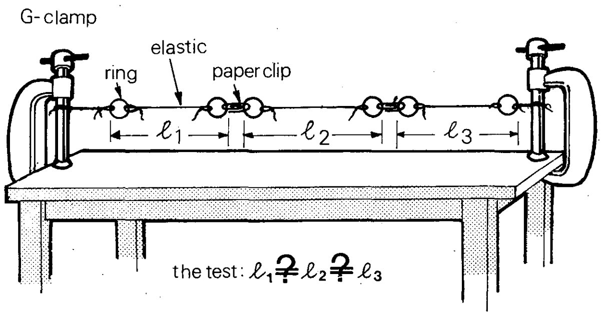
Preparation

Unless pupils are to be satisfied with very rough indications of accelerating forces, the three elastics used for pulling a trolley *must* be new and *must* be tested for equality of tension at standard stretch. The method of manufacture does not ensure this; furthermore, the force constant changes with age, and may change with use.

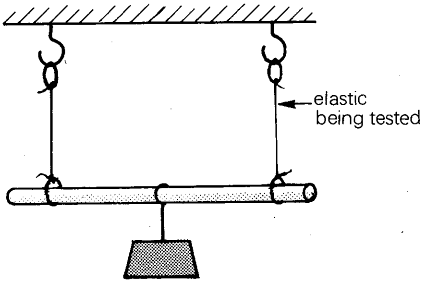
Even with new elastics the stock should be tested and sorted out into sets of three which all exert the same pull at standard stretched length. (The unstretched lengths need not be exactly equal: all that matters is their equality in use.)

Suggested methods of testing:

(i) Make a 'daisy-chain' of several elastics, joining them with paper-clips. Lay the chain on the table, stretch it, and measure the lengths of elastics, *while stretched*. Or,



(ii) Test pairs of elastics by hanging a bar on them, loaded at its mid-point. (See the sketch.) If the bar is not horizontal, the elastics are unequal.



Procedure

Pupils find the tilt needed just to keep the trolley moving down the slope at constant speed (once given a start). They must make their test *with the trolley dragging tape* because the tape adds some friction.

Pupils should satisfy themselves that once the trolley is started the distance from one dot to the next is nearly constant for a considerable run.

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

Then pupils repeat Expt 69b with their friction-compensated runways. They pull the trolley with one elastic, then with two elastics in parallel; and, if time permits, with three in parallel.

Each pupil makes a tape-chart for each of his trials.

Ask pupils what story about motion and force they can extract from their tape-charts.

More careful measurements (and *graphs*) should wait until Year 4. The experiment here is an introductory one for a general look. It should not drag on until it is worrying or tedious. It should only go on as long as it is fun. Having the tape-charts to take home will help to maintain enthusiasm.

Free Fall

Some pupils may have already investigated the motion of free fall with stones tied on a string (Home Expt H62) and most have general ideas about the motion. Now is the time for experiments on falling bodies, quantitative as well as qualitative.

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

Nevertheless, the motion of free fall with its constant acceleration is surprising and important; so, if time permits, pupils should investigate the motion for themselves.

Furthermore, this can help to solve a problem of equipment and space. If the lab has 16 timers but only 8 trolley runways, half the class can try timing free fall while the other half times a trolley.

The *type of motion* should be the important thing now, not the *actual value* of g, which can be measured in Year 4.

Free fall As a first casual look at free fall, each pupil should drop some object, such as a stone, and watch it fall.

Ask whether the falling object does go faster and faster. When pupils say 'yes', ask whether they really saw it moving faster and faster; whether they really know that or just think they ought to say so. Even if they admit they did not see it gaining speed, raise a question:

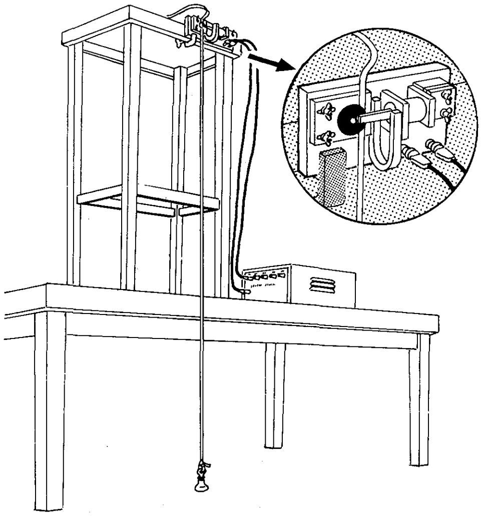
> 'The stone started at rest with no speed of fall. Later it was moving. What can you say about the motion, just from that?'

Then suggest an attempt at tracking the falling motion with timer and tape.

Class Expt 70 Investigate the Motion of a Falling Object: Free Fall with Timer and Tape

Apparatus

small objects such as stones, 1 for each pupil	
16 ticker-tape timers	item 108/1
16 rolls of ticker-tape	108/4
8 transformers	27
Sellotape	
16 G-clamps	44/1



Preparation

For part *(b)* set up each timer high above the floor, to provide a reasonable length of fall. A table top is too low. The top of a stool standing on a table is suitable.

If the falling object pulls the ticker-tape through a horizontal vibrator on the top of a stool, there will be friction troubles. It is better to clamp the vibrator on its side, against the edge of the stool or table, with the tape guide projecting over the edge.

It will save time if suitable lengths of tape have been cut from the reel beforehand, ready for use. Each pair of pupils will want several lengths, because a rehearsal or two will be needed.

Procedure

a. Each pupil watches the free fall of a small stone or other object. Discuss that briefly.

b. Each pair of pupils attach a brass weight or other suitable object to the front end of the tape, using Sellotape. They let it fall freely to the floor, pulling the tape through the timer. After rehearsal, each pupil makes his own tape record.

Each pupil makes his own tape-chart of ten-tick strips.

A picture gallery of tape-charts will help to show up the essential characteristic of the motion.

At this stage it is best to keep this a very rough measurement to see the *type of motion.* The experiment may be repeated in Year 4 to obtain a value for g.

All falling objects . . . *We* know that all fairly dense objects fall with the same acceleration. But then *we* have heard the 'Leaning Tower' story and we have enjoyed trying the experiment. But the result is a surprise to many young people —and many adult non-scientists too—an amusing surprise, even a delightful one. Galileo thought it surprising and important and Newton used it; but it sank to the unimportant position of being taken for granted for over two centuries, until Einstein saw it as a great property of nature, and took it as a basics for General Relativity.

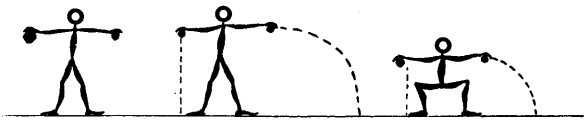
Every pupil should try the experiment, in simplest form, with no prompting towards the answer.

Class Expt 71 Falling Objects— The 'Leaning Tower'* Experiment

* Historians insist that Galileo never gave that public demonstration—if he had done so, letters describing it with surprise or anger would have travelled across Europe, and none have been found. Yet it is still popular with writers and enjoyed by many a young scientist.

Here we admit it is only a story but use the phrase as a name for a great fact of nature, essential in our knowledge of physics and the basis of General Relativity. Galileo certainly knew that fact. He even commented on the small but noticeable difference between an iron ball and a wooden ball: in a 30-metre fall the iron ball won by a hand's breadth.

Ask every pupil to release a heavy object and a light one, side by side, simultaneously. These may be coins or stones or any pieces of fairly dense material.



listen for simultaneous arrival

Dropping them from shoulder height in the class room will suffice; but a repetition from a much greater height at another time and place makes an excellent extension. The latter should not be a demonstration by a teacher; it should be an experiment by pupils or a demonstration by them at home.

Preface this experiment by asking what will happen. For once in the way, it is safe and fair to start with a strong incorrect impression, that one expects the heavier stone to fall faster—as the medieval Aristotelians taught. (They were, perhaps, foolish in their rigid unthinking repetition of Aristotle's statements—teaching by book instead of by real nature. Aristotle himself was a very wise man, almost certainly writing about objects falling against air resistance, with terminal velocity.)

After discussion and votes about what will happen, pupils should try dropping a variety of things.

It would be a mistake to offer special gadgets for simultaneous release. Pupils who rely on coordination of their two hands and brain will learn the better—and the reputation of science may gain.

Some pupils will try much less dense objects such as a sheet of paper (open, then crumpled), or a table tennis ball. We should not discourage such excursions into the region where the simple story fails. That is all part of scientific knowledge and the exceptions will stimulate discussion.

Many will be surprised at things falling with the same motion irrespective of mass; and they will suggest that the lagging of table tennis balls, scraps of paper, etc., is due to air resistance.

Comment on '*g*' being the same for all:

> 'This is strange. I can feel the heavy thing being pulled with a big force by the Earth. Why doesn't it fall faster than the light thing? That must be because the heavy thing also has a lot of stuff in it that needs more force to make it go faster and faster. The bigger thing has more WEIGHT (the Earth pulls more on it), *also* more MASS—more stuff to be moved!'

At all costs avoid, now and later, the phrase 'overcoming inertia'. Inertia is never beaten: it is always there.

Galileo: the fable and the thought-experiment We might tell pupils (as in *Pupils' Text 3*):

> There is a story, unfortunately untrue, that Galileo, the great Italian scientist and teacher who wrote about force and motion three and a half centuries ago, gave a wonderful public demonstration which surprised and shocked those who saw it. The story says he climbed to the top of the Leaning Tower of Pisa and dropped a little iron ball and a big cannon ball side by side. Everyone was astonished at the result, and some people were angry. They expected a big ball which weighed 10 times as much to fall 10 times as fast.
>
> (Long before that the Greek scientist Aristotle had said that a heavy object would fall much faster than a light one. But he was thinking of things falling against plenty of friction in air or in water and his idea was probably quite sensible.)
>
> Galileo did not make that public demonstration; but he certainly knew the remarkable property of falling objects that you have just seen; and he taught it to people. He also invented a 'thought-experiment' to upset people who were teaching Aristotle's statements blindly. Here is the kind of story he told:
>
> > 'Suppose I let three equal bricks fall to the ground, starting together. They are all alike. They will all fall neck and neck with the same accelerated motion and all arrive together.' His opponents agreed.
> >
> > 'Now suppose I repeat the experiment but first I chain two of the bricks together with a light invisible chain, so light that it isn't really there. Then, I suppose I have a double brick and a single brick. According to Aristotle, the double brick will fall twice as fast. Do you think that likely, just because that little chain is there?'
> >
> > 'Ah yes,' one of his opponents might say, 'one of that pair of bricks gets a little *ahead* and drags the other down faster than the single one.'
> >
> > 'Oh, I see,' Galileo would reply, 'one of the pair gets a little *behind* and drags the other backward making it fall slower!'
>
> Galileo made his opponents furious by making their arguments look foolish like that.
>
> **Air resistance** Galileo suggested a reason why a wooden ball was left a little behind an iron ball, and a scrap of paper flutters down much more slowly. He said that the less dense things are simply delayed more seriously by air resistance. He had no vacuum to show what would happen without any air; but he felt so sure that he predicted that a scrap of lead and a scrap of sheep's wool would both fall equally fast in a vacuum.
>
> Soon after that, Newton, who had a pump to make a vacuum, tried the experiment with a gold coin and a feather. Try that yourself.

Guinea-and-feather experiment Most laboratories have a 'guinea-and-feather demonstration', a long tube that has been pumped out and sealed. That is certainly something that pupils should see; but it is much better if they see the actual pumping-out done, and better still if they attend to the matter themselves.

(Those of us who watched a teacher turning the great tube over and trying several times to get the feather to start without sticking electrostatically, remember a feeling of doubt. We wondered whether it was a great demonstration or rather a swindle. That would never happen in the pupil's own hands: he would have as firm a conviction as that teacher did in earlier days.)

Use a motor-driven vacuum pump. There should be no mystery about that machine or sacred treasuring of it that discourages frequent use. Those are now more common in physics research laboratories than balances for weighing. They are expensive but quick, capable, robust, and long-lived; and maintenance with fresh oil is easy.

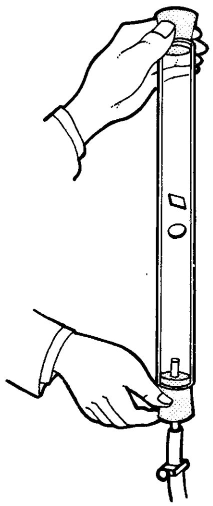
Therefore we urge teachers to make the guinea-and-feather experiment a *class* experiment. Pupils should be provided with a fairly short glass tube. A piece of metal the size of a $\frac{1}{2}$p coin* serves as the 'guinea'.

*A 2p coin has been suggested, but that is large enough to spoil the experiment by pushing the 'feather' down with it.

Class Expt 72 The 'Guinea-and-Feather' Experiment

Apparatus

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



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

Pupils work in groups of four.

Procedure

The pupils put a small coin and a scrap of paper in their tube. They close the tube with the bungs.

One pupil inverts the tube quickly, while the others watch.

Then each group in turn brings their tube to the pump. Pump out their tube for them. Remind them to listen to the pump—they can hear the air being ejected in decreasing amounts. Seal the tube with a clip on the short rubber tube.

Each pupil in the group should try inverting the tube quickly. Then they should let air in again and watch once more—that is their best chance of seeing how great the difference is.

Demonstration 73 Strength of the Earth's Gravitational Field *(OPTIONAL NOW)*

From time to time pupils meet a question concerned with the WEIGHT of some object, the pull of the Earth on it. That force is measured in newtons. Until we discuss Newton's Second Law in Year 4, the unit of force, a newton, will remain an arbitrary unit marked on instruments—like a metre or a foot for length. Even in Year 4 when a question involves the weight of something we should remind pupils that 'the Earth pulls with a force of about 10 newtons on each kilogram'.

In saying that, we are really stating the Earth's *gravitational field strength.* If teachers wish to give this very useful concept of field strength an early start, they may like to show a simple demonstration now. However, if it seems rather pointless, to either teacher or pupils, it is best postponed.

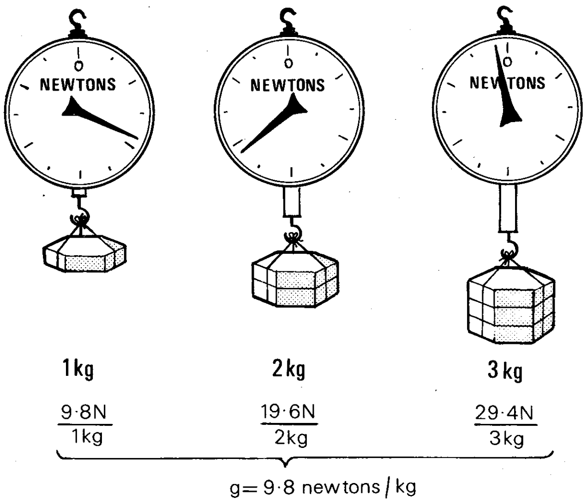
Apparatus

1 demonstration spring balance in newtons	item 212
several 1-kilogram masses	32

Procedure

Hang 1 kilogram on the spring balance. This needs no comment. (Decide whether to call the reading 10 N or 9.8 N throughout this set of tests.)

Hang 2 kilograms on the balance, then 3, then 5. In each case take the reading and explain that we can calculate the strength of the Earth's attracting field, 'like the price of an orange'. The



strength is the pull on each kilogram ('the price is the payment for each orange, however many oranges you buy'). Therefore again and again, dividing FORCE by the number of kilograms (MASS) we have a FIELD STRENGTH of 10 (or 9.8) newtons/kilogram.

This is not the stage at which to give further teaching about WEIGHT and MASS. That will be better in Year 4; but acquaintance now with the idea of FIELD STRENGTH will prepare for an understanding of magnetic and electric fields ahead.

Projectiles: Falling Objects with Two Motions

Pupils should see and understand the principle that Galileo arrived at—which formed such an important, perhaps subconscious, basis for Newton's treatment of accelerations and forces as vectors that add independently. That is, the principle that a body can have several separate motions, which are independent of each other. It is the principle of superposition which holds in mechanics, electromagnetism, optics* . . . though it must be modified in Special Relativity.

{**Teaching Vectors?** In physics teaching at this stage, vectors often acquire a bad reputation. Many teachers consider them simple as well as important; but class after class complains they are difficult. That surprising reaction may be due to pupils' seeing no clear use for them; it may be due to a swift move from 'obvious' addition to confusing subtraction—where a rule of thumb takes charge for problems on ground velocity when flying in a cross-wind. (Why should young scientists be dragged through those, when a pilot will learn it so quickly for his job? This is somewhat like the tradition of 'vernier callipers for all'.) And perhaps some prejudice filters down from upper levels where mathematicians are keen to expand into a sophisticated treatment of vectors before pupils are ready. On the other hand, some of the new mathematics teaching provides capable happy acquaintance with vectors; and teachers may want to make use of that link with mathematics as soon as it is available.}

{Whatever the cause, vectors may be unpopular with some classes; so we suggest vectors should not be taught now—except of course to those who ask.}

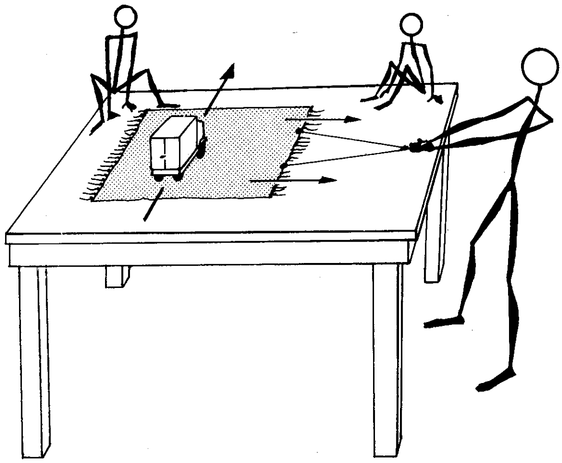
If some pupils want to know about adding motions we might suggest an experiment, thus:

An object can have two separate velocities: it can be moving at a certain speed due East, and with another speed due North; and having one motion does not interfere with its progress in the other motion. Try adding two real motions:

* But when it does not hold—as in transistors, or in our own ears, or in a crystal over-driven by laser light—the different behaviour is not unwelcome: it is very important.

Put a small rug on the table—or, better still, a mat of translucent plastic, so that marks on the table underneath are visible through it.

Place a clockwork toy on the rug and let it crawl steadily westward while you drag the rug steadily northward.



The toy's progress northward (due to your dragging the rug) is quite independent of its crawling motion eastward. The rug carries it just as far northward in a given time whether the toy is also crawling or not.

To an *observer sitting by the rug* the motion of the crawling toy is just the same whether the rug is being dragged or not.

Now show the progress of the toy as an *outside observer standing beside the table* would see it (relative to the table. Draw a scale diagram of velocities as follows. On paper, draw an arrow northward to represent the distance the toy crawls in one second. From the starting point, draw an arrow westward to represent the distance you drag the rug in one second. To find the 'sum' of the two motions, complete the parallelogram (here, a rectangle) and draw the diagonal from the starting point. The diagonal represents the toy's total or resultant travel in one second. You can see that if you try the actual experiment and watch how the toy is carried along that diagonal.

Or you can draw one arrow first, then continue with the other arrow, tail-to-head from the first one. That pattern shows the toy making first one motion and then the other. The final position of the toy on the table is the same whether one motion happens first, then the other, or both motions happen at the same time.

{**A further note to teachers** The two motions do not interact. That seems to us obvious and necessary. We consider it must be so.}

{Yet in fact this is something we have discovered about the world we live in, and generalized, and now take for granted. We learned it when we let something roll or slide or drop in a moving railway train—or, as Galileo pointed out, when we throw something across the cabin of a ship sailing steadily on a smooth lake. If we lived in a different world—a whirling centrifuge or an accelerating rocket—we might not find motions obeying that simple rule. (And we now know that, even in our ordinary world, very large velocities big fractions of the speed of light, do show different properties to different observers.)}

{Some pupils easily take the simple independence and addition property of velocities for granted; and we should encourage that.}

{Accelerations have the same additive properties; they too are 'vectors' that can be added by the parallelogram construction, according to which the 'effect' of two vectors together is the same as if first one occurred and then the other, in succession.}

{Forces too are vectors that add geometrically and do not interfere with each other. We have now made a deeper statement about the world we live in, because in professional physics we judge forces by the motion they produce. So we are now saying that when several forces act on a body each produces its own effect on motion, and one force does not interfere with the motion produced by another force. The total motion is simply the (geometrical) sum of all the separate motions that the separate forces would produce.}

{All this applies to the world of Galilean Relativity, in which forces and their effects can be superposed—the world for which Newton constructed his mechanics.}

Programme Simple addition, *and subtraction*, of vectors will be needed in Year 5; but the need and the method will be obvious to pupils then. For now, we suggest only an informal glimpse—without the formal name—in projectile motion.

Projectiles Let pupils discover for themselves that a stone falls with the same accelerated motion whether it is moving horizontally or not.

The two motions are completely independent, and that enabled Galileo to examine the *horizontal* motion of projectiles, which is free from any accelerating force. So, in an indirect way, he knew Newton's First Law from experiments with projectiles.

(When air resistance becomes important, as it does for objects of low density and for high speed, this simple story is masked by varying effects of air friction.)

Class Expt 74 Two Motions

Apparatus

Stones or other small, fairly dense, objects for pupils to drop and throw.

Procedure

Start by asking questions:

'What happens when you throw an object out sideways (horizontally)? As soon as you let go, it starts to fall; but what happens to its *horizontal* motion? Does that horizontal motion upset the vertical motion?'

Then each pupil tries the experiments sketched. (See note on p. 146.)

a. As in Expt 71, the pupil releases a small stone and a larger one side by side to fall. (He should just use his two hands and his brain to co-ordinate the releases, and not a special gadget.)

b. The pupil releases one stone to fall vertically and at the same instant throws another stone out horizontally.

(Again, with a little practice, his two hands and his brain do as well as any gadget. A gadget complicates pupils' impressions—as examiners find to their sorrow in answers to questions later.)

c. The pupil repeats part *(b)* starting the stones nearer the ground.

d. The pupil throws a heavy stone and a light stone both out horizontally together.

Discussion It may take some coaxing for pupils to work out general conclusions from those experiments; but it is worth much patient waiting because then they will consider the knowledge is the result of their own work.

Then ask pupils to transfer the result of part *(d)* to an Earth satellite. (They may not have realized that their falling stones *were* Earth satellites.)

Suppose a man in an artificial satellite could reach out of a window and leave an empty milk bottle just outside; where would the bottle be next morning?

Satellite orbit That suggests a general property of satellite motion: a satellite's orbit does not depend on its mass. A small moon and a large one will pursue the same orbit if given the same start.* Thus, as Newton found, in developing his theory, measurements of a small satellite's orbit cannot tell us its mass—and that posed Newton a problem for the Moon.

Then ask one of Newton's own questions:

Suppose you throw a stone out much faster. It would still fall but it would land farther away. Now imagine you shoot it out with a gun so fast that it falls just as much as the round Earth itself falls away from the tangent. What would happen?

That was Newton's approach to artificial satellites. Here it is just a question to catch some interest or start some thinking. Unless pupils pursue the matter, it is best left for the present.

A projectile's horizontal motion Pupils will have learned from their own experiments that a projectile's two motions—the vertical accelerated motion and the horizontal motion—operate completely independently.

They should suspect that the horizontal motion continues unchanged. Galileo's thought-experiment suggested that; and pupils may have seen it illustrated with a block of solid CO_2 coasting on level glass. Now they should see a direct demonstration: the 'frozen pearls'. The experiment takes trouble to set up but it is rewarding both as strong proof and as a delight to see.

* There is one modification: if the mass of the satellite is so great that it is comparable with the mass of its 'owner', the two pursue orbits round their common centroid.

That modification is important in the case of double stars but trivial for artificial Earth satellites and unimportant at this stage for Moon and Earth, or for planet and Sun.

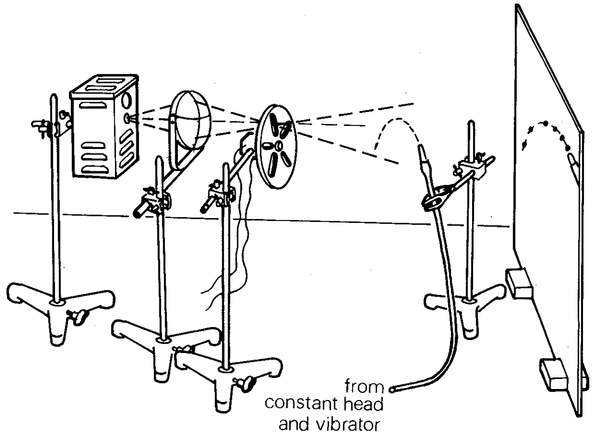
Demonstration 75 The 'Frozen Pearls': Pulsed Water Jet Parabola

Apparatus

1 compact light source	item 21
1 motor driven stroboscope with disk with 5 slits	134/1
1 ticker-timer vibrator	108/1
1 tank for constant head of pressure with rubber tubes for supply and overflow	166
rubber tube, 1 metre, thin walled, external diam. about 8 mm	562
1 L.T. variable voltage supply, a.c. (or variac (78) or transformer and rheostat)	59
4 retort stands, bosses, and clamps	503–506
1 Hoffman clip	522
1 bucket	533
1 lens (f 10 to 15 cm, large aperture)—not essential	
1 lens holder—not essential	
white screen or wall (or lamp and translucent screen)	
short glass tube for jet (e.g., from an eye dropper or make it from soft glass tubing 573)	
grid to make vertical lines (see below)	

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

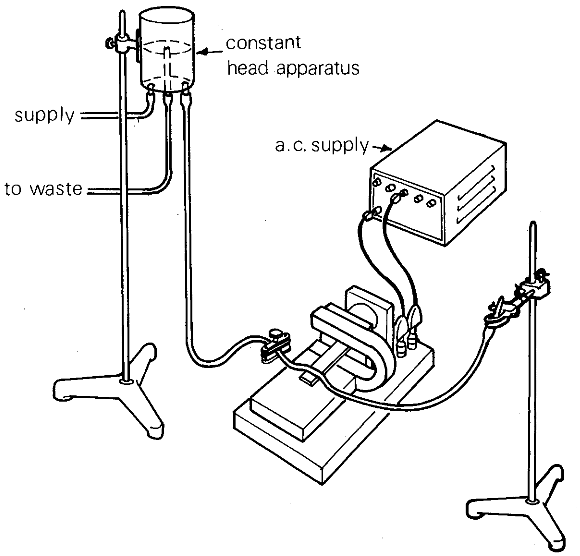
The grid may be either a set of vertical wires, spaced 2 or 3 cm apart on a frame, or a sheet of Perspex ruled or scored with vertical lines which will cast shadows.



Arrangement

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

Water from a constant pressure supply, held high above the bench, flows out through a rubber tube pinched by a Hoffman clip to reduce the flow to a small stream. The stream emerges from a short glass tube drawn out to make a jet.



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

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

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

Then the vibrating blade jolts the rubber tube with a gentle pumping action so that drops are formed steadily, 50 a second (or 100 a second if the vibrator is not polarized).

The jet is tilted to make a parabola; and the lamp and strobe disk throw a shadow of the stream on a screen.

The optimum voltage for the vibrator must be found by trial. So there must be means of varying the a.c. supply.

Procedure

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

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

Then interpose the strobe disk close to the lamp.

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

NOTES

(1) Use a strobe disc with 5 slits, not 6. Then with a synchronous motor running at 300 r.p.m. there will be 25 flashes a second, which will 'freeze' the motion of the drops.

(2) For easier control, the rubber tube may be passed *under* the blade so that it is actually squeezed 50 times a second; but that is not necessary.

(3) For sharper shadows, arrange a lens to form a real image of the lamp filament on the strobe disk, as in the diagram here; but this is not necessary if the compact light source is used.

Uniform horizontal velocity By just looking at this parabola of 'pearls', pupils can see that the *vertical* motion is accelerated but they can only guess that the *horizontal* motion may have constant velocity. That is why we impose a grid to mark the horizontal progress. Then we can see Newton's First Law in a new way; but even then some pupils have to be coaxed into seeing what is happening and understanding what it means.

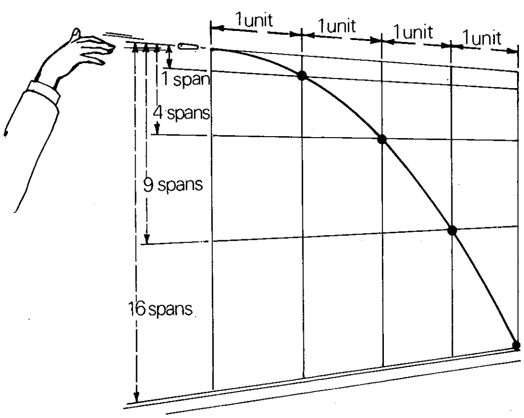
Vertical acceleration Some pupils will have measured 'total strips' in Expt 61 and found the proportions total travel 1 : 4 : 9 : . . . for total times 1 : 2 : 3 : . . . from rest. We hope they have made that discovery and have been pleased with it, because then they could do Home Experiment H62. Now we can make further use of it: plot a parabola and throw a projectile to follow it.

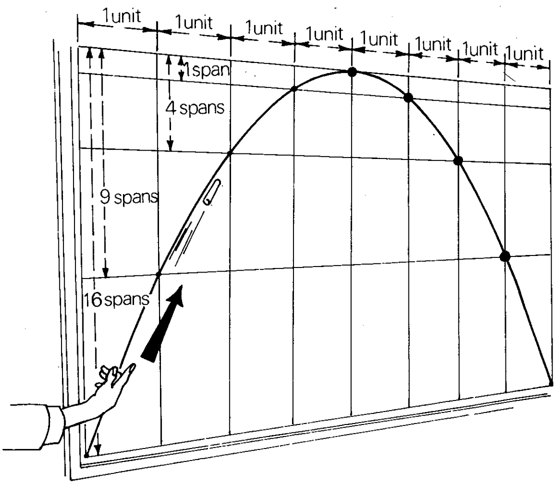
The plotting should be done as a demonstration, because the reasoning needs to be explained as one constructs it. But once they have seen it some pupils will try it again at home.

Demonstration 76 'The Clever Parabola' *(OPTIONAL)*

Construct a predicted projectile path on the blackboard.

Draw a horizontal line across the board near the top. This is the original line of fire. On that line mark points at 10-cm intervals 10 cm from 0, 20 cm, 30, 40, . . . Draw vertical lines through them. Then if the projectile maintains constant velocity it will progress across from one line to the next in equal time intervals.





To mark the projectile's vertical progress in total times proportional to 1, 2, 3, 4, . . . draw horizontal lines at the following distances below the firing line: 1 cm, 4 cm, 9 cm . . .

Sketch the projectile's path through the appropriate intersections, explaining that these assume constant horizontal velocity and constant acceleration vertically.

In the sketch here, we have marked the horizontal distance from line to line '1 unit' and have used '1 span' for the vertical unit, to emphasize the general nature of this construction. It is better here to use some such informal measures (perhaps measuring with a strip of paper) so that numerical concerns do not cloud the issue.

Then try throwing a small piece of chalk just in front of the blackboard. Practise to find the right muzzle velocity, then the chalk follows the sketched curve closely. This is a test of Galileo's rules, and ours, for the motion of a projectile.

This is more impressive if a 'full' parabola is plotted—up over and down, as in the second sketch.

Future Extension In Year 4 or Year 5 pupils should discuss projectile motion more fully. Suppose instead of giving a projectile a horizontal initial velocity, we fire it in any slanting direction, so that its initial velocity has a *vertical component* and a *horizontal component*. Pupils now expect to find the initial horizontal component continuing quite independently of the changes of vertical motion due to gravity. But what happens to the initial vertical component? In fact that also continues unchanged, except for friction, the changes due to gravity simply being added to it. Thus, *horizontal component, vertical component, and the vertical velocity that is gained on account of gravity acceleration* all add as vectors. Their resultant, the velocity at any instant, is tangent to the parabolic path.

And the projectile's path is shaped as if it continued with its initial velocity up its initial slanting path but fell from that slanting path by the distances of gravity-fall from rest. The same falls proportional to 1, 4, 9, . . . are there, whatever the size and direction of the initial velocity.

Final experiment Now in Year 3 we suggest concluding experiments on motion with a simple form of the 'Monkey-and-Hunter' demonstration. The usual form with the line of fire slanting upward is too sophisticated until pupils have grasped the general projectile story described above. If, instead, the gun is aimed horizontally at a 'monkey' at the same level pupils already know the story of the two motions—the bullet's and the monkey's—though they may be surprised to find them applied in this experiment.

In the original Nuffield programme we suggested firing up a slant with a special spring and ramp. Now a horizontal gun makes things simpler. The geometry is more obvious and the gun can be fired by lung power!

Demonstration 77 The Monkey and Hunter

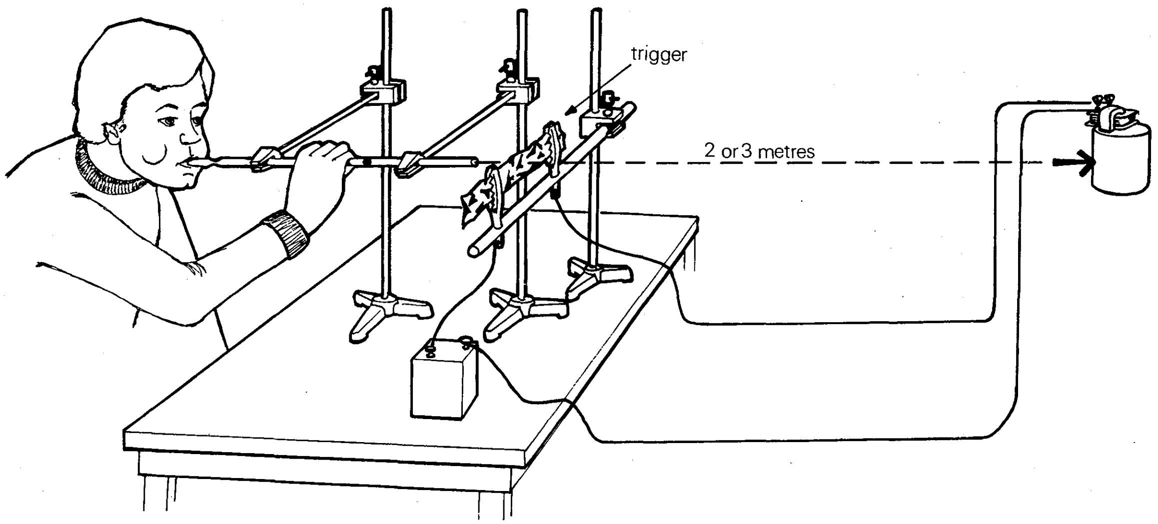
Apparatus

From Monkey-and-Hunter kit:	item 207
1 tin (8 to 12 cm diam.) for monkey	
marbles (or steel balls about $1\frac{1}{4}$ cm diam.)	
tube for gun (brass or glass, about 50 cm long; internal diam. such that marble or ball makes a very loose fit)	
short piece of rubber tubing to fit in gun	
1 coil (120 turns)	127
1 C-core	92G
1 L.T. variable voltage supply (d.c.) (or battery and rheostat)	59
4 tall retort stands, bosses, and clamps	503–506
lab stools	
2 long connecting leads (3 metres)	
1 muzzle trigger (see note below)	
aluminium cooking foil	

The muzzle trigger is a plate or rod of insulating material carrying two crocodile clips about 5 cm apart. The clips hold a strip of aluminium foil. The trigger is supported by a tall retort stand. When the gun is to be fired the trigger is placed so that the strip of foil is just outside the gun muzzle, ready to be broken by the bullet.

The gun must be firmly supported by two stands so that the aim is not upset when the hunter puts his mouth to the gun. To safeguard the hunter, there must be something to stop the bullet at the hunter's end: a small dent in the tube or a short piece of rubber tube pushed into it.

The coil and C-core make a good magnet; but any small electromagnet would suffice.



Preparation

The monkey (tin can) is held by the electromagnet (coil and C-core) until the circuit is broken. The circuit includes the strip of aluminium foil at the gun muzzle: so the monkey starts to fall the instant the bullet leaves the gun. To make sure the monkey is released immediately, reduce the voltage until the magnet only just holds the monkey.

Set up the gun tube, *horizontal*, on two tall stands. If possible, make it still higher by placing the stands on stools on the table.

Set up the magnet 2 or 3 metres from the gun muzzle. Adjust it so that the monkey hangs in the line of fire.

Procedure

Pupils' Text 3 tells the story:

A hunter fires his gun at a monkey. He does not know that a rifle bullet always falls with gravity acceleration, however fast it comes out of the barrel. So he aims straight at the monkey, who is hanging from a branch of a tree. (The hunter takes his aim by removing the cartridge and looking at the monkey through the barrel.)

The hunter fires; but the monkey, thinking he understands the danger, lets go at the instant the gun is fired. What happens?

First show that the monkey falls whenever the circuit is broken.

Then show how the circuit is broken by a bullet.

Finally install the monkey and fire a bullet. (If the bullet is somewhere in the middle of the barrel, the instructions are 'First breathe in, then breathe out'.)

Rehearsal is advised. A repetition may be requested. So spare bullets should be available.

OPTIONAL ADVANCED EXTENSIONS

These go beyond the scope of the present year. They are discussed here in case pupils with special interests wish to try them. The first, regarding areas, is not mentioned in Pupils' Text 3*; but the second, calculations of acceleration, is given there in the same dissected form as here.*

Area under a Chart or a Graph

Area of Chart → Distance Covered

(ADVANCED TOPIC, OPTIONAL NOW. A new insight for a very fast group.) Ask:

a. 'What does the length of each single strip really tell you?'

b. 'Suppose you take the length of the first strip of your chart and add the length of the second strip and add the length of the third. What does the *total* of these three lengths tell you?'

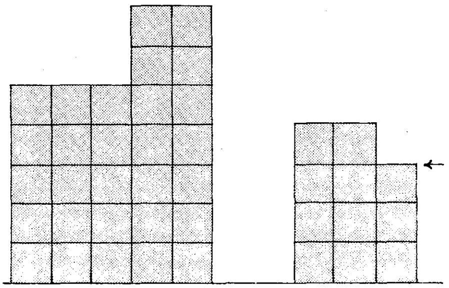
c. 'Look at your chart of strips and use a pencil to shade strips numbers 1, 2, and 3 (the ones whose length you have just added up). You have now shaded an area.

'Suppose you had a tape just 1 centimetre wide. In that case the area of a strip would be [LENGTH] × [WIDTH], and that is [LENGTH] × [1 cm].

'So, in fact, the AREA would be just plain LENGTH. In that case, what would that area you have shaded (for the first three strips) tell you?'

{This new idea, of using the area under a graph, is unfamiliar and difficult for many pupils. We should not try to teach it in a hurry. Pupils have not been waiting anxiously like Galileo to analyse accelerated motion. Therefore it is probably wiser to let the question about the area brew without much discussion, without a clear answer—as if the teacher himself were worrying about it and not quite sure what the area does tell. Then there is some hope that pupils will try later on to help clear up the matter.}

{If even fast pupils find this idea of using the area strange, it might be useful to offer some examples, even though this concept will not be needed until Years 4 and 5.}



Examples of charts (or graphs) leading to useful areas *(ADVANCED TOPIC, OPTIONAL NOW)*

(1) *Boy's Pay.* Make a chart to show the weekly wages paid to a boy doing various jobs.

He starts at £5 a week and he works like that for one week, another week, and another week (three weeks altogether). Then he does a more difficult job for two weeks and is paid £7 a week; then he has two weeks out of work, paid nothing; then two weeks on half-time of an £8 a week job, so he gets £4 each of these weeks, and finally a small job at £3 a week for one week.

How much money does he get altogether in the $2\frac{1}{2}$ months? Of course the easy way is just to add up his takings, week by week. But you could show the story by a chart.

Make a chart for those ten weeks. Draw it on squared paper, so that each square sideways means one week and each square upwards means one pound of weekly wage. Then the first week is one square wide and five squares high. In that week he gets five lots of £1 and there are five squares on that patch of chart. There is the same kind of story for later weeks. You can count the squares on the chart to find out how much he was paid for the whole 10 weeks. But that TOTAL NUMBER OF SQUARES on the chart is also . . .?

2(a) *Electric Power.* Power stations keep careful track of the power load from hour to hour through the day; because they want to be able to predict the big demand, and get turbines and generators going beforehand.

The energy running out from the power station is measured by instruments like an 'electric light meter' graduated in 'kilowatt·hours' of energy. (A kilowatt·hour is just a large package of energy, a little more than $3\frac{1}{2}$ million joules.)

But power stations also have POWER meters that tell them how quickly energy is flowing out to the power lines connected to the generators. The power meter shows the rate-of-energy-going-out in plain kilowatts. (A kilowatt means an outflow of 1000 joules *every second.*)

Suppose a small power station finds it is delivering:
2000 kilowatts from 8 a.m.–9 a.m.;
2000 kilowatts from 9 a.m.–10 a.m.;
1000 kilowatts from 10 a.m.–11 a.m. *and* 11 a.m.–12 noon;
3000 kilowatts from 12 noon–1 p.m. (lunch is being cooked).

Make a chart for that, with 1 square upwards for every 1000 kilowatts and 1 square along for every hour. *What does one single square on this chart mean?* It would mean 1000 kilowatts supplied for one hour and we call that 1000 kilowatt·hours. That is all 'kilowatt·hours' means. It means that number of kilowatts running out all the time for one hour (or some other number of kilowatts multiplied by some other number of hours to give 1000). 'Kilowatt·hours' are like 'man·hours' in old arithmetic problems about men digging ditches.

How many kilowatt·hours did that power station deliver between 8 a.m. and 1 p.m.?

Question (1) and question (2) (so far) will excite derision. 'Why bother with the area of a chart? Common sense and simple adding will do. Or if we must plot a chart we can just count the squares.' But now continue question (2).

2(b) *Changing demand.* Suppose in the afternoon from 6.0 p.m. to 8.0 p.m. more and more power is taken from the power station, so that the flow of energy (measured in kilowatts) rises steadily from 2000 at 4.0 p.m. to 10 000 at 8.0 p.m. Now how can you find the total output (in kilowatt·hours) in that time?

(3) Then return to ticker-tape charts and offer charts like those sketched. For them, ask what the AREA tells and leave that question to brew.

Looking ahead. A note about Year 4 There are developments of this work on tape-charts, acceleration, etc. in Year 4. Pupils will meet full discussions then. So it is better to let them enjoy simple experiments now, rather than hurry them into quick learning of analysis or algebra that would bring doubts with it at this stage.

{In Year 4 we shall draw a graph with speed plotted upwards and time plotted along—which is a refined form of this ticker-tape chart. Then, taking the case of constant acceleration, we shall arrive by geometry at formulae such as $s = v_0t + \frac{1}{2}at^2$. That is much better than the simple algebraic method which takes $\frac{1}{2}$ the sum of first and last speeds, where the $\frac{1}{2}$ comes from a *concealed* assumption of uniform acceleration.}

{Later still in Year 4 we shall plot a strange graph, with [VELOCITY] along the horizontal axis and [MASS] × [VELOCITY] upwards. That will give us an area which represents kinetic energy; and next year we must prepare for that very carefully. As an illustration to preface our use of that strange graph, we shall suggest in Year 4 offering some pupils a graphical method of showing that the area of a circle is πr^2 if π is defined as CIRCUMFERENCE/DIAMETER.}

Optional Calculations of Acceleration

In this year's work, pupils do not need to calculate out the value of accelerations from their tape records.

However, a few keen pupils—confident mathematicians—may like to try calculations such as the following, which are printed here and in *Pupils' Text 3* as *optional advanced extensions*. The printed version tries to lead a pupil through the calculation but teachers may need to give further help and encouragement.

(1) Acceleration of a trolley in centimetres/tentick in a tentick

If the feet of all your tentick strips stand on a base line, the slope of the slanting line through their heads tells you how fast the speed increased. If you measure the jump in height from one strip to the next, in centimetres, that tells you the *gain* of speed, in centimetres/tentick, from one strip to the next.

And since the strips are samples of the motion one tentick apart from strip to strip, that gain of speed is itself made in one tentick. So each jump in strip-height tells you the ACCELERATION in centimetres/tentick in a tentick.

If those units seem puzzling, think of a lift, which must accelerate when it starts to haul people up from the ground to the top of a building. You might measure the lift's speed in metres/minute. An express lift in a skyscraper might make *most* of its trip at a steady speed of 120 metres/minute. But in starting it would have to accelerate, and its speed might be:

0 at start
60 metres/minute, 1 second from start
120 metres/minute 2 seconds from start
(120 metres/minute steady speed after that)

Then, during the first two seconds the lift would have acceleration 60 metres/minute per second, meaning it would gain 60 metres/minute of speed *in each second.* That is its acceleration.

What is its acceleration in metres/*second* in each second?

(2) Acceleration of free fall, *g*

Suppose you recorded the free fall of a stone, with timer and tape. If you analysed your tape and obtained an acceleration 40 *centimetres/tentick per tentick,* what is that acceleration in *metres/second per second*?

How well does that result agree with the 'official' value 9.8 metres/sec^2?

Here is the argument to help you through the calculation:

The timer is fed by alternating current which makes 50 cycles per second. Therefore the timer's tentick is 10 lots of $\frac{1}{50}$ second.

1 tentick $= 10 \times \frac{1}{50}$ sec or $\frac{1}{5}$ sec.

The falling stone gained 40 cm/tentick in each tentick.

That is a gain of SPEED.

What is that *gain of speed,* 40 *cm/tentick,* in *metres/second*?

40 cm/tentick means 40 cm in 1 tentick.

That is the same as 40 cm in $\frac{1}{5}$ sec.

That is the same speed as . . ? . . cm in 1 sec
or . . ? . . metres in 1 sec.

So the falling stone was gaining . . ? . . metres/sec in each tentick.

There it was gaining ... ? . . metres/sec in each second.

The stone had acceleration . . ? . . metres/sec per sec
or metres/sec^2.

CHAPTER 5

GASES

Molecules in motion; molecule models; behaviour of gases

A serious study of kinetic theory (with a prediction for the pressure by considering momentum-changes) will come in Year 4. Here we offer a little preparation for that by revising some qualitative ideas from Year 1, but our chief aim is to let pupils do and see.

There are models, arguments and speculation; and experiments on pressure, volume and temperature relationships for gases. Throughout this chapter qualitative kinetic theory is used as a background for interpretation.

'CATCHING UP' OR REVISION

Some pupils will remember, from Years 1 and 2 or from *Combined Science*, the picture of gas molecules in motion and the models to illustrate it. Others may be starting Nuffield physics now. So we offer some experiments and commentary for catching up (or possibly for revision). The symbol † indicates such material, which need not be repeated now if pupils have seen it and remember it. However the discussion often extends beyond the earlier treatment. This material is included in *Pupils' Text 3*.

†Models (for catching up or revision)

Pupils should see models of gas molecules in motion, to help their thinking about pressure, collisions, random movement, and Brownian motion.

Show a three-dimensional model, a handful of small metal balls kept in motion by a vibrating membrane at the bottom of a tall transparent tube. The membrane is driven by a cam on a small electric motor. The 'molecules' can be kept at various temperatures by adjusting the supply to the motor.

Three-dimensional Model of a Gas: Description of Equipment

TUBE. The 'gas' is held in a Perspex tube about 5 cm diameter 40 cm high, open at the top, closed by a rubber sheet at the bottom.

THE 'MOLECULES'. 12 dozen small phosphor bronze balls are needed for some experiments, fewer for others.

RUBBER BASE. The base is driven up and down rapidly by a piston on an eccentric device driven by an electric motor. The kit should include several spare rubber bases.

THE MOTOR. Any small motor—e.g. the toy motor of the energy kit—will suffice. The fractional horsepower motor shown in the sketch will run the piston equally well, but such a large motor is quite unnecessary here. (*Note.* An early Nuffield model was driven directly by an electrical vibrator; but there were failures due to overloads.)

CAP. The top of the tube is closed by a metal cap. This prevents balls from escaping and reduces the noise.

PISTON. A light paper piston, supported by a wire through a hole in the cap, acts as a lid for the 'atmosphere'. Tiny loads of cardboard placed on it enable the model to simulate an enclosed sample at various pressures.

BALL FOR BROWNIAN MOTION MODEL. An expanded polystyrene ball, as used in electrostatics, is suitable. An irregular scrap of the material would make a more lifelike model of a smoke speck. For a close model, the Brownian motion particle should be much more massive than the small 'molecules'. But in practice it is better to use a light large ball. Then the small balls provide enough buoyancy to keep it from falling down fast.

†Demonstration 78 Model of Air Molecules. Three-dimensional Model for Kinetic Theory

Apparatus

1 three-dimensional kinetic model kit	item 11
1 fractional horse-power motor (or any small motor) with a belt	150
1 L.T. variable voltage supply	59
1 retort stand, boss, and clamp	503–506

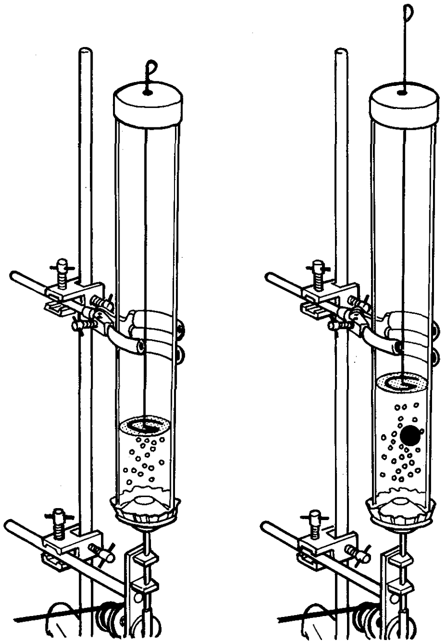
Preparation

Fix the rubber base over the lower end of the plastic tube. Clamp the plastic tube in a vertical position.

Adjust the height of the tube so that the rubber base is 1 or 2 mm above the vibrating rod in its mean position.

The electric motor drives the vibrating rod. Connect the d.c. L.T. variable voltage supply to the armature terminals of the motor, and to the field terminals, in parallel.

Put the small phosphor bronze balls in the tube, so



that they rest on the rubber base—enough balls to cover two-thirds of the base. The vibrating rod and rubber drum keep the balls in random motion.

Put the brass cap over the top of the tube: it prevents balls escaping and it cuts down the noise.

Procedure

Start with a low voltage—the model works effectively on 4 to 6 volts—and increase to the safe maximum, 12 volts. Ask pupils to watch how the atmosphere of balls changes as the 'temperature' is increased.

We hope pupils will also notice fewer 'molecules' in the higher parts of the tube.

Then install the paper piston inside the tube, to act as a movable lid for the 'atmosphere'. The wire holding the disk should pass through the hole in the brass cap.

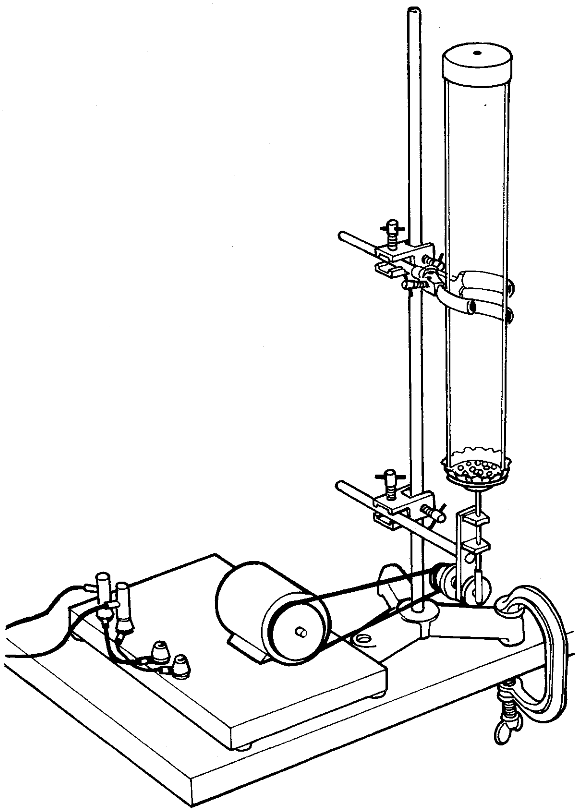
Switch the motor on and off. When the base is vibrating, the disk rises to a position where its weight is just balanced by the force due to the pressure of bombarding 'molecules'.

Add small cardboard loads on top of the disk.

Imitate the Brownian motion by suspending an expanded polystyrene sphere among the small balls of the model.

(Some teachers like to place a translucent screen and lamp behind the demonstration to show it in silhouette against a bright background.)

(Like the two-dimensional model, this model —already used in Year 1—will illustrate further aspects of gas behaviour in Year 4.)



Discussion Explain that we think air pressure is simply the effect of bombardment by molecules. If so . . . ?

Leave that question to brew. Even if no pupils can guess, issuing an answer straight away would not encourage thinking and understanding. Instead, presently suggest having another look at the three-dimensional model.

Only much later give the simple answer that each molecule has a closer crowd of moving molecules just below it than just above. Better still, wait for that till Year 4—the *asking* of the question is our essential teaching now.

The collisions must be elastic—they must bounce back without loss of motion energy, on the average. Otherwise, if they lost ever so little at each collision the air would soon be 'dead' at the floor of the room.

But gravity is there, to make molecules fall. Why don't all the air molecules fall down crash to the floor, however else they are moving?

Molecules *do* fall downward. But they are also made to move in all kinds of directions by collisions. Since air does not collapse to the floor, any molecule must have a greater chance of collisions that knock it *upwards* than collisions that knock it *downwards*. How can that happen?

If pupils notice the gradation of density in the model, point out that this a good model of our atmosphere. ('Why is it harder to breathe at the top of a mountain? Also, what are the troubles of a deep-sea diver?') Pupils can imitate the atmosphere with their two-dimensional model, if they tilt the tray slightly.

Hot walls Some pupils may ask why we have to keep on supplying energy to the walls or piston in a model, in contrast with a real gas, whose molecules keep going of their own accord. The chief answer is: the walls of the model are 'cold'; but the walls of the gas container are as hot as the gas —their molecules are in violent vibration, and 'give as good as they get' when the gas molecules hit them. See the discussion in *Pupils' Text 3.*

Two-dimensional model As a class experiment, give each pair of pupils a tray of marbles which they keep in constant agitation. They place the tray on the table and move it with rapid, jerky, vibrating and rotatory motions.

The noise is reduced if a thin sheet of cork is placed in the tray as a carpet; then pupils can hear the individual collisions of 'molecules' with walls and with each other; and can distinguish by ear between those two kinds of collision.

Although it is only two-dimensional, this model simulates the behaviour of gas molecules more closely than some three-dimensional ones. By choosing the colours of marbles so that each tray has only one marble of some prominent colour, pupils can watch the movement of that marked marble through the crowd. They can see its slow progress (diffusion) and its many different velocities. They can visualize its mean free path. They can change the 'temperature' of the collection.

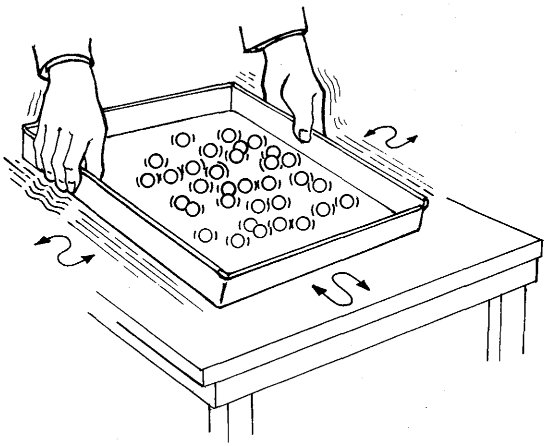
†Class Expt 79 Marbles in a Tray: Two-dimensional Kinetic Theory Model

Apparatus

Two-dimensional kinetic theory model kit	item 12
16 trays, with cork-lined bottoms	12A
400 marbles (about 15 mm diam.)	12B
32 large marbles (about 25 mm diam.)	12C

Any rectangular tray will suffice, provided it has *vertical* walls and is fairly massive.

Pupils work in pairs. Each pair should have a tray and two dozen coloured marbles. Each tray should have one marble of a distinctive colour among the collection of other colours, so that pupils can watch its progress.



Procedure

Pupils follow these instructions:

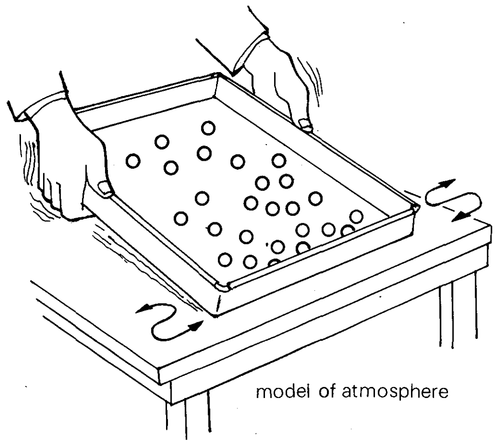
*　*　*　*　*

Put two dozen marbles in a tray, to represent air molecules in the room—or any gas molecules in a box.

(i) Agitate the tray by sliding it about on the table with a rapid irregular shaking motion, to imitate the hot walls of the room. Watch.

(ii) Illustrate a higher temperature.

(iii) Listen to the sounds. Can you hear the different kinds of collisions, some on the walls, others between marble and marble?



model of atmosphere

(iv) You can imitate the atmosphere (with its population thinning out higher up) by giving the tray a *very slight* tilt, and then keeping it tilted while you agitate it.

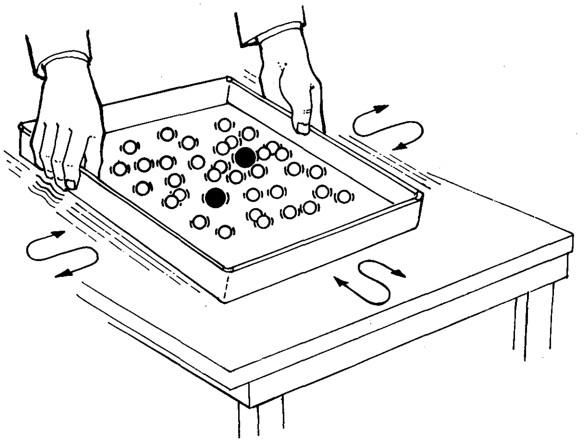
(v) Place a larger object, such as a big marble, among the marbles and watch what happens to it when you agitate the tray. That suggests what

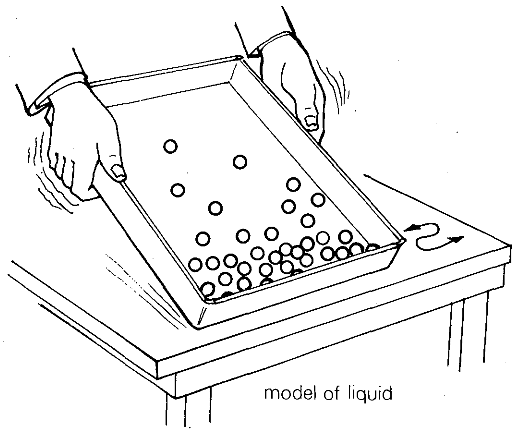
might happen to something much larger than an air molecule, if it is floating in air. You can see that in real life by watching tiny specks of white smoke in air.

(vi) For a model of a compressed gas, add more marbles and agitate the tray. Crowd all the marbles into half the tray, with a ruler. Continue to agitate the tray and see the gas expand when you remove the ruler.

(vii) To make a model of a liquid, add still more marbles; tilt the tray to make 'liquid with vapour above it'.

(viii . . .) There are still more things you can do, such as watching one particular marble.*





model of liquid

Home Expt H79 Model of Air Molecules

This experimenting with a simple model is something we hope pupils will also do at home. Setting it up is trivial: the main activity is showing-and-explaining teaching theoretical physics to people at home.

Any tray or glass dish with sides that are vertical will do. A bright 'tin' baking tray about 30 × 20 cm with edges about 2 cm high, does well, *provided the edges are vertical.* Most ironmongers stock trays with edges that slope outward (and marbles do not rebound well from those); but from time to time a line of trays appears with vertical sides, costing little. Two dozen glass marbles from a toy shop is the only other thing required.

The cork floor is unnecessary but an experiment with soft carpet would be interesting.

Imagination *Pupils' Text 3* also suggests an imaginary model: a dozen or two pupils act a pantomime of air molecules, sliding about a room at random. The walls of the room would be lined with many more pupils closely packed, with linked arms, bouncing about violently.*

{**Note on models: are models true?** Pupils should see models, preferably in several forms. Remind pupils that those are 'teaching-models' to *illustrate* the 'thinking-model' which *is* the whole kinetic theory. Such 'teaching-models' cannot prove the theory right—any more than a film made by a programmed computer can—but they can help people to visualize and understand the theory.}

{In some cases a teaching-model is not even meant to show what we think the real thing is like.}

{As we develop the idea of a thinking-model, we should give gentle warnings that even a thinking-model is not the real thing. Yet it is the nearest we come to understanding 'real nature'. It is all-we-know put into a speculative picture. This kind of warning is dismaying when young

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* Teachers with a large number of pupils available have tried a *real* pantomime like this and have found it active and noisy but a very successful model with pupils at this stage.

* As a special project, a pupil might gather statistics of velocities by taking photographs with a not-too-short exposure. This has been done at university level as a research project.

people first meet it; but they can learn to enjoy using thinking-models. They can think in terms of models with much greater freedom and skill and imagination once they realize the great scope of scientific models and theories as we use them.}

{**Imagination in models** We might contrast a tray of marbles as a model to help our thinking about gas molecules—to suggest a line of investigation, or to illustrate a technical term such as mean free path—with the use of a cardboard model of a diesel engine or a huge wax model of a flower. Both kinds are teaching-models; but the last two are used to aid people in visualizing; the first is used for constructive reasoning with imagination.}

{Modern theoretical physics uses models as essential parts of the framework of knowledge; but we take great care to remember that the words, phrases, descriptions, are only parts of *models*. Without imaginative thinking in terms of models, scientific knowledge would be merely a pile of facts, codified here and there in laws—little more than a handbook of data and a few formulae.}

{We can put little or none of this to young pupils at the present stage. It would probably be unwise even to try. Yet 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; and still more when we use 'thinking-models' (theory) to build pupils' knowledge.}

Brownian Motion

Brownian motion is not conclusive evidence* for the existence of rapidly moving air molecules, but it gives strong support. A personal look at Brownian motion—utterly different as an experience from just seeing a film, or even from being shown a demonstration at the hands of an expert teacher—plays a very important part in our building up of confident and cautious knowledge of atoms and molecules.

This is so important that we feel all pupils should see the Brownian motion of smoke specks again now, whether they have seen it before or not. Pupils who saw it in Year 1 will be pleased to see it again, now that they know so much more and they will enjoy showing it to any others who have missed it.

Therefore schools teaching Nuffield Year 3 need smoke cells and microscopes if they are to do justice to our programme. Schools which teach Nuffield Year 1 or Combined Science will have smoke cells already. But other schools now need to obtain them.

The Whitley Bay smoke cell is far the best for a clear view.

* That this is due to bombarding molecules is clear—once we have accepted the concept of molecules—from the fact that measurements of Brownian motion (in air or in liquid) yield consistent estimates of the Avogadro number, and thence of molecule masses.

Brownian Motion in Smoke. Description of Equipment

SMOKE CELL. The smoke is put in a small vertical glass tube, closed at the bottom, with the bottom blackened. Light is concentrated into a narrow line across the tube by a cylindrical lens.

LAMP. The lamp is attached to the cell, so that the illumination cannot shift as pupils use the cell. The lamp is a horizontal festoon lamp used in cars.

THE LENS. Light is focused on the smoke by a horizontal piece of glass rod. That produces a line image of the filament in the smoke.

In order to minimize convection, the lamp is placed *below* the level of the glass rod, so that the image in the tube is *very nearly at the top*.

For proper imaging (necessary to make the cell work well), the lamp, rod, and cell must be spaced as follows: from filament to surface of rod, one rod-diameter; from surface of rod to axis of smoke cell, one rod-diameter.

If teachers make their own smoke cells they should follow this geometry carefully, because trials have shown that deviations from that produce much poorer results.

MICROSCOPES are needed. For viewing the smoke cells, *at least one microscope is needed for every four pupils*. That is not an unnecessary luxury, since we want pupils to see the Brownian motion for themselves. Joining in a queue to use one demonstration microscope would be tragic; it would lessen that feeling of being personally involved as an observer so seriously that it would harm our programme. (And replacing this experiment by a film would be worse still, even more indirect and undesirable.)

Eight microscopes per class make a large demand on the provision of equipment. We hope that the physics class will be able to borrow enough microscopes from the biology department—the authorities there may be more willing to lend their microscopes to pupils at this age than in Year 1. If not, we are sure that microscopes should be bought.

These microscopes need not be elaborate instruments but they must have an objective with a large aperture to take in plenty of light so that pupils see the motion of the smoke particles clearly. (A microscope with a tiny aperture may suffice for an adult physicist; but pupils, to whom the use of a microscope is strange and the thing they are looking for is stranger still, need better illumination.)

A high-power objective is not needed—not even suitable. Any focal length between 10 and 30 mm will suffice (preferably the usual 18 mm), and eyepiece 10X. *It is essential for the objective to have large aperture*, and there must be sufficient clearance between the stage and the objective for the Whitley Bay smoke cell.

(Beware of the well-made, cheap, toy microscopes with high magnifications but small apertures.)

Class Expt 80 Evidence of Air Molecules in Motion: Brownian Motion of Smoke in Air

Apparatus

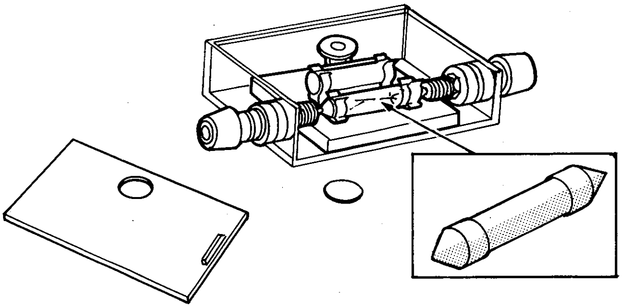
8 microscopes (see special note above)	item 23
8 Whitley Bay smoke cells	29
8 transformers	27
8 (or 1) squeeze bottles for smoke‡	29/2

‡ *Warning*. Putting smoke in the cell can be frustrating for beginners. Several methods have been suggested and tried:

a. A smouldering drinking straw, with the smoke running down (!) through the straw to the cell. *The smoke (of wax particles) is too coarse and the straw diverts attention.*

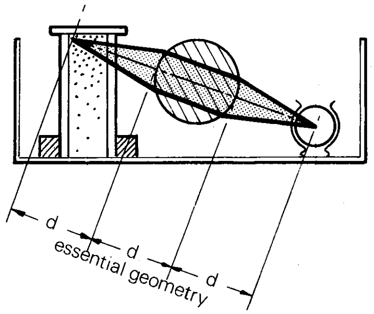
b. Cigarette smoke from the teacher's mouth. *The smoke is damp and too coarse.*

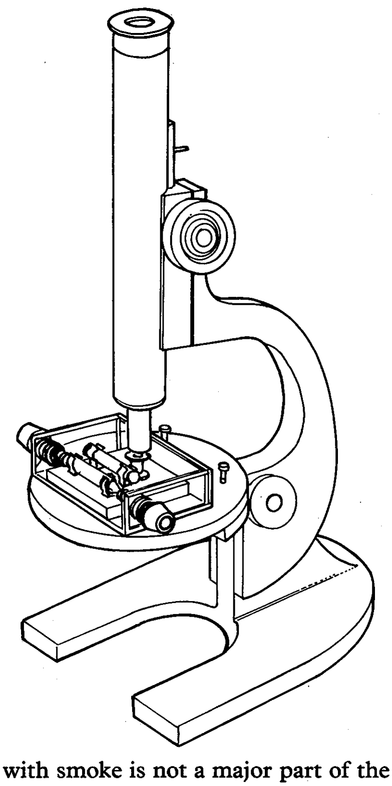
c. Smouldering string or paper or match or cigarette held just above the top of the cell; or the smoke transferred by eye dropper. *Good.*



d. A squeeze bottle filled with smoke and pressed *gently*. *This is best*. A piece of smouldering rope (or brown paper) provides the smoke; but if it touches the wall of the bottle the wall may melt so the rope must be held by clips to a central post in the bottle. A very gentle puff provides more than enough smoke.

Pupils may have trouble managing the smoke bottle and they are apt to puff out much too much smoke; so, as the filling with smoke is not a major part of the experiment, we suggest the teacher should carry a smoke bottle round and fill each smoke cell, at least for beginners.





Preparation

Make sure that old smoke ash has been cleaned out of the smoke cell itself.

Place the cell on the microscope stage and *clamp it there* if possible. Connect 12 volts from the transformer to the terminals on the smoke cell.

Procedure

Pupils work in groups of four (not more, or there will be long delays). They follow these instructions:

* * * * *

Light the end of a piece of rope and put the smouldering material in the squeeze bottle.

Remove the cover from the smoke cell and very gently inject a little smoke into the cell—or ask your teacher to do that.

When the cell has a little smoke in it, slide the cover on. Focus the microscope on the cell. To focus the microscope you must use a special method to keep the valuable lens from being hurt. If it touches the slide or some object on it it might be scratched. Squat down till your eyes are level with the smoke cell. Move the body of the microscope very slowly down until the bottom of the lens *almost* touches the cell. Then sit or stand and look through the microscope; and *raise* the body of the microscope until you see the Brownian motion of the smoke specks.

* * * * *

Warn pupils that there are convection currents ('breezes of warm air') which carry the whole army of particles drifting across the field of view; and that the drifting motion is not what we are looking for.

Also explain that particles out of focus make large, round patches of light. These characteristics seem simple enough to us but can spoil the experiment if pupils are worried by them.

(NOTE. The demonstration of Brownian motion in a liquid is also good to see; but it should *not* take the place of this essential look at smoke in air, as it will seem irrelevant and misleading. A little Indian ink added to water provides carbon particles small enough to show appreciable Brownian motion with a high-power microscope objective, preferably used as a water-immersion lens.)

Diffusion

Diffusion fits in with our picture of gas molecules in constant motion in a vast open space. Pupils should see at least one diffusion experiment now.

There are good traditional demonstrations that use an unglazed porcelain jar; but, for speed and clarity, we suggest two others: diffusion of bromine (from a closed capsule), in air; and an ingenious demonstration that uses soft blackboard chalk.

If pupils following the earlier version of Nuffield Physics have seen bromine diffusion in Year I, they might now see diffusion through chalk—described in *Teachers' Guide 4*. But in this revision we have moved bromine diffusion out of Year 1. We now suggest it as the best choice for Year 3, with diffusion through chalk in Year 4.

Bromine Diffusion: Description of Apparatus, and its Care

MAIN TUBE. The diffusion tube is a closed glass tube (40 to 50 cm long, 5 cm diameter) with only one opening to a wide side tube near one end, with a rubber bung.

A glass tube through the bung carries liquid bromine to the main tube, so that only bromine vapour and not liquid comes in contact with the rubber. (Nevertheless, the bung must be replaced by a fresh one unless used again on the same day.)

STOPCOCK AND CAP-TUBE. The glass tube that runs through the bung is part of a glass stopcock with large bore—8 mm 'Interkey type'. The stopcock must be large, 8 mm bore and must be spring held to prevent accidental loosening. Ordinary quality suffices: high vacuum quality is unnecessary.

The design of including a stopcock—which may seem unnecessary in the case of diffusion in *air*—enables the experimenter to separate the two processes:

(i) Release of bromine by breaking the capsule.
(ii) Admission of bromine to the main tube.

Teachers will find that separation into two stages is both a comfort in manipulating the apparatus and an advantage in showing pupils what is happening.

A short piece of fairly thick-walled rubber tubing connects the other end of the stopcock to a glass 'cap-tube' with a bromine capsule inside.

Bromine Capsule. The glass capsules each contain 1 cm^3 of liquid bromine. In teaching, one may say 'like a tiny wine bottle, with a neck which is easily broken to release the liquid'.

Cleaning the apparatus. After the experiment put the whole apparatus in a plastic bucket half full of dilute ammonia solution and take the apparatus to pieces under the solution. Plunge the lower end of the apparatus in first, remove the bung from the main tube; then dismantle the stopcock etc. The apparatus can then be washed with ordinary detergent, dried, and assembled later. For silicone tap grease, use acetone.

It is sensible to wear rubber gloves for this cleaning process. Rubber gloves are not necessary during the main experiment. They will not increase the teacher's dexterity and they will invest the experiment with an air of danger which it does not deserve.

Drying the tube for immediate re-use. If the apparatus is to be used for several classes on the same day it will need to be dried quickly after cleaning. The design of a closed tube with only one entry is a safety measure but it makes drying the tube a slow process. Unless spare tubes are available, we recommend a hair dryer to blow hot air into the tube after a final washing with alcohol.

Maintenance. Before the apparatus is used, clean the stopcock and put fresh grease on it. Vaseline is better than tap grease (which may contain rubber and become more messy in contact with bromine). Vaseline, like paraffin wax, is inert. Avoid the modern form that has air bubbles in it—which may make the tap leak.

The rubber bung must be replaced by a fresh one when bromine has hardened its face. A bung can be used for several experiments in the course of a few days, but if it is kept longer the rubber will harden and may crack or damage the glass side-tube. Then a new bung must be used.

The bung must make good contact with the glass side-tube. To ensure that, moisten it with saliva. On no account use Vaseline or the bung may ooze out of the tube. If the bung seems likely to slip out, wire it in.

Unless the short piece of rubber tube that carries the capsule is to be used again very soon after, throw it away after use and install a fresh piece when the experiment is repeated.

Demonstration 81a Bromine 'Gas' Diffusing in Air

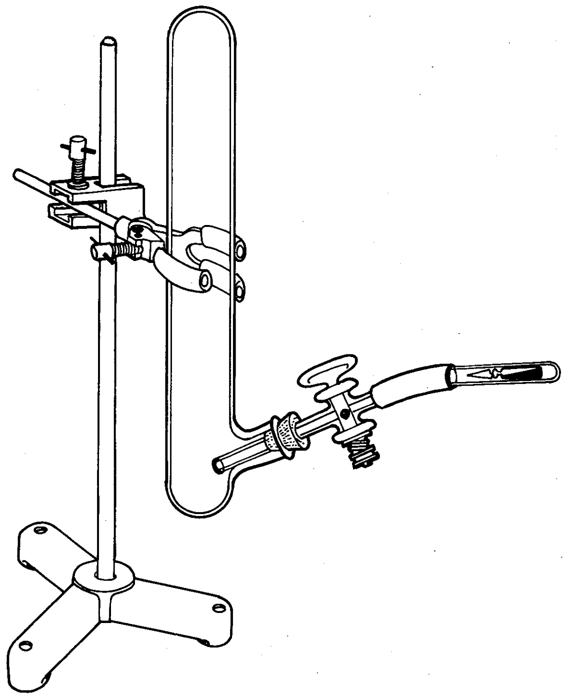
Apparatus

1 bromine diffusion kit	item 8
1 retort stand, boss, and clamp	503–506
1 translucent screen	46/1
1 lamp	46/2
pliers	
ammonia solution, $\frac{1}{4}$ strength	
beaker (1000 cm^3) for ammonia	513
plastic bucket	533
(hair dryer for tubes)	

Safety

Bromine is a dangerous substance. If liquid bromine splashes on the skin it makes a bad blister. Bromine vapour will attack the skin and will produce a sore throat if inhaled. Bromine attacks almost any common material except glass and paraffin wax.

Great care should therefore be taken with this important experiment. However, with the sealed capsules in which the bromine is supplied and the apparatus and procedure that we recommend, it is safe in the teacher's hands. The beaker of ammonia solution should *always* be at hand, at every stage of preparation and experiment. Then if any bromine escapes it can be treated before it does harm.

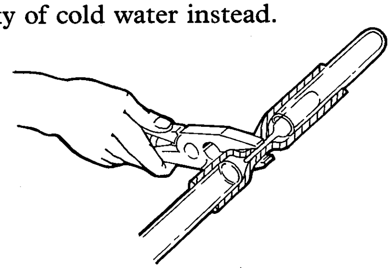


(Sodium thiosulphate, photographic 'hypo', is sometimes suggested as an alternative to ammonia. We have found it slower and less convenient.)

Ammonia combines with bromine to form harmless white ammonium bromide. Strong ammonia solution '0.880', diluted to quarter strength, provides an excellent safeguard.

If bromine splashes on table or skin, pour ammonia solution on at once.

Ammonia should not be used near eyes, use plenty of cold water instead.



Preparation

(See the suggestions for cleaning, maintenance, and drying given above.)

Clamp the main tube firmly in a vertical position in front of the translucent screen. A lamp behind the screen shows the tube silhouetted against a bright background. The bung should already carry the stopcock with its tube pushed nearly all the way through, so that it will deliver liquid bromine to a place just above the bottom of the main tube.

Fix the bung in place; and wire it in if necessary.

Procedure

Show a capsule of bromine against the translucent screen (or show it with an overhead projector). Place the capsule in a cap-tube. Hold the cap-tube upright and push a short piece of rubber tubing gently onto it. Push the other end of the rubber tubing on to the outer tube of the stop-cock. (The rubber tubing must fit tightly. It should not be too short or there is a danger of pulling it off the glass tube when squeezing it—6 cm is sufficient, 4 cm is too short.)

Keep the stopcock closed. Explain that the capsule is about to be broken. Squeeze the rubber tubing with pliers to break the neck of the capsule. (It is usually easier just to bend the rubber tubing with fingers, though that is not quite so safe.)

Liquid bromine will run down to the entry of the stopcock. Point to it there, and warn pupils to watch carefully.

Give a signal and turn the stopcock to admit the bromine to the main tube. Leave it for some time so that pupils can see the diffusion in progress.

Vacuum? Some teachers reporting on Year 4 are anxious that the cream of this experiment with bromine in a vacuum should not be skimmed off by its being shown even once before. However some pupils in Year 3 will not continue physics in Year 4 and (if they have not already seen it) they should see bromine released in vacuum now.

If pupils of their own accord suggest that the experiment would run differently with vacuum and clamour to see it, the vacuum version should certainly be shown now.

Demonstration 81b Another Experiment with Bromine? (Bromine Diffusing in Vacuum)

Apparatus

As for diffusion of bromine in air with the addition of:

vacuum pump	item 530
pressure tubing (1 to 2 metres, according to location of pump)	563
connector to join pressure tubing to wide stopcock tube	563/A = 8I

Preparation

Clamp the main tube firmly. Make sure the stop-cock is clean and well greased with vaseline.

Make sure the rubber bung is a fresh one that fits securely and will not let air leak in. Moisten it with saliva to ensure good contact.

Place an opaque white screen behind the apparatus (or a translucent screen and lamp).

Procedure

Connect the motor-driven vacuum pump to the stopcock and pump the main tube out to a good vacuum (as indicated by the sound of the pump). Turn the stopcock off. Remove the pressure tubing. Attach the short rubber tube with cap-tube already loaded with a bromine capsule.

Leaving the stopcock closed, break the capsule. Warn pupils to watch carefully. With a count down, open the stopcock quickly.

An optional look to the future Bromine makes diffusion visible. When we release bromine at the bottom of a tall tube of air we may ask why, if its molecules are moving very fast (actually 200 metres/second) they do not spread all the way up the tube at once.

The answer to this question is worth waiting a long time for. It is not obvious to pupils that if molecules of bromine and of air had no size at all but were just points, bromine would spread right through the tube at the full speed of its molecular motion. It is not obvious that the slow spreading of the brown bromine through air shows that one kind of molecule or the other, or both, must have some considerable size. After this question has rested in pupils' minds for a time, ask questions that lead to the answer, such as:

Suppose I throw this piece of chalk straight out among you, past your heads. Do I stand a chance of hitting someone's head? Suppose you were all pinheads with practically no head at all, each head the size of a table tennis ball, would I stand the same chance of hitting a head?

Or this:

Imagine you are trying to run across a room which is crowded with people who are all moving about. What will happen to you? What happens to the other people?

We do not pursue that now but we promise that in Year 4 we shall use the diffusion of bromine to make an estimate of molecular size.

Data for Air Molecules (A Note for Teachers)

We do not suggest giving pupils numerical data for air molecules; because we can offer no evidence for the data at the present stage. However teachers may find it useful to have the following privately in mind.

SPEED. We estimate molecular speed from measurements of pressure and density of a sample. Air molecules at room temperature have an *average* speed about 500 metres per second ($\approx$ 1650 feet per sec; more than $\frac{1}{4}$ mile per sec). Compare that with the speed of sound, 340 metres per sec ($\approx$ 1100 feet per sec).

SIZE. An air molecule is not a round object and not a hard solid one like a billiard ball; but we estimate an *average* diameter for an air molecule, using the rather gentle collisions that molecules make at room temperature. We calculate an estimate from the mean free path and find a diameter about 0.4×10^{-9} metre or 0.4 nanometre.

SPACING APART IN ATMOSPHERIC AIR. We measure the change of volume from liquid air to air. (This should be a demonstration in Year 4.) From that we find that air molecules should be spaced apart 9 or 10 molecule diameters in ordinary air.

MEAN FREE PATH. We estimate the mean free path of a molecule (the average distance that one molecule travels before it hits another) from bromine diffusion. We find it is about 100 nanometres in ordinary air.

AIR. So air molecules are about half a nanometre in diameter; are spaced apart about 4 nanometres; and travel about 100 nanometres between one collision and the next, with average speed 500 metres/second.

The Teaching and Use of Gas Laws

{The formulation of gas laws in the last three centuries clarified knowledge of gas behaviour and advanced both physics and chemistry. Knowledge of gas laws was particularly important in chemistry two centuries ago, when Lavoisier was raising a great science still farther from alchemy with the help of systematic nomenclature: and later as atomic theory developed. And now in physics, modifications of gas laws are important in low-temperature studies. At the other extreme, gas laws are the primitive starting point on very-high-temperature studies for nuclear fusion.}

{However most of our pupils are not worried about the history of chemistry—they will take much for granted—nor will they find the neat laws of gas behaviour very romantic, except for the idea of absolute zero.}

{Behaviour at very low and very high temperatures may be thrilling, and relevant to modern technology, but if there is any discussion of them, the simplest acquaintance with the traditional gas laws would more than suffice. That is why we suggest teachers should show Boyle's Law by a simple clear demonstration; and we urge teachers to economize as much as they feel they can in experiments on gases and temperature-changes.}

{We do *not* suggest combining our various gas laws to a general law, $PV = RT$. We leave that for colleagues to do in other sciences where they need it. At a more advanced stage in physics it is, of course, useful. At the moment it would seem a formality rather than a clever combining of separate pieces of knowledge; and it might involve us in awkward statements about the temperature scale used for T.}

Temperature

Pupils have a picture of gas molecules flying about with random motion, making collisions, but only after a long trip compared with their own size or even their average distance from a neighbour. Ask what happens, in such a picture, when we make a gas hotter.

Pupils probably know that if a tin can sealed up full of air is heated the pressure in it will grow bigger and it may even burst. A quick demonstration is popular.

Demonstration 82 Air Heated but not allowed to Expand: Increase of Pressure on Heating *(OPTIONAL)*

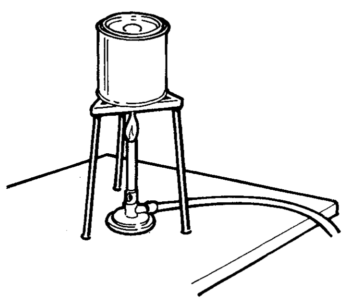
Apparatus

1 Bunsen burner	item 508
1 tin with well-fitting, push-in, lid	
1 tripod	511

A Nescafé type of tin is suitable.

Procedure

Close the tin firmly. Heat it over the Bunsen burner until the pressure blows the lid off.



Show pupils a gentler, more scientific, test with a glass flask of air connected to a Bourdon gauge that reads *absolute pressure*.

Qualitative Demonstration 83 Air Heated but not allowed to Expand: Increase of Pressure with Temperature *(OPTIONAL)*

The apparatus for this preliminary *qualitative* demonstration is the same as that for the pupils' *quantitative* class experiment (84), which follows. For details of equipment see Expt. 84.

Apparatus

1 Bourdon pressure-gauge	item 67
1 250-cm^3 flask (*not* 500 cm^3)	548
1 bung with glass tube and rubber tubing	549/2
1 tall aluminium container	76
1 Bunsen burner and tubing	508
1 tripod	511

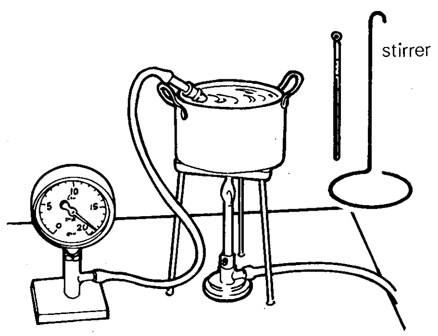
If ice is available a container of ice and water should be ready as well.

Procedure

Arrange as in the sketch. Connect the flask by rubber tubing to the pressure-gauge. Heat the water in the container till it is nearly boiling and plunge the flask into it. Pupils watch the gauge.

Cool the flask again by plunging it in cold water. This should be shown *very quickly*. The aim is only to show *there is a change of pressure* in a confined gas when it is heated. Measurements should follow at once in the class experiment.

The flask should be well covered by water, preferably right up to its neck; but that is not essential in this *qualitative* demonstration. (Explain that a neck left out in the cold would be very poor physics for the *quantitative* class experiment which follows now.)



Programme: Experiment and Discussion

Experiment As soon as is convenient after that qualitative demonstration pupils should do the class experiment with measurements (Expt 84).

Discussion: molecular picture At the same time, ask questions about interpreting the heating of a gas in terms of molecular behaviour. Ask pupils to think about molecules in air that is heated in a closed container:

What happens to the pressure of air *when heated like that*? If pressure is just the result of molecules bombarding the walls, *why does the pressure change*?

How can the molecules make a bigger pressure? There are just as many as before. (We doubt if the heating can manufacture extra molecules.) So the same lot of molecules make more pressure. How?

We hope pupils will say, 'The molecules must bombard the walls more often *or* more violently.'

Then, we hope, pupils can be coaxed into the comments: 'If more often, the molecules must be moving faster; and, if more violently, something must have changed to make the collision more violent.' Suggest that, if a gas molecule makes a more violent collision when it hits a wall, that must be because *it is moving faster*.*

So both suggestions, *more frequent* collisions, and *more violent* collisions, lead to the idea of molecules moving faster in a hotter gas.

{For our own thinking as physicists, now reverse the story; *if* molecules move faster, they *will* make more violent collisions—consider momentum—and they *will* arrive back at a wall for another bang more often. So we might expect the speed to appear *twice over* as a factor in the pressure. With a fast group we might even encourage them to guess that perhaps PRESSURE varies as $(\text{SPEED})^2$—which more careful examination in full kinetic theory shows is so, at constant volume.}

(With a very fast group suggest that a gas molecule's motion energy (K.E.) which clearly increases with temperature, might be a good way of measuring the temperature itself. At most we should only suggest that, at this stage. We shall return to it in Year 4.)

Looking for Absolute Zero

'Why do we learn this?' To modern young scientists looking for—or 'verifying'—a relationship between physical quantities, we say 'the relationship is important'; and pupils who collect facts, from interest or from habit, reply, 'But, we know it already.' Then they find the search artificial and tedious.* Here that danger is strong, unless we first build a need to know, a *wish* to know—about a romantic outcome of absolute zero.

Leading questions Therefore teachers may want to prepare for Expt 84 by questions which pupils will find in *Pupils' Text 3*:

What must happen to the *motion* of air molecules when you heat some air? What happens to their motion when you *cool* the air?

Think of cooling the air in a bottle more and more: colder . . . colder . . . colder . . . *Could you cool it till its molecules had no motion at all?*

Suppose there were such a temperature: somewhere far down on the scale of the thermometer at which molecules would have (for practical purposes†) no motion. What would the PRESSURE be like at that temperature?

Point out the assumption: we take it for granted that our picture of gas molecules is reliable. If we trust that picture, we expect the pressure to fall to nothing.

Of course before they got down to that temperature real air molecules would form a liquid and then a solid. Yet you can imagine an 'ideal' gas and discover what the temperature *would* be at which that gas would collapse with no useful motion.

Pressure and Temperature for a Gas

As a class experiment, pupils make measurements with a flask full of dry air.

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* Here the imaginary pantomime may be helpful. Ask what we could change about a pupil-molecule to make his collision with one of the wall people more violent? We expect pupils to answer, without our having to tell them: 'only his speed, unless he changes his "squashiness" '—and we say 'molecules do not do that (at ordinary temperatures)'.

* Traditional verifications have harmed the reputation of physics, for beginners and even at advanced levels. We have seen young pupils carefully measuring a specific heat capacity which they did not need; and older pupils being shown laborious tests of $v = n\lambda$ at different points in the electromagnetic spectrum—when some of the measurements had to be assumed and the relationship itself already seemed geometrically obvious.

† The remark in parentheses is a bow to Quantum Mechanics, which holds that molecules keep a small but inaccessible share of 'zero-point energy' of vibration even at absolute zero.

This investigation leading to the Pressure Law is the only *class* experiment in the programme concerned with gas laws. Measurements of VOLUME and TEMPERATURE (Charles' Law) and of PRESSURE and VOLUME (Boyle's Law) are *demonstrations* with expensive—but simple and clear—apparatus. Therefore schools should have sufficient equipment to make this pressure law experiment a genuine class investigation with its important outcome of an absolute-temperature scale.

There should be one Bourdon gauge for every *four* pupils—if more than four work together, the sense of ownership will be lost and the instruction '*plot your own measurements*' (to discover absolute zero) will be meaningless.

Pupils measure the pressure with a Bourdon gauge and the temperature with an ordinary mercury thermometer. They should use as large a range of temperature as possible, taking only a few measurements, since this is a matter of looking for a simple law rather than going into precise detail.

The change of pressure when air is heated from melting-ice temperature to boiling-water temperature will seem disappointingly small. And with a simple dial gauge the pressures may not be read very precisely. Yet this form can yield quite good results—the points on the graph near to a straight line, and the estimate of absolute zero not too far from $-273\,^{\circ}$C, provided it is arranged carefully and pupils are warned about stirring and total immersion.

Since both the other tests of gas behaviour, to show Charles' Law and Boyle's Law, are now *demonstrations* it is important to make this first test, P vs. T, a *class experiment*. So, although the Bourdon gauges are only used for this, they should be provided—at least eight for a class of 32.

Details of Apparatus for Air Pressure *vs.* Temperature

FLASK. The sample of air should be in a round-bottomed flask with a rubber stopper, not a cork one. The stopper should be wired in, unless it fits very well indeed. A little saliva will help.

The tube from flask to gauge should be as narrow and short as is convenient; but the error introduced by the 'dead space' of air in the tube is likely to be smaller than that due to the dead space in the gauge—and both will be trivial compared with the large error that will arise if the neck of the flask is not fully heated. Therefore the sizes of flask and water bath must be chosen so that the body of the flask *and its neck right up to the rubber stopper* are immersed in the heating water. Otherwise the temperature measurement is meaningless—only *some* of the sample is at the recorded temperature. A 250 cm^3 round-bottomed flask can be immersed fully in the aluminium container (item 76) or in a 1000 cm^3 tall beaker (item 513). (But a 500 cm^3 flask is too large.)

The flask must be gripped at the *top* of its neck, where the rubber stopper is, with a good clamp on a massive stand. The clamp must be brought down till the bottom of the flask almost touches the bottom of the container. (In early trials the flask was sometimes allowed to extend out of water with unsatisfactory results!)

STIRRER. Constant stirring is essential. A stirrer should be made of stout wire bent to a ring and handle.

BOURDON GAUGE. This should be arranged to read *absolute pressure*, so that when it is open to the air it reads atmospheric pressure. Therefore since it is really a differential gauge, it must be set for the altitude of the locality. That saves us the usual worries about 'remembering to add the atmosphere'. We recommend this experiment with a direct reading gauge very strongly, instead of one which involves columns of mercury and an added barometer.

Class Expt 84 Measurements on Air being heated: Variation of Pressure with Temperature, leading to the Concept of Absolute Zero

Apparatus

8 Bourdon gauges	item 67
8 250-cm^3 round-bottomed flasks (*not* 500 cm^3)	548
8 aluminium containers	76
8 bungs with glass tubes and rubber tubing	549/2
8 Bunsen burners	508
8 tripods	511
8 thermometers	542
8 retort stands, bosses, and clamps	503–505
ice	
[8 deep beakers (1000 cm^3) for ice	513]

Pupils work in groups of 4.

Preparation

Pupils heat the flask in water in the aluminium container. The flask must be firmly clamped to hold it fully under water. The water level must reach the top of the neck of the flask, which should be tilted. Therefore it is best to have each flask already clamped and held in a stand at the right level.

Procedure

Pupils take several pairs of readings of pressure and temperature. They must stir the water in the heating bath vigorously all the time. Encourage stirring that carries bubbles down into the water.

Before each reading, pupils must remove the Bunsen burner and continue to stir for a few minutes to bring the air sample to the same temperature as the water outside.

If melting ice is used for one of the measurements, it is essential to have the flask completely surrounded by it. It is best to put ice and a little water into the container, then push the flask down into this sea of icebergs, then add more ice on top, so that the whole flask is surrounded.

Pupils plot a graph of PRESSURE against TEMPERATURE *for the temperature range of their measurements*. They draw a 'best straight line'.

The graph is likely to be straight enough to justify drawing a 'question-asking' straight line* which tests whether the plotted points (the true results of the experiment) fit closely an ideal simple law—which is what we would *like* to find, because it makes our description of nature easy and simple.

If some pupils have points that do not seem to suggest a straight line, organize a 'picture gallery' of everybody's graph. That will enable the class to extract a general conclusion—as in a professional research team's work.

Then suggest each pupil should extend his line backwards to look for absolute zero—*Pupils' Text 3* describes that as a separate Experiment 84X. That requires a new graph with its temperature scale extending 300 °C below the ice point. Even though that crowds the experimental points into a very small region, pupils should draw that second graph. For one thing, it emphasizes the practical risk of losing sight of the behaviour of real gases.

However, some faster pupils may suggest a safeguard against that practical risk: 'Go back to the first graph with the more limited temperature-range and *calculate* the position of absolute zero from it by working backwards along the slope.' Pupils who suggest that, should certainly try it, though we should encourage them to draw the graph as well. When a young pupil wants to find something very exciting—as absolute zero should be—he can face quite complicated questions of arithmetic or geometry and deal with them successfully.

Pupils should emerge with a clear idea that, *judged by a mercury thermometer*, gas pressure runs down an almost straight line as temperature falls, a straight line *directed towards* zero pressure at a temperature somewhere between −250 °C and −300 °C. And we call that 'absolute zero'.

'Extrapolation' Discuss extrapolation at some point, not as an artificial preliminary but when questions arise. *Pupils' Text 3* says:

Give pupils the result of accurate measurements, −273 °C, but let their own experiment retain its full importance as an 'experiment of principle' to enable them to claim they understand the measurement and to boast that, given facilities, they could make an accurate measurement themselves.

Absolute scale of temperature We can then make a simplification, by shifting our zero to that 'absolute zero' and reckoning all temperatures from there. We call that an 'absolute scale'. All we do is add 273 to all our Celsius temperature numbers.

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* *A note about types of graphs and their uses.*

Graphs are used to exhibit data, as a hospital temperature chart does. In the 'grammar' of graphs we might call that use '*indicative*'.

Graphs are used to enforce a definition, as a straight line is drawn between two fixed points to *define* a new temperature scale. We might call those '*imperative*'.

There are also '*interrogative*' graphs where an experimenter plots his measurements and then draws a straight line to ask the question, 'How close to a simple linear relationship do my experimental rules run?' In that case we may call the line chosen and imposed on the graph of points a '*question-asking line*'. That seems the best description of the graph suggested here of gas PRESSURE against TEMPERATURE BY THE MERCURY THERMOMETER.

However when we adopt the gas thermometer to define our scale of temperature, a straight line drawn between gas pressure and *gas-thermometer* temperature just expresses a definition: it is '*imperative*'.

Point out that the absolute scale is not used in giving the temperature of the weather or in giving a boiling point in chemistry; but that it is a remarkably clear, simple temperature-scale for our general thinking in physics.

A risky guess Look back at what you have done. When you continued your graph (or calculated) on down to find absolute zero, you were making a risky guess that the behaviour would stay the same. Continuing beyond all measurements like that is called '*extrapolation*'.

Extrapolation is a risky business, trusting or pretending that what you have observed continues on and on.

Did the Sun rise in the East this morning? Did it rise in the East yesterday? Did it rise in the East many a morning before that? Are you willing to *extrapolate* those observations into the future and say that you are *sure* the Sun will rise in the East tomorrow? Are you *quite sure*? . . .

Suppose you were not a human being but were a butterfly who emerged from a chrysalis on a warm day in early summer and flew about from flower to flower, day after day. What would you observe about the weather? A fine day, another fine day, another fine day, . . . If you were that insect, you might extrapolate and predict that every day in the future would be fine. You would not foresee the wintry day which would end your happy flights.

Extrapolation and interpolation Extrapolation would be very risky, if we trusted it for the molecules of a real gas like air or carbon dioxide. If we cool any gas enough, it fails to remain a gas. You may have seen carbon dioxide jammed together into cold solid crystals of 'dry ice'. Some day you will see air that has been cooled down and pushed together so that its molecules (having less energy of motion at that low temperature) hang together in a liquid.

Yet we can safely make the extrapolation *in imagination* and find a useful 'absolute zero' as a starting point for the grand Kelvin scale of temperature.

'Interpolation' means reading something off a graph between two measured points on it. (Or you can calculate an intermediate value between two values given in some table.) Interpolation is useful in science and engineering; and, if carefully done, it is safe. But in developing new science and technology, extrapolation is more important.

Although extrapolation is risky; *it is the way in which some of the great discoveries have been made.* Scientists guess what might happen if they continued our knowledge into unknown region; then they try to test their guess by experiments. And sometimes those experiments lead them in quite a new direction of knowledge.

Extrapolation is rash but sometimes very fruitful; interpolation is safe but dull.

Kelvin absolute thermodynamic scale In moving to an absolute scale, we need not change the fundamental scheme of temperature-measurement. We *could* still have a scale that extends the mercury-in-glass thermometer's scale. But the close agreements among many gases, and later the development of thermodynamics, persuade us to re-define our temperature measurement for gas thermometers and then finally move to the Kelvin absolute thermodynamic scale.

All we need tell pupils at this stage is the shift to an absolute scale by adding 273; and our adoption of a gas thermometer as standard instead of one using mercury expansion.

Pupils' Text 3 describes the choosing of the Kelvin scale and mentions its advantages; and there are comments on the mercury scale. Pupils will probably conclude that the Kelvin scale is just the scale of a gas thermometer—clumsy, but more general, and far more extensive in range. References to an ideal gas and to a heat-engine basis are there, but those probably seem too remote.

This *Guide* has a note for teachers on the philosophy of gas laws and temperature just after the account of the Charles' Law investigation on page 176.

Volume and Temperature for a Gas: Charles' Law

Experimentally, Charles' Law is difficult to demonstrate accurately and the simpler forms of apparatus usually given to pupils are not very precise.

Charles' Law seems to most people a more obvious way of looking at gas behaviour than measuring the pressure. In our programme, however, we look at the pressure changes first because we are talking about pressure in terms of our molecular model and can give a more convincing idea of absolute zero that way—it is easier to picture the pressure collapsing to nothing when there is no bombarding molecular motion than to say there is a special temperature at which the gas will *shrink to no volume*.

Charles' Law: Description of Apparatus

Instead of the usual capillary tube with a bead of mercury as index, we suggest a new *demonstration* design which has worked well in trials. The sample of air is enclosed in a glass tube which is heated in a tall beaker of water. The sample is enclosed by a piston of oil, as in the Nuffield Boyle's Law apparatus; but in this case the piston ensures a constant pressure instead of applying a range of pressures.

A stopcock at the top of the tube makes it easy to change the sample of dry air and to adjust the pressure to atmospheric before starting the demonstration. The lower end of the tube is bent round and up to make a U-shape. Its open end is connected by plastic tubing to an open oil reservoir. Oil fills this device, from the reservoir all the way over to a point near the bottom of the leg that contains the sample of air.

Except for very small differences, due to the head of oil, the pressure of the sample remains atmospheric as the water is heated from room temperature (or even icepoint) to somewhere near boiling point of water. With a translucent screen behind and a scale marked in centimetres, the volume measurement is like that in the Boyle's Law demonstration.

In trials, extrapolation of the graph-line gave $-240\,°C$ for absolute zero—suggesting that considerable care is needed to heat slowly, and stop heating and stir for some time before each measurement.

Demonstration 85 Air Expanding at Constant Pressure: Charles' Law

Apparatus

From Charles' Law kit*	item 203
special glass U-tube with plastic tubing	203A
1 large beaker, tall-form, 2000 cm^3	203B
piece of centimetre ruler (must withstand boiling water)	203C
rubber bands	203D
stirrer	203E
open dish for oil	528
supply of oil	
1 Bunsen burner	508
1 tripod	511
1 demonstration thermometer	145
1 retort stand, boss, and clamp	503–506
gauze to support beaker	510

Preparation

Place the glass device in the beaker on the tripod, almost touching the bottom. Clamp the device firmly so that it will not be upset by stirring.

Fill the open reservoir dish with oil.

Open the stopcock. Hold the open end of the plastic tube upright about 10 cm below the level of the stopcock. Pour oil into the plastic tube through a small funnel until it fills the whole device except for 10 cm of air under the stopcock. Place a finger on the open end of the plastic tube, close the stopcock, and invert the end of the plastic tube under the oil in the reservoir.

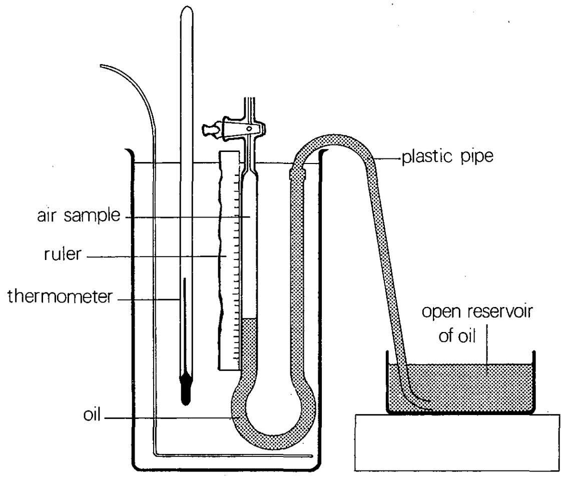
If the experiment is to be done with dry air, fill the whole device with oil as above. Attach a drying tube to the stopcock and then let oil flow back to the reservoir until a 10-cm column of air has been drawn in through the stopcock.

Procedure

Fill the beaker with cold water. Stir well. Heat slowly, and take half a dozen pairs of readings of volume (measured by length of air column) and temperature.

Before each measurement, remove the flame and stir for 2 minutes. A general rate of heating of about 1 °C/minute is suitable.

Each pupil should then plot a graph of LENGTH OF AIR COLUMN against Celsius TEMPERATURE.



Kelvin scale of temperature again? If the graph has points near a straight line, each pupil should draw his own choice of 'best straight line' on this graph, to test for simple behaviour.

Then ask whether that line would extend backwards to the *same* absolute zero. Since all the graphs are derived from the same set of measurements in the demonstration, it seems justifiable for the teacher to plot a demonstration graph for the extrapolation. That will save time and will direct attention to the important outcome.

* This is a new Nuffield Physics item.

Deciding on the best, fairest line to draw on that graph should be by pupils' vote.

The graph points to an 'absolute zero' where *ideally* the air would occupy no VOLUME at all. Pupils may find that harder to picture for a real gas than PRESSURE falling to zero.

Explain that more careful measurements lead to the *same* 'absolute zero' as for pressure: 273 degrees below 0 °C.

Gas Laws and Temperature: A Note to Teachers

{**Experimental summaries or definitions?** As long as either Charles' Law or the pressure law (which we might call X's Law) is an experimental law, it connects gas behaviour with readings of temperature on a mercury thermometer.}

{If we find that the experimental points, for either set of measurements, lie very close to a straight line we may say that gas volume (or gas pressure) varies directly as absolute temperature on the extended scale *of the mercury thermometer*. And we may suggest using a gas thermometer to extend the mercury thermometer's scale by extrapolation. However, that gas thermometer would then be only a secondary servant, like a platinum-resistance thermometer, or a thermocouple thermometer. (The latter has a somewhat curved graph of e.m.f. *vs.* mercury-thermometer-temperature, but yet we can use it as a secondary thermometer by calibrating it against a mercury thermometer.)}

{In all this we do not escape from the original lucky choice of the expansion of mercury as our measure of temperature. That was lucky, because mercury-expansion plotted against gas volume (or gas pressure), gives a graph nearer to a straight line than the expansion of most other liquids. In that sense we can, of course, say that 'mercury expands uniformly' without committing the illogic of a circular argument—but only in that sense.}

{We may wish to break with older tradition, and start afresh with a new temperature-scale which we consider more universal, because different gases agree closely in providing the scale. Then we must *define* absolute temperature on our gas thermometer scale as directly proportional to either pressure or volume (in each case the other variable quantity being held constant). The moment we do that, Charles' Law (or X's Law) becomes *automatically* true: it is simply a definition of what we mean by temperature on our new scale. The experimental law would now be one which says that mercury does expand fairly uniformly *when temperature is measured on the gas-thermometer scale*.

{In modern practice we do adopt the gas thermometer as our ultimate *practical* standard, for three reasons:

a. Since a widely differing assortment of gases all agree closely in yielding the same scale, some of us have a mystical feeling of satisfaction that we are no longer attaching 'temperature' to a particular liquid metal. That is probably only a relic of a childish seeking of 'the "really-true" temperature'.

b. As a practical standard, a gas thermometer is more reliable, though it is clumsy and difficult to handle. Mercury thermometers suffer from the bad behaviour of the glass of their bulb. Glass is not a proper solid, but rather a supercooled liquid, which is always complaining about its previous treatment. A mercury thermometer which has recently been heated has a sagging glass bulb that is slowly shrinking back to its earlier volume, meanwhile making the mercury read too low. The tale of such difficulties grows when we try to use a mercury thermometer with great precision over a long period of time. A gas thermometer also has a bulb of glass (or silica), but the vindictive memory of the material has a *relatively* small effect on the measurements we make with the big volume of gas inside.

c. We go one step farther and define a universal scale of temperature by considering the efficiency of an ideal heat-engine (carnot). In that, we can, in imagination, use any working material we like, always with the same resulting scale of temperature. Then we find, a surprising outcome of further reasoning, that our new scale agrees with the scale of an *ideal* gas thermometer. In ordinary temperature ranges, real gases differ from the ideal behaviour by small amounts, which can be measured.

{So we can use gas thermometers directly to measure in °A or K.}

{We cannot labour any such discussion of the philosophy of temperature measurement with our young pupils. Yet we should not suggest changing to a gas-thermometer definition and then give the impression that we still find Charles' Law and X's Law experimental laws for gases! We should give *some* hint that we are changing now to a new definition of temperature, enshrined in one or both of those laws.}

Boyle's Law

Ask what will happen if we keep temperature constant but let pressure and volume change. It is usual in teaching to start with Boyle's Law, but here with our emphasis on energy it seems easier to treat the effects of temperature change first. We have the advantage now that pupils will not forget that Boyle's Law sums up the behaviour of air at constant temperature.

{Here we suggest a demonstration to save time. Quite precise measurements of volume and pressure of gas can be taken with standard apparatus available in schools: so precise that deviations from Boyle's Law can be noticed. (Unless a specially uniform tube is used for the sample, variations of PV are more likely to be due to uneven cross-section than to deviations from Boyle's Law.) However, at this stage, we are still building acquaintance with nature rather than precision of technique. We wish to give pupils the best apparatus we can provide without entailing a long subsidiary explanation of measuring the pressure or volume.}

{Teachers will differ in their choice here: some will wish to have simple apparatus that shows Boyle's Law quickly; others will prefer to give a careful introduction to apparatus that gives a very satisfying series of constant products. We favour the former strongly for our programme.}

Description of the simple Nuffield apparatus

This has the sample of dry air in a wide glass tube with a coarse scale of volume beside it. The sample is compressed by driving up the tube a piston of oil from a reservoir.

There is an air space above the oil in the reservoir and the pressure is increased by pumping more air into that space with a foot pump. The pressure at the reservoir is measured on a Bourdon gauge—which must be graduated to read absolute pressure for the sake of clear teaching.

This makes a direct and clear demonstration but it does not give very precise measurements.

Demonstration 86 Boyle's Law

Apparatus

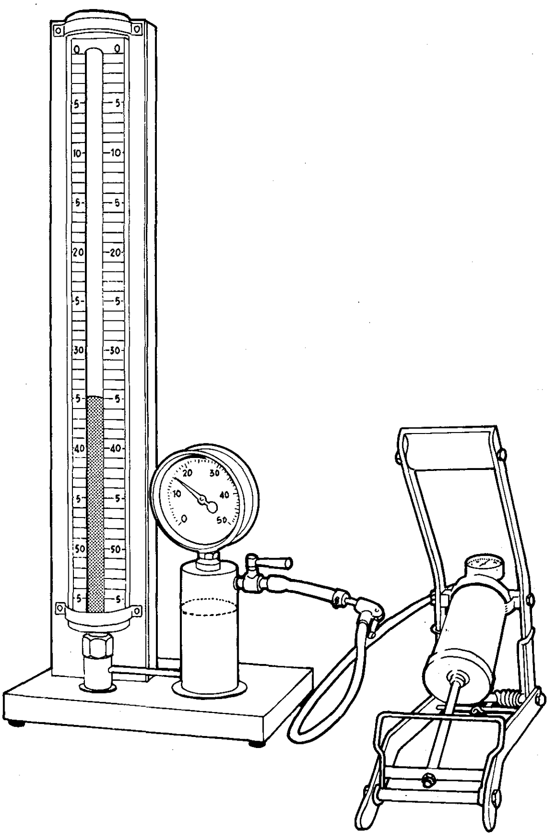
1 Boyle's Law apparatus	item 109
1 footpump and adaptor	45

Procedure

Apply pressure to the oil in the reservoir by gentle use of the footpump. Read the Bourdon gauge and the corresponding length of the air column and record them.

Each pupil should try multiplying PRESSURE by VOLUME.

NOTE. To fill the apparatus with oil, unscrew the Bourdon gauge with a spanner. Fill the reservoir with oil of low vapour pressure. Redex is suitable and clearly visible. It is necessary to tilt the apparatus in the final stage of filling in order to get enough oil into the main tube. When refixing the gauge, tighten the nut enough to get a good seal, but not so much that the thread is damaged.



Graphs Plotting graphs of Boyle's Law behaviour is interesting work for neat fingers, but may take more time than we wish to spare at the moment. We suggest simple arithmetic and, at most, quick crude graphs for now.

History. We might tell pupils:

Three hundred years ago, the Honourable Robert Boyle reported to the Royal Society of London his discovery 'concerning the Spring of the Air'. He was experimenting on a sample of air, as if it were a spring, to see if it fitted with Hooke's Law. He made his own glass apparatus to hold a sample of air. He changed the pressure from four atmospheres to a small fraction of an atmosphere and measured pressure and volume at a number of stages. He kept the temperature constant—or, rather, nature kept it constant, because he did his experiment in a room which did not grow hotter or colder.

Air does not fit with Hooke's Law. Air has quite a different relationship between pressure and volume, and Boyle discovered it, as he said, 'not without delight and satisfaction'.

Different apparatus for Boyle's Law If the more usual apparatus with mercury and a movable tube is used, we should be careful to explain to pupils what the aim of the experiment is. For example:

Some of you already know what Boyle discovered; and in that case you will be trying your skill against the apparatus, to see whether you agree with the behaviour that Boyle found.

Other people have carried out the same experiment very carefully and there is no doubt that Boyle's story, a simple one, is followed very closely by gases such as air. So—we must be honest—you are not discovering something unknown; but we hope you will enjoy making measurements to see whether they fit together in a satisfying way.

[Some of your neighbours have not heard of Boyle's discovery. They will have extra fun: they can try to find out what Boyle discovered without knowing the answer. Please don't tell them.]

Boyle's Law After the experiment, make sure that pupils know that PRESSURE × VOLUME gives a constant value, the same value for one pressure after another.

Theory and Boyle's Law

A very simple theory *(AN OPTIONAL EXTRA NOW)* With a fast group it is good to offer a tentative theoretical discussion—to be taken up properly next year. *Pupils' Text 3* says:

Think of our picture of molecules flying about with rapid motion in all directions and making pressure by bombarding the walls of the container. Suppose you have a box of gas like that and carefully put more molecules in (like a collector putting more beetles in his box) until there are just twice as many in the box as before. What would that do to the pressure?

(When there are more molecules, they will collide with each other more often and may even get in each other's way. But does that matter? Think of a molecule flying along on its way to hit a wall and make a contribution to the pressure. Suppose that molecule does meet another on its way, head-on. They collide and bounce away in opposite directions: they simply exchange jobs.)

[What would you do if you were driving a car along a very narrow mountain road, too narrow to pass another car, and met another car going the opposite way? Suppose you had to get to your destination urgently . . . The drivers might exchange cars and each drive backwards. That's what molecules do in a collision: they exchange jobs. In general collisions should not make a noticeable difference to the pressure.]

So, with twice as many molecules in the box to do the bombarding, we should expect double the pressure.*

If you could see the population of molecules, it would look twice as crowded—twice as many molecules in each cubic centimetre in the box. But there is another way of crowding molecules till there are twice as many to the cubic centimetre. Start with the original (single) lot of molecules in the box and push one end of the box with a piston until the volume is halved—just as you saw in the Boyle's Law demonstration. Then once again you would have twice as many molecules *in each cubic centimetre.*

The pressure-gauge could not know any difference between those two ways of doing the crowding. So you may expect *double pressure* with *half the volume.* And that is just what Robert Boyle found.

That is the kind of thing we like a theory to do for us. We like it to predict something that we already know, because then we think we are making a helpful picture. Then we ask new questions about the picture; we let it help us to make further predictions.

For example, we could ask how a gas would behave if it had very fat molecules; or if its molecules attracted

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* In fact this simple story conceals a very important assumption. *We are assuming that molecules do not interact.* If in their flight through the box, molecules attract each other, or repel each other, for a tiny but appreciable fraction of the time, then putting in more molecules will give those forces play for a larger fraction of the time and we shall see a deviation from this simple story. We are also assuming that the molecules have negligible volume. Otherwise, putting in more molecules would shorten the paths between collisions by the size of molecules themselves and thus make the bombardment of the walls slightly more frequent and thus make the pressure increase more than we expect from the simple story. We should not even mention such matters to pupils now; but we should keep them in the back of our mind.

each other when quite far apart. Think about such a gas. *How would that change our prediction of Boyle's Law?*

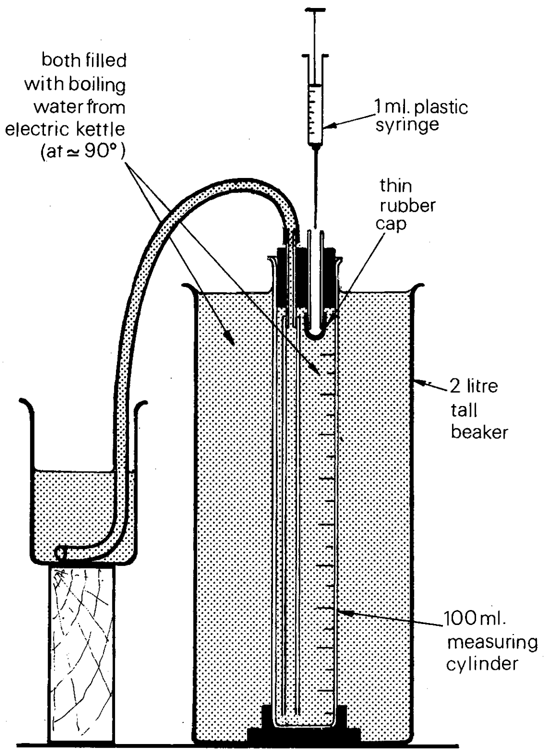
Actually, we find that real gases do not quite fit with Boyle's Law in their behaviour: and, with the help of imaginative thinking, we can understand their misbehaviour and find out very interesting things such as the size of a single molecule.

As an example of modifying Boyle's Law with the help of 'theory'—here just common sense—pupils may like the following 'question to think about for the future', in *Pupils' Text 3*:

Suppose you could make the pressure of air ten times as big . . . a hundred times as big . . . a thousand times as big, and so on, would the volume shrink to 1/10 . . . 1/100 . . . 1/1000 . . . 1/1 000 000 without limit?

Gas . . . Liquid *(AN OPTIONAL EXTENSION NOW)* The question above may lead to a suggestion of liquefaction. A delightful demonstration illustrates the large change of volume. This is an important measurement in Year 4.

Demonstration 85X Change of Volume, Liquid to Gas, using Petrol *(OPTIONAL NOW)*



Apparatus

From Change-of-Volume Kit*: item 204

measuring jar 100 cm^3	204/A
special rubber stopper† for measuring jar with 2 tubes inserted	204/B
plastic tube to extend to bottom of measuring jar	204/C
plastic tube to carry over to beaker	204/D
small rubber cap (to be pierced by hypodermic needle)	204/E (= 148/2)
hypodermic syringe 1.0 cm^3	204/F (= 148/3)
2000 cm^3 glass beaker, tall-form	204/G
wire stirrer	204/H
1 beaker, 400 cm^3	512/2
Petrol‡	

* New Nuffield item.

† If the jar has a pouring lip, the stopper must extend below the lip to prevent leakage there.

‡ Ordinary petrol does well. Do not use cigarette lighter fluid: its boiling point is too high.

Procedure

Place the measuring cylinder in the tall beaker. Put about 200 cm^3 of water in the small beaker. Fill the tall beaker and the measuring cylinder with hot water (80 °C). Close the cylinder with the bung and bring a plastic tube from the outlet in the bung over to the water in the small beaker.

Push the needle of the syringe through the rubber cap on the short tube in the bung. Inject 0.1 cm^3 of petrol.

As the petrol expands to vapour the displaced hot water runs over into the small beaker.

To reverse the change, take the measuring cylinder out of the large beaker and stand it on the table. Wait for it to cool to say 60 °C. (The end of the plastic tube must stay under water in the small beaker.)

An Important Use of Theory

Even our simple qualitative theory can yield a useful interpretation of evaporation. The discussion of the energy-changes ought to wait until Year 4 but pupils who will finish physics with Year 3 should not miss this important topic.

Evaporation Discuss the mechanism in terms of molecules and simple knowledge of energy. (However, remember that the main discussion of Conservation of Energy comes in Year 4.) *Pupils' Text 3* says:

Remember how you used your tray of marbles to illustrate a liquid. Try it again if you like. Then think about some water in an open beaker. In any liquid the molecules are crowded much closer together than in a gas. They collide with neighbours much more often. Between collisions they move at about the same speeds as in a gas at the same temperature; but they are often in the field of attraction of neighbours, and that makes the liquid hang together.

At the surface of liquid some molecules are bounced outward by collisions with neighbours just below. They are like rockets fired into space, on a tiny scale. Real rockets are pulled down by gravity and most of them come back to Earth: only a few have more than escape velocity and get away altogether.

Water molecules that are bounced out are pulled back by the attraction of many water molecules in the liquid near the surface; and most of them fall back again. Only a few molecules that have been bounced out extra hard can escape. That escape *is* evaporation.

A molecule that does escape has to give up some motion-energy in escaping. In other words, an escaping molecule has to pay an 'exit-tax' out of its store of motion-energy. Only a molecule that happens to have, *at the moment, much more than average motion-energy* has enough to pay that tax.

If only those 'extra rich' molecules escape, what must happen to the temperature of the liquid that remains? Think about this very important question. Then discuss your answer with your teacher. Can you invent an experiment to test your answer? (Hint: lick your finger.)

We hope that pupils will themselves answer the question and argue that evaporation must be a cooling process. They can verify that by experiment.

We should tell pupils that the cooling—or else the extra supply of heat for replenishment—is large. The latent heat of vaporization of water is five or six times the heat energy needed to warm up the same mass of liquid water from melting point to boiling point.

{Although only 'extra-rich' molecules escape, they lose some of their kinetic energy while escaping, because they are pulled back by neighbours in the liquid. So the vapour consists of 'impoverished extra-rich' molecules. And in fact the average K.E. of molecules in the vapour is much the same as that of molecules in the liquid.}

{However, the molecules are crowded much closer in the liquid so that a molecule is in the attractive force-field of neighbours much of the time; therefore it has considerable negative potential energy. When vapour is formed, the latent heat of vaporization is a measure of the molecular K.E. that is taken away to cancel out that negative P.E.}

Practical applications of evaporation Mention the use of evaporation in refrigerators. Discuss the part played by evaporation in keeping our body temperature steady. When we work hard and over-heat (by the waste heat that our 25%-efficient* muscles produce) water comes out through the pores of exposed skin and cools us by evaporation. *Pupils' Text 3* says:

Keeping cool When you run or climb or do any other energetic job you not only draw upon food-energy for your muscles to do the job; you also turn a lot of food-energy into heat. Whether you like it or not, you over-heat. Or rather you *would* over-heat, and feel uncomfortable with a fever, if your body did not run an automatic cooling system. You sweat and where your damp skin is exposed—face, hands, arms—water evaporates. And that cools you.

In very damp weather or in a very crowded room, water condenses again on your skin almost as fast as it evaporates. Then sweating no longer cools you; and you feel uncomfortable. (The air in a stuffy crowded room is not rich enough in CO_2 to make you uncomfortable: it is the water vapour in the air—from people's breath—that makes your head ache. You still sweat, but the water cannot evaporate successfully and cool you. You develop a temporary fever.)

Boiling Pupils are apt to have careless views of the essential nature of boiling—a fixed(!) boiling point; or vapour 'pushing the outer air away' (when in fact vapour molecules diffuse through air easily); or a vague story of more copious evaporation with no clear reason for the *constancy* of boiling temperature. We need to ask 'what tells you water is boiling?'; and insist on the clear answer, '*bubbles* of steam'.

As we know, those bubbles cannot form and grow in the liquid until the vapour pressure in them matches the outside atmospheric pressure. Then they are an easy, unlimited, resort for evaporation. The liquid boils away as fast as we provide heat to pay the 'exit-tax' of latent heat. Thus, evaporation acts as a thermostat for a boiling liquid. (And the energy needed to pay the 'exit-tax' makes distilling an expensive business.)

* Our muscles could be as much as 70% efficient, *if we made them work infinitely slowly*. But for muscles in ordinary active use 25% is rather high.

There is a magnificent experiment, which unfortunately sounds undignified: pupils heat water in a small beaker and watch it carefully. They see small bubbles forming from dissolved air; but when boiling starts there is quite different formation of vapour in bubbles.

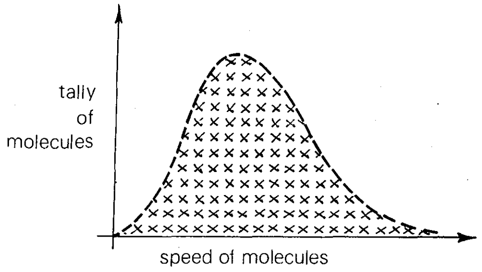
Pupils' Text 3 says:

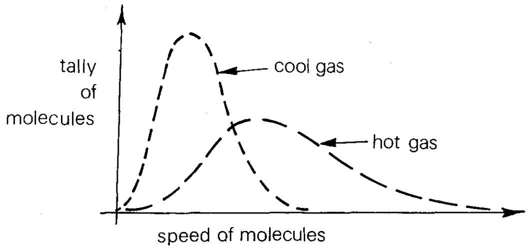
Evaporation also acts as a thermostat for a boiling liquid. A boiling liquid always makes bubbles of vapour (steam). Once the liquid is boiling, supplying more heat simply equips more molecules with enough motion-energy to evaporate into vapour bubbles. Therefore the temperature stays constant at the 'boiling point'.

Distribution of speeds While we are discussing uses of the molecular model some pupils may ask about the speeds of molecules. As they watch the teaching-models they see that an individual molecule changes its *speed* frequently. The whole collection of molecules has a great variety of speeds, all of them changing at each collision. The speeds have a statistical distribution around a constant average which is characteristic of the temperature.

Many pupils will miss that, and think that all molecules have the same speed, for a given temperature. We might draw their attention to the variety of speeds but we need not emphasize it at this stage.

(In chemical changes involving gases it is often the few extra-energetic molecules in the high-energy 'tail' of the distribution that start the reaction, and run it.)





CHAPTER 6

ELECTROMAGNETISM

Experiments with magnetic fields, currents, forces, meters, motors and electromagnetic induction

We now leave gases and use the electromagnetic kit for a further series of class experiments with electric currents and magnets.

The work with the electromagnetic kit has been placed near the end of our suggested programme for this Year, so that it can expand to fill whatever time is available.

All should do the class experiments described in this chapter. And any who did not meet a voltmeter informally in Year 2 as a 'cell-counter' should proceed to it (Chapter 7).

Chapter 7 then offers faster pupils a first quantitative treatment of potential difference and measurements of electrical power. And it provides a model power line experiment with very important implications for all pupils.

Chapter 8 offers faster pupils a very brief look at electric fields, chiefly so that they can understand the deflection of a stream of electrons in a fine-beam tube. We trust all pupils will see the fine-beam tube in action now.

At the very end of this Year (Chapter 9) we suggest for all a brief return to magnetism to leave pupils with an example of theory. This is an almost unique example of a theoretical treatment that is within the compass of understanding of young people and yet shows the power of theory to build scientific knowledge. We hope that the discussion and test will not be omitted or postponed. They are placed here as an important stage in pupils' learning about theory.

ELECTRIC CIRCUITS AND MAGNETISM

Catching up or overlap from earlier years Some pupils may have learnt a lot about circuits and currents with the Worcester circuit boards in Nuffield Year 2 or in Combined Science. For them, a revision of that work would be discouraging and unnecessary, because they will soon remember enough now that they are embarking on a new aspect.

Other pupils in Year 3 may have missed practical experience with electric circuits almost entirely. For them a few, quick, *class* experiments with circuit boards (Year 2) may be the best way to help them to catch up and start electromagnetism without a prejudice that electric circuits are difficult and mysterious.

For all pupils, we offer in *Pupils' Text 3* a series of reminder-notes and questions to help them 'remember what electric circuits do'. We also provide a vocabulary of electrical terms—not to be learnt by heart but to be available for reference, to dispel the reputation that 'electricity is full of strange words taken for granted'.

The New Aspect: Electromagnetism

Knowledge Class experiments will carry pupils through remarkable progress from a simple look at magnetic fields to a first feeling of understanding power stations.

Never mind if all that takes weeks. It should be a progress of delight, like that of confident bathers swept along by a great river, without being stopped by rocks of note-taking and map-drawing or stranded on an island marked with three-fingered signposts.

Yet there are many bathers who are not confident, and even the best of swimmers can lose his head. So, in this exploration, teachers, who know the journey, will need to give encouragement and support to pupils at different stages. We hope that all will arrive with delight and a sense of powerful knowledge.

Magnetic Fields

Traditionally, the teaching of electromagnetism starts with maps of magnetic fields of permanent magnets, using iron filings or a small compass needle. However, there is a good reason here for introducing this study by the field associated with an electric current. Pupils have already been using currents to pull a magnet in the Worcester current balance. They are familiar with currents and we want to lead them rapidly on to meters, motors, relays, and dynamos.

Electromagnetic Kit

All the work with the Westminster electromagnetic kit should be done by the pupils themselves. They should be given plenty of time, with the teacher doing his utmost to avoid giving the detailed instructions which would turn these experiments into a drill of following the teacher's physics instead of finding out one's own.

A class experiment should not be *preceded* by a demonstration, either with a spare set from the kit or with demonstration apparatus. However, in some cases, a class experiment may be *followed* by a demonstration, to clear things up or reinforce what has been learnt. As far as possible such demonstrations should be placed a considerable time after the class experiment.

If a particular class experiment provides some knowledge or skill that is needed for use at a later stage, the demonstration should be postponed until just before that later stage, when it provides excellent revision. Even then it may be better to return to a quick repeating of the class experiment.

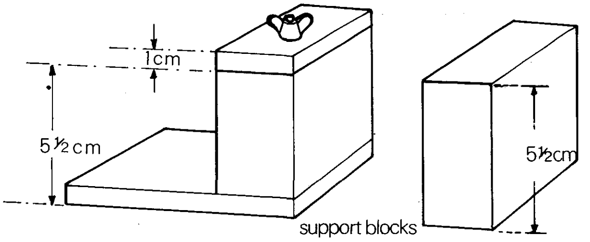
Westminster Kit: Equipment and General Instructions

THE KIT. This is designed for pupils to do their own experimenting. It contains enough equipment for a class of 32 pupils, working in pairs. If more than two pupils share a set of apparatus, this series of class experiments will lose much of its value.

WIRE. The wire that pupils use is PVC insulated copper wire, SWG 26. The kit contains 16 reels, one per pair. It will be easier for the running of the lab if each pair has a reel of this wire. Then they can take the length they need for each experiment.

WIRE STRIPPERS. There should be a pair of wire strippers (item 84) for each pair of pupils.

SUPPORT BLOCKS. (New Nuffield item.) Unless the particular commercial form of low-voltage supply that the School uses happens to have spare terminals which can be used as anchors, each pair of pupils should have two 'support blocks'. These are blocks of wood, one plain one, one with a clamping plate and wing nut. These are convenient for holding a card for iron filings, etc.; and necessary for the electric bell and buzzer models.



THE D.C. SUPPLY. Since currents will make the magnetic fields, each pair of pupils will need a d.c. supply for many parts of this group of experiments. It should be of very low voltage, one or two volts; but IT MUST BE ABLE TO SUPPLY A SHORT-CIRCUIT CURRENT OF A FULL 8 AMPS. For many of the magnetic-field experiments the large current through a short wire or coil is not a luxury: it is a necessity.

If the d.c. is derived from a rectifier and transformer fed by the mains a.c., it does not need to be smoothed; full-wave rectified a.c. will do. An accumulator could be used; but most dry cells would soon fail to give a large enough current.

THE A.C. SUPPLY. In some of the experiments a large-current low-voltage (1 or 2 V) a.c. supply will be needed. This may be incorporated in the d.c. supply. The transformer in it, centre-tapped for full wave rectification, can provide 1 V a.c. and 2 V a.c. Or a separate small transformer can be used.

Electromagnetic Kit: General Instructions

INSTRUCTIONS TO PUPILS. When pupils use iron filings for a magnetic field, they should be asked to:

> 'Clamp the card on one support block, and rest it on the other. Sprinkle iron filings on the card. Tap the card. Turn the current on. Tap the card again with finger or pencil. Turn the current off soon. After the experiment, tip the iron filings onto a spare sheet of paper, for return to the pot.'

These instructions, *which will not be reprinted here for each experiment*, should be issued to pupils each time, as guidance or reminders.

STRIPPING WIRES. As part of their experimenting, pupils should strip the ends of wires themselves—that preparation should not be done for them beforehand.

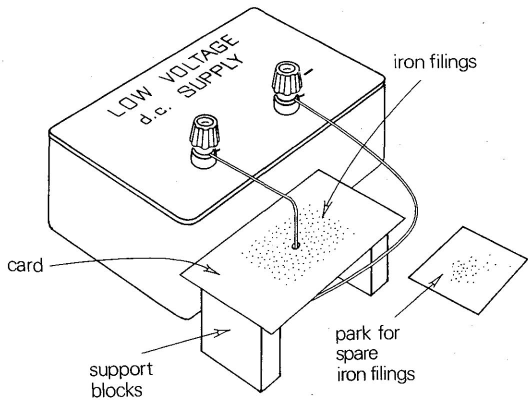
IRON FILINGS. After an experiment with iron filings, pupils should dump their filings on a spare sheet of paper, so that they can be collected.

CLEANING MAGNETS. Pupils may spend time and trouble in cleaning magnets without full success. It is probably better to collect the magnets and clean them afterwards. If one brushes filings *away* from the poles, most of them fall off. Sellotape or a lump of plasticine will help greatly in cleaning.

Class Expt 87a Look at the Magnetic Field of a Large Current in a Straight Wire

Apparatus

From electromagnetic kit, 16 sets of:	item 92
PVC-covered copper wire	92X
card or board	92V
iron filings	92 E & W
plotting compass	92D
16 *pairs* of support blocks	219 (=92 CC)
16 sheets of paper (pack for iron filings)	
16 wire strippers	84
16 low-voltage d.c. supplies	104

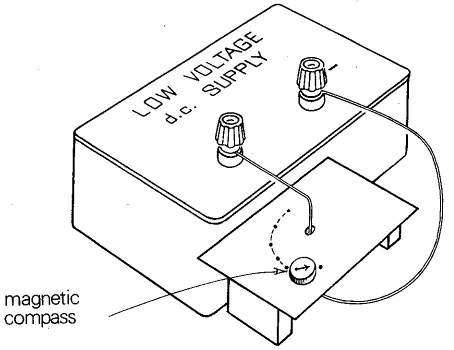


Pupils work in pairs. Each pair will use about $\frac{1}{2}$ metre of wire.

Preparation

Make a small hole for the wire in the centre of each card.

Make sure the d.c. low voltage power supplies give at least 8 amps on short-circuit.



Procedure

Each pair takes $\frac{1}{2}$ metre of wire and follows these instructions:

* * * * *

Remove the insulation at the ends with wire strippers.

Fix the card on support blocks: put the wire through the hole in the card and connect to the low voltage d.c. supply.

(i) Switch on. Sprinkle iron filings on the card. Tap the card gently with a pencil and watch.

(ii) After this, park the iron filings on a spare sheet of paper and explore with a small compass

(iii) Reverse the supply connections to see what effect this has on the compass needle.

* * * * *

Continuing experiments Pupils should go straight on with the series of magnetic-field experiments. However, since there may be questions and discussion concerning fields, we offer here some comments on teaching, some of which refer to the first experiment above, while others refer to much later experiments on currents and forces.

Fields

We suggest the following treatment as a way of making the name useful without deflecting attention from learning by experiments.

Tell pupils the filings show the pattern of a 'magnetic field'—something that the current 'produces', or something that goes with the current, something that is ready to push or pull magnets. The 'field' can make a small magnet, a compass needle, turn and lie along its pattern-lines.

Postpone any explanation of iron filings being temporary magnets—pupils should be busy making and looking at patterns quickly, one after another.

It will be a simplification to introduce the word 'field' now. But it would be unwise to develop the idea of a field further at the moment.

{There is a modern fashion of saying that only if we teach in terms of fields shall we make our teaching (a) up to date—in line with Relativity—and (b) clearer and easier for pupils.}

{Statement (a) is certainly true; but statement (b) needs to be modified by considering the age and stage of pupils. In Year 3, using the word 'field' as a short name is helpful; but if we insist that the thing we thus name has important extensive and intensive properties we are likely to make fields seem rather mysterious, and to endow the name itself with too much importance. Freud once wrote 'Words and magic were, in the beginning, one and the same thing'.}

The unimportant rules The direction of the lines can be related to the direction in which a compass needle on the card aligns itself. We must remember that this direction is only a convention.

In the teaching of electromagnetism, the habit has grown up of giving considerable importance to this convention which enables us to put arrows on magnetic lines of force, and to the later rules which enable us to predict the direction of the force on a current-carrying wire in a magnetic field, and the direction of an induced e.m.f.

Such rules are tested in traditional examination questions, as a trick way of finding out whether pupils have been taught that material. If the candidate just guesses, he has even chances of getting the example on the rule right or wrong—and that does not seem to make the question a very sensible test.

Worse still, the rules (and mnemonics used by pupils) may take charge and appear to some pupils to be the main substance of electromagnetism. It seems tragic to have pupils think that by twisting fingers and thumb of one hand (and perhaps holding their heads upside down) they can 'explain' how an electric motor works.

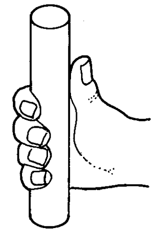
Of course those rules have their place: in advanced training, future physicists do need some quick rules for directions. Some physicists say that the rules are also essential for pupils who are to become electrical engineers; but we are told that sensible electrical engineers just turn on the current and see which way the wire moves.

However, there is one important connection: the directions given by the motor-rule and the dynamo-rule are related to each other—this *relation* is not just a convention; it is provided by experiment in a way that is *consistent with the conservation of energy*. A reversal of one component in that relation between the rules would suggest the possibility of perpetual motion.

We suggest that teachers should try the interesting experiment of giving no emphasis to any of these rules when they meet an opportunity for them; but should wait until they find a rule is really needed, and then provide the rule when the pupils themselves see that it is needed. We hope teachers will try this experiment of waiting for clear need—as felt by pupils as well as teacher.

A simple, useful rule Instead of a 3-finger rule, we suggest the following right-hand rule, which will be useful later in predicting forces. (This is the only rule of the kind that might be useful in examinations—but even this would be unimportant.)

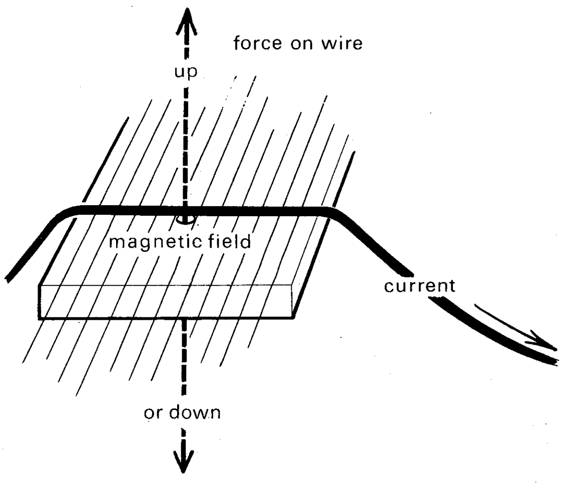
Use your right hand. Point your thumb along the direction of the current. Try to curl all your fingers round your thumb. Then the direction of your fingers shows the way the circles of magnetic field go round the wire. That is, they show the way the North-seeking pole of a compass-needle would point, near the wire.



If you have a *coil* carrying current, you may curl your fingers round your right thumb as before. Then, if your fingers curl the way round the current is flowing round the coil, your thumb points the way the magnetic field goes *through the middle of the coil.*

The experimental fact Pupils do need to remember the fact that when current and magnetic field are at right angles, the force is perpendicular to both.* *That* can be illustrated with thumb and two fingers of either hand, without giving them any labels.

When a current runs horizontally North and South across a horizontal magnetic field that runs East–West, the force is either up or down. We should accept 'up-or-down' as a sufficient statement of the orthogonal fact.



* When the magnetic field is not perpendicular to the current, only its component perpendicular to the current is effective, and the force is still perpendicular to the plane of both; but O-Level teaching—and examining—should be restricted to the case where all three are mutually perpendicular.

The answer 'up-or-down' In discussions and in tests, the distinction between a vertical (up-or-down) push and a sideways (left-or-right) push or one in the third direction (in-or-out) is much more important for a young person's understanding of something like a motor or an ammeter than the distinction between the two *senses* in each of those choices.

Then in describing the working of a very simple electric motor with one rectangular coil, we do not need to contort our hand to predict which way each side of the coil will be pushed by the magnetic field: we can just point to one side of the coil and say:

> 'This side will be pushed up-or-down. Which way will that *other* side be pushed?'

We hope to elicit the answer 'down-or-up'.

Œrsted's experiment Pupils should make a quick bow to one of the greatest experiments in the history of electromagnetism, and try Œrsted's experiment. He held a small compass needle near a wire and discovered the magnetic field of a current, in the middle of giving a lecture! That was in Denmark in 1812, when batteries were new and little was known about electric circuits.

Class Expt 87b Œrsted's Experiment

Apparatus

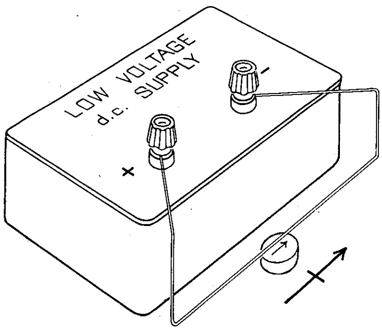
16 low-voltage d.c. supplies	item	104
From electromagnetic kit, 16 sets of:		92
PVC-covered copper wire		92X
iron filings		92 E & W
plotting compass		92D
16 wire strippers		84

Pupils work in pairs. Each pair will use about $\frac{1}{2}$ metre of wire.

Procedure

Pupils send a *large* current through a short straight horizontal wire. They hold the compass needle above and below the wire and watch.

They may also try sprinkling iron filings on the wire itself when the current is flowing.



OERSTED'S EXPERIMENT

If a pupil points out that this is just the previous experiment turned over on its side, give great praise.

Exhibition 87c Posters of Magnetic Fields

Apparatus

iron filings	item	92 E & W
support blocks		92CC
cardboard		92U
d.c. low voltage supplies		104
magnets to make fields		92A, B, I
coils to make fields		92F, X
floodlamp		218
photographic safelights		303
developer		308/1
hypo		308/2
normal bromide paper		308/3
2 dishes, photographic		308/4
sink for washing		

Procedure

Pupils make various field patterns with iron filings on sheets of bromide paper. They illuminate each sheet with bright light and develop and fix the picture.

Magnetic field of current in a hoop-coil
Pupils should go straight on to try a hoop-coil.

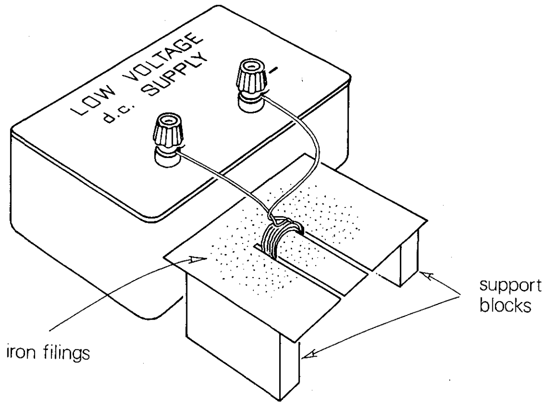
Class Expt 87d Magnetic Field of Hoop-Coil Carrying Current Apparatus

Apparatus

From electromagnetic kit, 16 sets of:

	item 92
PVC-covered copper wire	92X
card or board	92V
iron filings	92 E & W
plotting compass	92D
wooden rod	92F
16 wire strippers	84
16 low-voltage d.c. supplies	104
16 *pairs* of support blocks	219 (=92CC)

Pupils work in pairs. Each pair will use about 1 metre of wire.



Procedure

Pupils follow these instructions:

* * * * *

Wind 5 or 6 turns, closely spaced, on a wooden rod. Twist the ends to prevent unwinding. Slide the coil off the rod and into slots cut in a card. Connect the coil to the low voltage d.c. supply.

Sprinkle the board lightly with iron filings and look to see whether there is a magnetic field when there is not current. Then switch on the current, tap the board gently with a pencil, and watch.

Try a small compass, if you like, instead of iron filings. That will tell you which way the lines of the field run.

Try reversing the current.

* * * * *

(If a pupil says that the pattern *near the wires* is just the same as the previous pattern for the straight wire, give great praise for good observation and a flexible mind—but do not announce the idea to the whole class as a thing to look for.)

Long coil Pupils build up a long coil of many turns, making a close-wound solenoid.* They look at the external pattern with iron filings.

* The name 'solenoid' is a curious one, with an odd history of confusing definitions in some dictionaries. It would be wiser at this stage to avoid the air of mystery and just call it a 'long coil'.

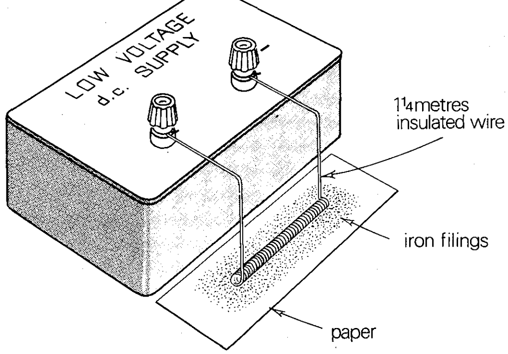
Class Expt 87e Magnetic Field of Current in a Long Close-wound Coil

Apparatus

From electromagnetic kit, 16 sets of:

	item 92
PVC-covered copper wire	92X
iron filings	92 E & W
plotting compass	92D
card or board	92V
16 wire strippers	84
16 low-voltage d.c. supplies	104
16 pencils	
16 sheets of paper	

Each pair will use about $1\frac{1}{4}$ metres of wire.



Procedure

Pupils follow these instructions:

* * * * *

Wind a coil firmly and closely on a pencil. Lay the coil on a sheet of paper, sprinkle with iron filings. Switch on the current, tap the board and watch.

Also try using a small compass after the iron filings.

* * * * *

Notebooks

Pupils are seeing these shapes of fields for the first time, in most cases. If we ask them to sketch what they see in notebooks, it takes so much time that it breaks up the experimenting into short pieces of seeing a real field separated by long pieces of drawing. And the sketches are apt to be rather unlike the true patterns.

Therefore, we suggest that pupils should *not* make sketches of the fields in their notebooks while doing these class experiments. This should be a time for seeing and learning quickly; and hurrying on to exciting things like an electric motor. Then, when pupils meet that, they will see the sense of knowing about magnetic fields and may be ready to draw some things in their notebook.

We hope teachers will post up large sketches and photographs of magnetic fields, *after* pupils have made them and seen them for themselves. These posters should remain on exhibit for people to learn the shapes by their continual presence, rather than by attempts at sketching.* Reflect that this is what some artists recommend for developing taste for pictures: they put good reproductions of great pictures on the walls but do not ask young people to try copying the great masters in an art appreciation class.

Solenoid and making magnets Ask pupils what they think the magnetic field might be like inside the tunnel of a long coil. Ask them how they could find out; and encourage them to suggest making an 'open coil' of turns, spaced well apart, so that one can see the magnetic field inside. When they use a solenoid to magnetize bars of steel, they should know that there is a strong uniform field inside.

* In a humane examination of the electromagnetism part of this programme, examiners would expect some general familiarity with magnetic-field patterns, and their interpretation. They would expect some simple sketches, but not careful, accurate drawings.

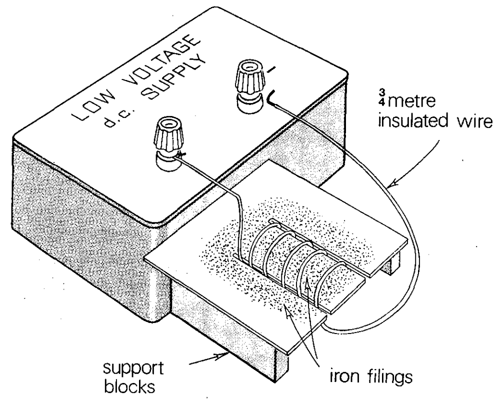
Class Expt 87f Magnetic Field inside an Open Coil carrying Current

Apparatus

From electromagnetic kit, 16 sets of:

	item 92
PVC-covered copper wire	92X
wooden rod	92F
iron filings	92 E & W
plotting compass	92D
card or board	92V
16 wire strippers	84
16 low-voltage d.c. supplies	104
16 *pairs* of support blocks	219 (=92CC)

Pupils work in pairs. Each pair will use about 1 metre of wire.



Procedure

Pupils follow these instructions:

* * * * *

Explore the magnetic field *inside* a coil. Wind 5 spaced turns on a wooden rod. As before, slide the coil off the cylinder and into slots in a card. Connect the coil to a low voltage d.c. supply.

Sprinkle iron filings on the card, paying particular attention to the field inside the coil. Switch the current on, tap the card and watch

Also try using plotting compasses.

* * * * *

Making Magnets

Pupils should now make a small electro-magnet and then a permanent magnet. Even if they have done that before they had better try it again, because they now know something about the magnetic field used for magnetizing.

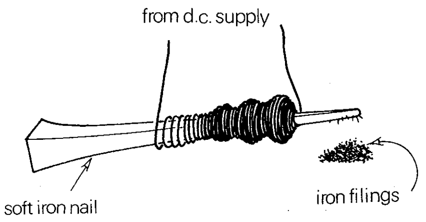
Class Expt 87g Simple Electromagnet

Apparatus

From Westminster electromagnetic kit, 16 sets of:

	item 92
PVC-covered copper wire	92X
iron filings	92 E & W
16 large nails (soft iron)	52M
supply of tintacks or paper clips, etc.	
16 wire strippers	84
16 low-voltage d.c. supplies	104

Pupils work in pairs. Each pair will use about $1\frac{1}{4}$ metres of insulated wire.



ELECTROMAGNET

Procedure

Pupils follow these instructions.

* * * * *

Wind a few dozen turns round an iron nail. Send a large current round the coil. Is the nail a magnet? Try it with iron filings. Turn the current off.

Also offer your electromagnet some larger bits of iron, such as tintacks or paper clips.

What happens each time you turn the current off?

* * * * *

Commentary Offer some information, as in *Pupils' Text 3*:

Most nails are made of iron or fairly soft steel (which is iron with some carbon melted in with it to add some strength). An iron nail or any other core of soft iron seems to stop being a magnet when you turn the current off. Soft iron makes a good *temporary* magnet.

The iron filings you have used are chips of soft iron and they become temporary magnets when they are in a magnetic field. You can see that they stop being magnets when the current is turned off, or when a permanent magnet is taken away, since they no longer cling together strongly in patterns.

Class Expt 87h Making a Permanent Magnet

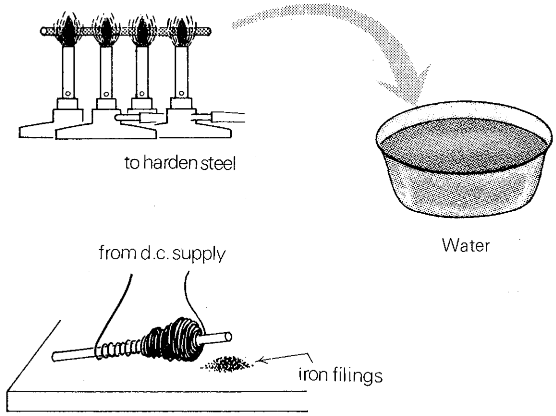
Apparatus

For pupils: as for the previous experiment (Electromagnet) but with the following instead of the large nails:

16 rods of hard steel‡	item 226
The teacher will need:	
1 de-magnetizing coil (300 turns or 2400 turns)	item 147D or 128
transformer or L.T. a.c. supply	27 or 59

‡ The steel rods may be knitting needles or pieces of clock spring. As a poor substitute for economy short pieces of thick piano wire can be used.

Pupils work in pairs. Each pair will need $1\frac{1}{4}$ metres of insulated wire.



MAKING A MAGNET

Preparation

Make sure the hard steel samples are not magnetized. If any are, de-magnetize them by passing them slowly through a coil carrying a.c. For the 300-turn coil, use about 6 V a.c.: for the 2400-turn coil, use about 20 V a.c.

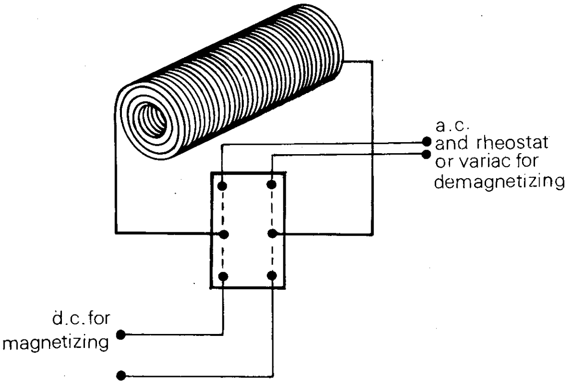
Procedure

Pupils wind a few dozen turns on the hard steel rod. They make tests with iron filings before and after turning off the current.

Class Expt 88 Magnetizing Coil *(OPTIONAL)*

If the coil that was used for de-magnetizing is available, connect it to a d.c. supply and let pupils magnetize things with it. With a long rod, they must pass the rod through the coil, with the current kept on. They can place a short rod inside the coil and switch the current on for a moment.

(For the 300-turn coil, use a 4-volt d.c. supply. For the 3600-turn coil, use a 20-volt d.c. supply.)



Permanent Magnets

†Experiments for catching-up or for overlap from earlier years Some pupils will have explored the behaviour of magnets in Year 2 or in Combined Science. They should go through any of Expts 89b *(i)* to *(iv)* they like, as quick reminders.

Other pupils may have missed experimenting with magnets. To catch up they should do Expt 89a for a start and then Expt 89b *(i)* to *(iv)*.

Class Expt 89a Permanent Magnets
(for newcomers to catch-up)

Apparatus

From electromagnetic kit, 16 sets of:	item 92
ticonal magnets	92A
plotting compass	92D
magnadur magnets	92B
iron filings	92 E & W

reels of thread or fishing line
tintacks, nails, paperclips, etc.
pieces of brass, glass, etc.

Procedure

Encourage pupils to try anything they like with magnets. (But warn them about watches.)

Class Expt 89b Magnets: Quick Reminder Experiments *(for old hands, and for newcomers when they have played with magnets)*

Apparatus

From electromagnetic kit, 16 sets of:	item 92
pair of ticonal magnets	92A
pair of magnadur magnets	92B
reel of thread	92
plotting compass	92D
pepper pots and iron filings	92W

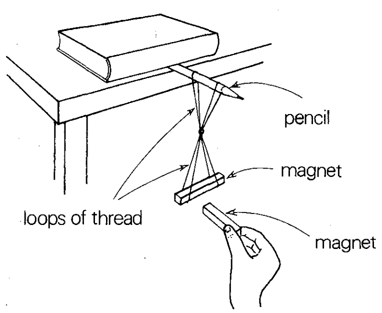
16 sheets of paper (park for iron filings)

Pupils should suspend a magnet from a pencil anchored by a pile of books—not by a retort stand unless stands of wood or brass are available.

Preparation

The compasses are cheap. Discard badly balanced ones and any with sticky pivots. Check their polarity. It is easily reversed: if so, de-magnetize and re-magnetize.

If the magnetization is weak—shown by slow oscillation in the Earth's field—place the compass in a strong field (in magnetizing coil or in the space between two ticonal magnets).



Procedure

Pupils follow these instructions:

* * * * *

(i) Poles. Put iron filings on a bar magnet. It seems to have special places that we call 'poles'.

What happens at the poles? Where are the poles, usually?

(ii) Poles and Compass. Hang a magnet in a cradle on a thread so that it can twist and point in any direction. It turns round until it points roughly North–South. We call the pole which turns and points towards North 'the North-seeking pole'.*

A compass is just a small magnet on a sharp pivot. So the end of a compass needle that points North is a *North-seeking* pole.

(iii) Forces between Poles. Feel magnet poles exerting forces on each other. Use some small strong bar magnets. (These may be made of special material called ticonal.)

Do two North-seeking poles pull or push each other? Do they attract or repel?

What does a North-seeking pole do to a South-seeking pole?

(iv) Testing Poles. Use a compass needle, whose North-seeking pole is marked, to find which is the North-seeking pole of a bar magnet.

* * * * *

---

* If in the early stages we say 'North pole' some pupils get entangled in the paradox 'the Earth's North magnetic pole is a South pole'. If we insist on using 'North-seeking pole' and 'South-seeking pole' until a later stage when there is clear understanding, the paradox will never appear.

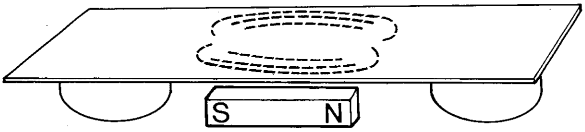
Fields of Magnets

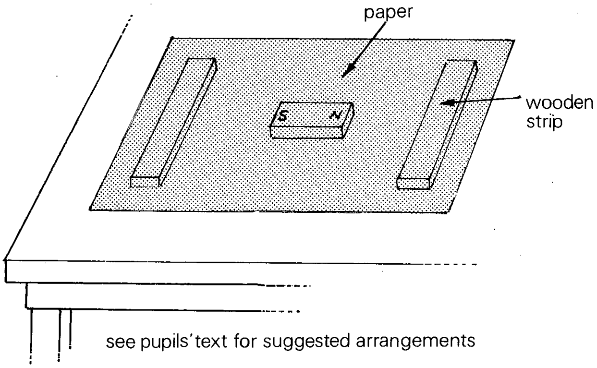
Pupils should look at the field patterns of some permanent magnets. This should be done quickly, without making notes—contribution to the Exhibition will be of more use; and we want pupils to get on to motors and meters and dynamos.

Class Expt 89c Fields of Bar Magnets

Apparatus

From electromagnetic kit, 16 sets of:	item 92
pair of ticonal magnets	92A
pair of magnadur magnets	92B
iron yoke	92I
card	92V
iron filings	92 E & W
plotting compass	92D
pair of aluminium rings (or slats of wood)	92 Q & R
16 sheets of paper (park for iron filings)	





Procedure

Pupils use aluminium rings or slats of wood to hold a card over the magnets. (The support blocks are too high for this.)

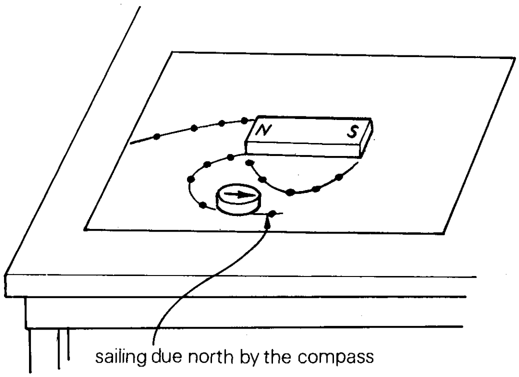
Pupils follow these instructions.

* * * * *

Use iron filings to show the magnetic fields of:

(i) A short bar magnet. *(Where else have you seen this pattern?)*

(ii) Two bar magnets near each other in various positions.



Also try placing a compass needle near a short bar magnet. Push the compass along the table, 'sailing due North by the compass'.

* * * * *

Pupils will use magnadur magnets, with poles on their large faces, for many experiments. They should look at their field, and then make a strong horseshoe magnet with them.

Class Expt 89d Slab-shaped Magnets

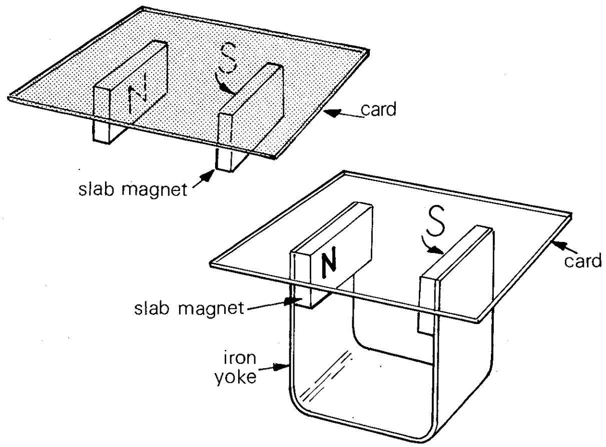
The magnadur slab magnets have poles on the large faces. Leave pupils to discover this for themselves.

The magnet is practically a sheet of dipoles. The idea of a dipole is a valuable one that we should encourage advanced pupils to use; but to beginners we should simply say that this is an unusual shape of magnet—most magnets are long and narrow.

Warning. Rough treatment will not harm the magnetization of these magnets; but, being made of ceramic, they can chip and fracture like china. If two are placed near to each other, oriented to attract, they may move together violently enough to do damage. Broken ones can be repaired by cementing with Araldite.

Apparatus

From electromagnetic kit, 16 sets of:	item 92
pair of magnadur magnets	92B
iron yoke (mild steel)	92I
iron filings	92 E & W
plotting compass	92D



Procedure

Pupils place a magnadur magnet upright on a long edge. They hold a card on top and look at the field with iron filings, and with a compass.

Then they place two magnadur magnets on the inner faces of the iron yoke, with opposite poles facing inwards. They place a card on top and look at the field with iron filings.

If pupils pour tintacks into the gaps they will get an impression of the strong uniform field.

Discussion of Magnetic Fields

Hold a general discussion of field patterns. Explain how Faraday* liked to imagine the patterns were pictures of elastic tubes which make the forces between magnets. *Pupils' Text 3* says:

If you like Faraday's idea:

a. You can see the lines that run from a magnet's North pole to another magnet's South pole clutching and pulling the poles towards each other.

b. You can see the lines from two North poles swinging away from each other, elbowing the poles apart.

c. You can even make predictions when you see a field pattern. Imagine a small magnet placed across the uniform field between large North and South poles. The combined field seems to tug at the small magnet's poles to wrench it round. That is the picture of a small compass needle being pulled round till it points along a magnetic field.

Faraday carried his picture of tubes still farther and used it in thinking about his discovery of dynamos.

Tubes or lines of force are useful for thinking; but it would be a mistake to think they are really there.

Ask pupils where they saw the pattern of a bar magnet's field before. We hope some will say 'It's the same as the field of a coil of that shape and size.'

But the coil has to have a current running round it. Might there be currents in a bar magnet? Suggest that such currents would have to be frictionless. This may be an opportunity to mention electrons in orbits.

* Pupils within reach of the Royal Institution (Albemarle Street, off Piccadilly, London W1) should be encouraged to visit Faraday's lab. This is not a museum-reproduction; it is the actual room he used, with his own apparatus on view. There is also a magnificent teaching-exhibit of Faraday's work—one of the finest displays of scientific history anywhere in the world.

Electromagnets

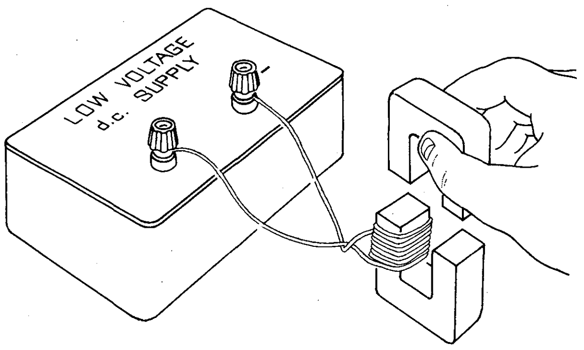
Pupils have made a small electromagnet. Now they should make a large strong one and try its 'lifting force'. They should also look at its field pattern.

Class Expt 90a Large Electromagnet: Forces

Apparatus

From electromagnetic kit, 16 sets of:	item 92
pair of C-cores	92G
PVC-covered copper wire	92X
16 wire strippers	84
16 low-voltage d.c. supplies	104

Each pair will use about $2\frac{3}{4}$ metres of wire.



Procedure

Pupils follow these instructions:

* * * * *

Wind about 20 turns of insulated wire round one leg of a *soft iron* C-core from your kit. Send a large direct current through that coil. Offer this electromagnet some iron nails.

Then offer your electromagnet another C-core (without any coil) and feel the force. (The end faces of both C-cores must be very clean for this experiment to do well. Before you try it, wipe any grit or iron powder off those faces with a piece of tissue or with your thumb. To make quite sure, hold the two C-cores tightly together, with the current off; slide a clean piece of paper between the faces and pull it out again while you hold the two C-cores together. The paper will wipe the faces clean.)

* * * * *

Ask: 'How strong is your electromagnet? What happens when you switch the current off?'

Class Expt 90b Field of Big Electromagnet

Apparatus

From electromagnetic kit, 16 sets of:	item 92
C-core	92G
card (or board)	92V
PVC-covered copper wire	92X
iron filings	92 E & W
16 low-voltage d.c. supplies	104
16 wire strippers	84
16 *pairs* of support blocks	219 (=92CC)

Each pair will use about $2\frac{3}{4}$ metres of wire (the same as in Expt 90a).

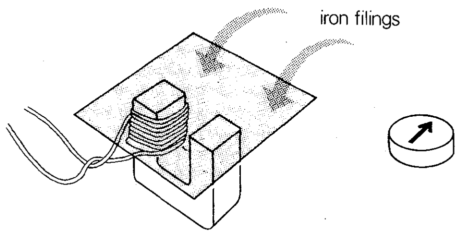
Procedure

Pupils use the electromagnet they made in the previous experiment 90a.

Pupils follow these instructions:

* * * * *

Place your C-core electromagnet on the table



with its end-faces upward. Put a card on top of its faces and sprinkle iron filings.

Do you see any field when the current is off? What do you see when the current is on?

You can find whether the poles at the faces are North-seeking or South-seeking by bringing a small compass near.

* * * * *

Practical Applications: Buzzer, Bell, Relay

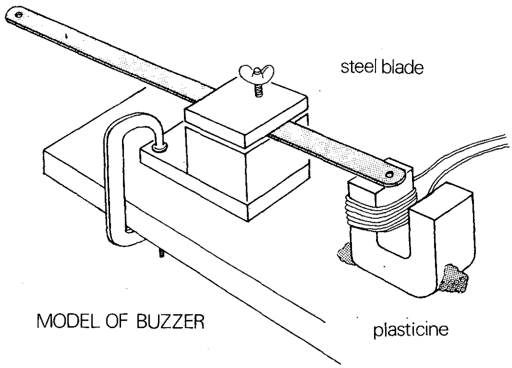
Pupils should make their own working models of these devices. The buzzer is easier to set up than the model bell; so it should come first.

Class Expt 91 Making a Buzzer

Apparatus

From electromagnetic kit, 16 sets of: item 92	
C-core	92G
PVC-covered wire	92X
16 low-voltage a.c. supplies	104 (a.c.)
16 wire strippers	84
16 support blocks with wing nuts*	219 (=92CC)
16 hacksaw blades	120
16 lumps of plasticine	570
1 demagnetizing coil	147D or 128
1 transformer or L.T. a.c. supply, for demagnetizing	27 or 59

Pupils work in pairs. Each pair needs about $\frac{3}{4}$ metre of wire.



MODEL OF BUZZER

The hacksaw blades must be demagnetized before each class. Many that have been used before, and even some brand new ones, will show an assortment of magnetic poles along their length! Pass each blade through a coil carrying a.c. taking it *slowly* away. (Test with iron filings for successful treatment.)

Procedure

To obtain a satisfying buzz pupils need to adjust the blade to resonance with the alternating current magnet. Show them how to change the length and clamp the blade tightly on the support block. (Loose clamping allows broad, weak, uneven response.)

An *unmagnetized* blade is attracted to the electromagnet core every *half* cycle; so the resonant frequency is 100 Hz. It will not help pupils to tell them that: simply ask them to find the best length by trial, always clamping the blade after each change.

Pupils follow these instructions:

* * * * *

Wind 30 turns of wire on one leg of the C-core.

Support the C-core on a lump of plasticine to raise it about $\frac{1}{2}$ cm. That holds the a.c. electromagnet still and raises it so that the hacksaw blade in the support block hovers just above the end of the core's leg.

(If you like, try d.c. first through the electromagnet to see the blade being attracted.)

Connect the coil to a low voltage *alternating* current supply. To make the blade vibrate a lot *you must tune it to the alternating supply*. If the blade is too short it naturally vibrates too fast—faster than the switching to-and-fro of the current. If the blade is too long it vibrates too slowly to respond well.

Start with about two-thirds of the blade projecting out from the support block. Clamp it tightly. Try it above the a.c. electromagnet.

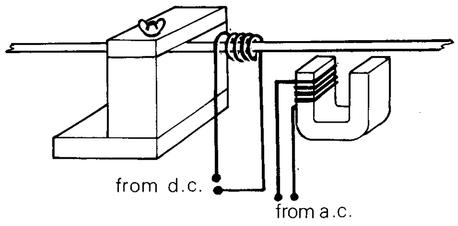
Loosen the clamp of the support block and change the projecting length of the blade. Clamp it tightly and try it above the a.c. magnet again. Continue trying till you find the best length of blade for a good buzzer. You must clamp the blade tightly for each trial.

* * * * *

* Support blocks are blocks of wood, suggested (instead of an unorthodox use of spare terminals on the low-voltage supply) for holding cards for iron filings, blades, etc. They are especially needed here. The one used here is a block with a lid and wingnut to clamp the hacksaw blade. It has a long foot to prevent its falling over.

Demonstration 91X Polarized Buzzer
(OPTIONAL EXTRA)

If the hacksaw blade is *magnetized*, it will be attracted once per cycle; then its natural frequency needs to be 50 Hz for resonance. Since this requires both explanation and arrangement we suggest this as a demonstration—though some pupils might like to work on it as a project.



Apparatus

As for Class Experiment 91:

1 C-core	item 92G
PVC-covered wire	92X
1 low-voltage a.c. supply	104 (a.c.)
1 wire stripper	84
1 support block with wing nut	219 (=92CC)
1 hacksaw blade	120
1 demagnetizing coil	147D or 128
1 transformer or L.T. a.c. supply, for demagnetizing	27 or 59
1 lump of plasticine	570
In addition:	
1 low-voltage d.c. supply	104
1 large G-clamp	44/1

Procedure

Demagnetize the blade, to remove uneven residual magnetization.

Set up the a.c. electromagnet as in the class experiment.

Clamp the blade in the support block. It is advisable to clamp the support block to the bench.

Slip a loose 35-turn coil of insulated wire on to the blade and move the coil close to the support block. To keep the blade magnetized, connect that coil to a *separate* low-voltage d.c. supply.

Find the resonant length of blade by trial. For average blades of length about 31 cm, the resonant length for 100 Hz is 7 to $9\frac{1}{2}$ cm; and the resonant length for 50 Hz, with the polarizing coil in action, is 11 to $12\frac{1}{2}$ cm.

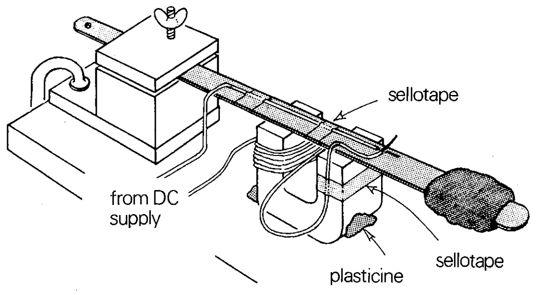
Class Expt 92 Model Electric Bell

Apparatus

From electromagnetic kit, 16 sets of:	item 92
C-core	92G
PVC-covered wire	92X
16 low-voltage d.c. supplies	104
16 wire strippers	84
16 support blocks with wing nuts	219 (=92CC)
16 hacksaw blades	120
32 lumps of plasticine	570
1 demagnetizing coil	147D or 128
1 transformer or L.T. a.c. supply, for demagnetizing	27 or 59
sellotape	

Procedure

The C-core wound with 30 turns of insulated wire that was used for the buzzer is used here. A lump of plasticine on the far end of the blade represents the knob to hit a bell but it should not actually hit anything—there is not sufficient power available. The noise as the blade strikes the C-core will be sufficiently pleasing.



MODEL OF ELECTRIC BELL

There is no question of adjusting to resonance in this case.

Pupils follow these instructions:

* * * * *

Clamp a hacksaw blade firmly in a support block near one end. Place your electromagnet just under the other end of the blade.

Anchor the C-core to the table with a lump of plasticine.

Load the free end of the blade with a lump of plasticine or block of metal so that it vibrates naturally quite slowly, a few times a second.

Make a 'contact-breaker' by fixing two pieces of bare wire with sellotape, one on the blade, the other on a leg of the electromagnet, so that when the blade bends it breaks the contact and turns current off. The blade should almost touch the electromagnet core when it breaks the contact.

Connect up to the low-voltage d.c. supply.

* * * * *

Class Expt 93 Making Your own Relay

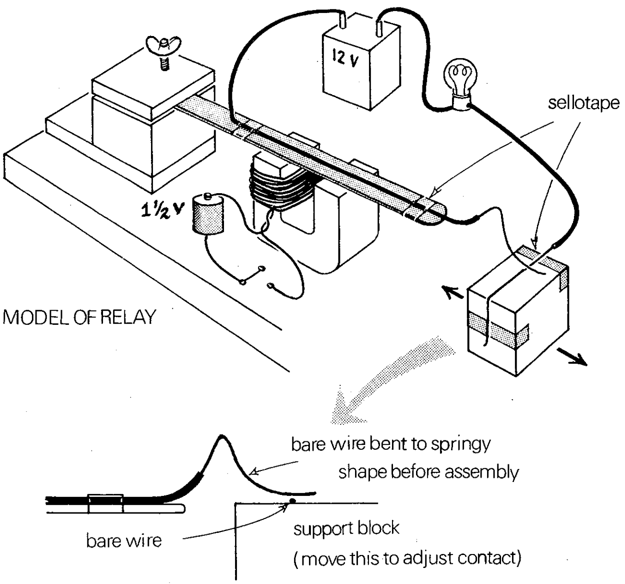
AIM. Success with a home-made device, however ramshackle.

Apparatus

From electromagnetic kit, 16 sets of:	item 92
C-core	92G
PVC-covered copper wire	92X
16 hacksaw blades	120
16 *pairs* of support blocks	219 (=92CC)
16 $1\frac{1}{2}$-volt cells	52B
16 switches or tapping keys	52L
16 lumps of plasticine	570
sellotape	
'large current' apparatus to be controlled, e.g.	
several 12-volt batteries	176
16 12V 24W lamps	72
16 lampholders	74

Procedure

Pupils have these instructions and explanation.



(Instructions for arranging the contact wires would be long and puzzling if given in words. In this case they are given by fully labelled sketches, here and in *Pupils' Text 3*.)

* * * * *

A relay is an automatic electric switch. A small current sent through the relay's coil makes the relay switch on (or switch off) a big current.

Or a small current may make a different relay connect up *several* other circuits.

A relay hands a switching signal on from one circuit to another. That is why it is called a relay, after a *relay* race in which one runner hands the torch on to the next.

You will find relays by the thousand in a telephone exchange, and huge relays in a power station, and controlling relays in any factory with automation.

Convert your model electric bell into a relay.

Use the C-core with 30 turns of wire around one leg, as for the buzzer and bell. Prop up the C-core on the table with a lump of plasticine.

For the small control current to operate the relay, connect the electromagnet coil to a $1\frac{1}{2}$-volt cell in series with a switch.

Disconnect the contact-breaker wires of your electric bell, and rearrange them so that when the blade is pulled by the electromagnet they *make* contact. (Follow the sketch.)

Connect the two wires that make contact in a separate circuit with a battery and a lamp (or an electric motor).

Adjust the contact of the two bare wires by moving the plain support block nearer to the electromagnet or farther from it.

When you press your switch in the control circuit the lamp in the other circuit should light up.

If you like, convert your relay into a 'locking relay' which will keep a motor or lamp running once you have pressed the switch. For that, you need to connect the two 'contact-maker' wires to the terminals of your switch in the control circuit. Then once contact is made it will not matter whether the control switch is on or off!

★ ★ ★ ★ ★

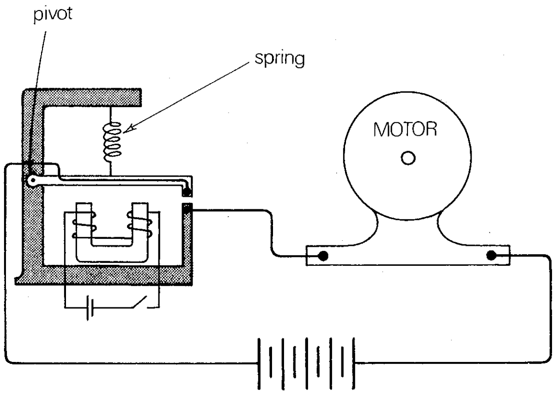
Demonstration 94 Commercial Relay *(OPTIONAL)*

Here is a place where a demonstration will reinforce the class experiment rather than spoil it; because a commercial relay operates quickly and surely and can control a large current.

Apparatus

small commercial relay;	
e.g. RS type 40 (2 pole c/o)‡	item 307
$1\frac{1}{2}$-volt cell	53B
Fractional horsepower motor	150
12-volt battery or d.c. supply	176/59
Switch or tapping key	52L

‡ RS type 40 has input resistance 185 ohms, will control 12 V circuit.



COMMERCIAL RELAY

Procedure

Arrange the control circuit: cell, switch and relay. Arrange the circuit to be controlled: battery and motor.

Show the small-current control circuit switching the large current motor.

Ammeters could be inserted. If so, both instruments should have the same range.

In Year 2's work with the Worcester Circuit Board, pupils looked at the simple properties of magnets; and by using the simple current balance, they established the fact that a force can exist between a magnet and a current-carrying coil. The time has now come to continue this exploration.

CURRENTS MAKE FORCES

Force on a wire carrying current across a magnetic field Ask pupils to look for a bridge between two separate things they know about: a current in a wire, and the field of a magnet. They pass a large current through a movable wire and put that wire in a strong magnetic field.

Class Expt 95 Wire carrying Current across a Magnetic Field: Exploring the Force

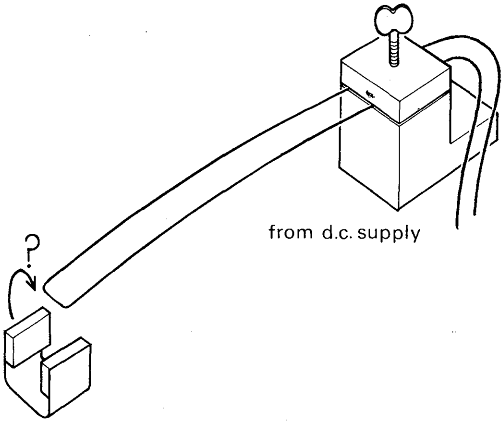
This experiment should start as a pure investigation. We hope pupils will themselves find that there is a force on the wire at right angles to the current and at right angles to the magnetic field; and that a reversal of the current will reverse the direction of the force.

This is a difficult but very important discovery. It deserves at least a complete period without the teacher 'giving the show away'. Of course, if pupils do not discover the story—and a number will not—the teacher must later on give help.

Apparatus

From electromagnetic kit, 16 sets of: item 92	
iron yoke	92J
pair of magnadur slab magnets	92B
PVC-covered copper wire	92X
copper wire, bare, SWG 32	222/1
16 wire strippers	84
16 *pairs* of support blocks‡	219 (=92CC)

‡ These may be needed if the terminals of the d.c. supplies are not suitable as supports.



Procedure

95a Simple Introduction

Pupils make a long rectangular loop of thin copper wire and connect it to their low-voltage d.c. supply. The easiest way to support the loop is to clamp the open ends in the support block which has a wing nut. Then the closed end of the loop projects our horizontally, sagging a little.

They place slab magnets on the yoke and bring it near the remote end of the loop when a current is flowing.

For best progress, give no further instructions except to say 'Try placing the magnet any way you like; but keep it near the far end of the loop.'

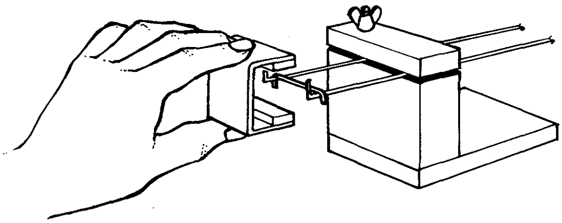
If necessary, suggest to some 'Try switching the current off.'

95b Movable Bridge

Pupils work in pairs and follow these instructions:

* * * * *

Strip three lengths of 26 SWG wire about 15 cm (or, better, obtain three lengths of thicker *clean* bare copper wire).



Attach two lengths to the low-voltage d.c. supply, to make a pair of parallel horizontal rails. (Turn its end down to prevent its sliding off.)

You know from your previous experiment how to place the U-magnet. Place it so that you expect it will make the bridge move.

Try switching the current on and off. Also reverse the current.

* * * * *

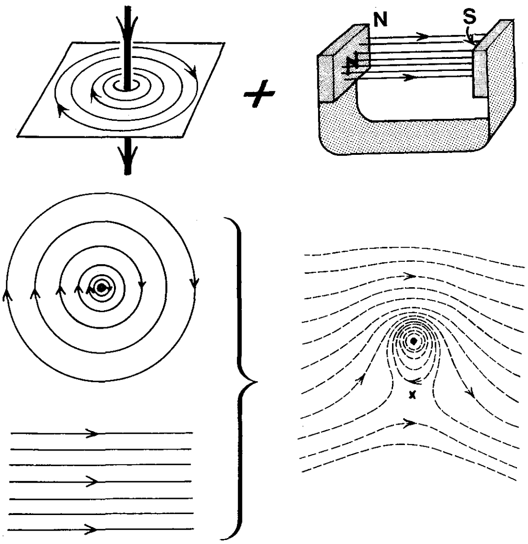
Pupils will see the motion and know that there must be forces at play, but the three-dimensional geometry will remain obscure. This is where we hope teachers will come to the rescue with clear sketches and statements—and now perhaps a demonstration. (But, as we urged above, no emphasis on direction rules.)

The strange direction of force Pupils will need clear (illustrated) statements that the force is *ALWAYS perpendicular to the wire* and to the magnetic field. If the wire lies *along* the field, the force is zero. If the wire is perpendicular to the magnetic field force is greatest. We find maximum force when wire, field, and force are mutually perpendicular.

At this point it is useful to show a thumb and two fingers, *without labels.*

The Catapult Field

Point out a possible description of the new discovery in terms of magnetic fields. The U-magnet has a magnetic field—a strong one in the gap between its poles—and the current in the wire has a field—circles round the wire. What happens when those two simple forms of magnetic field are combined? We *know* what happens: the wire moves; there is a force on it. But do the magnetic fields combine to make a pattern which illustrates that?



Pupils should see that pattern, with real magnets and current, not just a picture of it, and not an all-too-convincing film.

Give a demonstration of the pattern; pass a large current through a straight wire and arrange magnets (or coils) to make a uniform magnetic field across the wire. This pattern is sometimes called the 'catapult field' because, if interpreted with the realistic enthusiasm of a Faraday, it shows the wire being catapulted by the combined field.

Thus the pattern offers some pupils a satisfying picture or 'explanation' of the force.*

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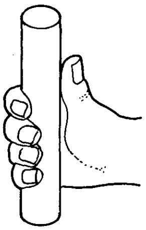
* And it will provide the best 'finger-rule' for the direction of motor forces. If pupils insist that they themselves want a rule, we say: 'To sketch the field, once you have seen it, sketch the two separate fields, roughly, on top of each other. Remember that the lines of horseshoe magnet's uniform field run straight across from N to S: and the circles of the straight wire's field run the way given by your righthand fingers-and-thumb rule.



(That says, "Look at your right hand. Curl your fingers round your thumb. Point your thumb along the current in the wire, then your curling fingers point the way a compass would point round the circles.")

Then combine the fields in a *rough guess* at the catapult field. All you will need to decide is where the 'neutral point' is. Then you will know which way the wire is catapulted.'

This is a field pattern that each pupil should look at carefully. In a demonstration it is best to show each component field separately first, then the resultant field.

Though it takes considerable time and trouble, this is best of all done as a class experiment, with pupils looking for the pattern on a smaller scale. The demonstration should be shown first so that pupils know what to look for.

Demonstration 96a Catapult Field

For a clear demonstration, the current through the straight wire should be nearer 100 amps than 10. Provide the equivalent of that large current by running the wire several times up through a cardboard sheet, carrying each turn up and over far away and down and back to make the next turn.

We want a uniform magnetic field that extends over a wide area and is unobstructed by whatever device produces it. A pair of slab magnets will suffice; but a pair of Helmholtz coils* is an advantageous luxury.

Apparatus

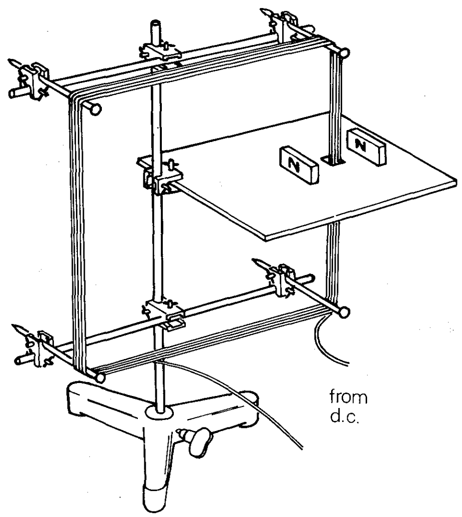
From electromagnetic kit:	item 92
2 magnadur slab magnets	92B
PVC-covered copper wire (40 metres)	92X
iron filings	92 E & W
card (40 cm × 50 cm)	
string	
1 sheet of paper (40 cm × 50 cm)	
1 L.T. variable voltage supply	59
1 demonstration meter	70
1 d.c. dial (5 A)	71/2
2 retort stands	503, 504
8 bosses	505
2 rods (25 cm)	504
4 short wooden dowel rods (10 cm)	565

---

* These are two coaxial circular coils, separated by one coil radius from centre to centre along the axis. That arrangement provides a nearly uniform magnetic field over a large region between the coils.

This is the only place where we really benefit from Helmholtz coils in this programme. We may find them provided by manufacturers in apparatus for deflecting electron streams; but there a single circular coil would make things easier to see and it would make the geometry of measurements simpler. The electron stream would be bent into an orbit in the plane of the coil where its field is quite uniform enough for measurements.

Our electron stream experiments do *not* need Helmholtz coils or justify them. Those coils have somehow come into elementary demonstrations with the intention of increasing accuracy; but our apparatus is liable to other errors which undo that precision. And in fact the electron stream in e/m measurements is far from the axis where text books calculate the field! Anyway, we wish to make our e/m experiment a simple estimate rather than a precision measurement.



Preparation

Make a large coil: 10 turns of insulated wire from the kit, in the shape of a square 50 cm × 50 cm. This coil will be set up in a vertical position with one leg through a hole in a horizontal card where the field will be shown.

Forming the Coil. Arrange a retort stand with two cross rods and four wood dowels, as in the sketch. The dowels should be at the corners of a vertical square, about 50 cm × 50 cm. Wind 22 metres of wire in 10 turns with 1 metre at each end for connections. Tie the coil with thin string at several places to keep it together.

The Card for the Field. The coil should remain on the retort stand. The card needs only a hole, off centre, and a slit as in the sketch.

Procedure

Connect the ends of the coil to the d.c. terminals of the L.T. variable voltage supply, via an ammeter reading to 5 A.

Put a sheet of paper with a slit in it on the cardboard.

First show the magnetic field due to the current alone. Adjust the current to about 3 A, sprinkle iron filings, and tap the paper sharply with a pencil.

Then switch off the current and sweep the filings away. Place two magnadur slab magnets on the paper, about 15 cm apart with unlike poles facing, so that the centre of the card, where the coil passes through, is mid-way between them. Sprinkle with iron filings, tap with a pencil, and show the uniform field in the central region.

Again sweep the filings away. Turn on a current of 3 A, sprinkle iron filings, tap with a pencil, and show the catapult field.

When the catapult field is clearly visible, turn down the current to avoid overheating the wire. The field pattern will remain.

After pupils have seen the demonstration they should try it themselves, using their low-voltage d.c. supplies. Suggest the following arrangement.

Class Expt 96b Catapult Magnetic Field *(OPTIONAL)*

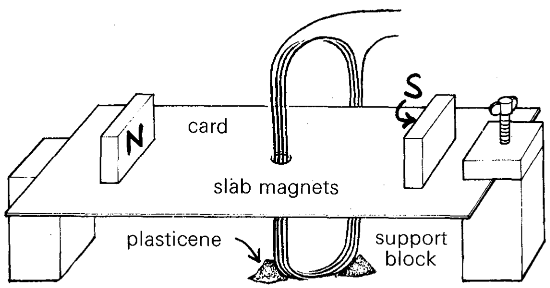
Apparatus

From electromagnetic kit, 16 sets of:

	item 92
pair of magnadur slab magnets	92B
PVC-covered copper wire	92X
iron filings	92E & W
16 wire strippers	84
16 low-voltage d.c. supplies	104
16 *pairs* of support blocks	219 (= 92CC)
16 stiff cards or pieces of hardboard 35 cm × 10 cm	
16 lumps of plasticine	570

The cards must be sturdy. Strips of thin plywood would be better, with a central hole already drilled and a saw-cut made to get the coil in.

Pupils work in pairs. Each pair will use about 1 metre of wire.



Procedure

Pupils follow these instructions:

* * * * *

Place the support blocks about 30 cm apart and use them to hold and support the long card.

Wind a hoop coil of 3 or 4 turns, of diameter about 10 cm.

Make a hole in the centre of the card and cut a slit from one edge to the hole so that the coil can be arranged to pass through the hole. (Better still, make no slit but form the coil by passing the wire again and again through the hole.)

Support the coil with a lump of plasticine.

Place two slab magnets upright on the card near the ends, about 25 cm apart.

Connect the coil to the d.c. supply. Sprinkle iron filings on the card and look for the catapult pattern.

* * * * *

Ammeter and Motor

Uses of catapult forces Ask pupils whether we can put this catapult force to use, whether we could produce rotary motion and drive machinery.

The kit includes materials for making a model moving-coil ammeter and a simple electric motor. We provide instructions* here, and in the *Pupils' Text 3*; but teachers will find it much more fruitful to try the kit out and develop their own way of giving it to pupils with as little direct help as possible. Then they will be ready to give hints to those who need them.

Model ammeter This gives a deflection when d.c. is sent through its coil. If a.c. is used, no deflection will be seen but the meter will buzz.

* Since some teachers may prefer to let pupils make the motor before the ammeter, we give full instructions for each—we avoid letting instructions for one depend on the instructions for the other.

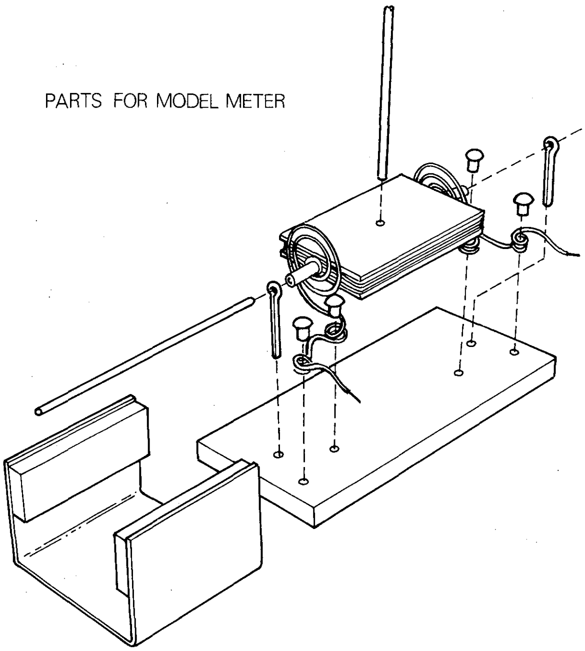
However, it is probably easier for pupils to see the need for the motor's commutator and understand its working after they have made their model ammeter work. That is one reason why it is probably better in this early teaching to make the model ammeter before the model motor. The other reason is: the *dynamo* experiments which come later will then find the motor there ready for use.

Class Expt 97 Making an Ammeter: Model Moving-Coil Meter

Apparatus

From electromagnetic kit, 16 sets of:	item 92
PVC-covered copper wire	92X
base	92J
armature	92H
steel yoke for slab magnets	92I
pair of magnadur slab magnets	92B
2 split pins	92K
knitting needle	92M
4 rivets	92L
16 wire strippers	84
16 drinking straws	53A
16 low-voltage d.c. supplies	104
16 rheostats (10–15 ohms)	541/1
low-voltage a.c. supply	104 (a.c.)
commercial galvanometers and ammeters to be exhibited	

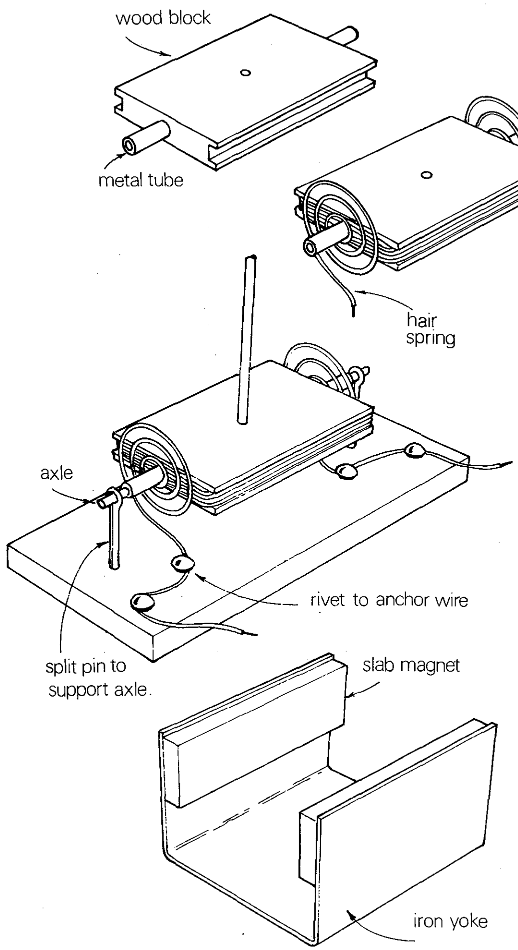
PARTS FOR MODEL METER



The wood base has holes to receive split pins which serve as bearings for the armature; also 4 holes for rivets to anchor the lead-in wires and spirals.

The armature former is a wood block with an aluminium tube as axle already fixed in it. A knitting needle put through the tube and supported by the split pins provides a convenient bearing with not much friction. The wood block has a channel in its edge for the coil.

Pupils work in pairs. Each pair needs about $2\frac{3}{4}$ metres of wire.



Procedure

Pupils follow these instructions:

* * * * *

Wind a coil of $10\frac{1}{2}$ turns of wire on the wooden block. Make sure the coil begins and ends at *opposite* ends of the block.

Wind a couple of tight turns round the tube at each end to anchor the ends of the coil. Leave $\frac{1}{2}$ metre of spare wire at each end.

Coil each end of spare wire into a loose flat spiral of 4 or 5 turns. Use plenty of wire for each spiral. If the spirals are too tight (because the overall length is too short), the meter will be insensitive.

Slide the knitting needle through the aluminium tube in the block and support it by the two split pins.

Explain to pupils that the split pins can be turned so that the knitting needle jams in the eye of the split pin and is thus held firmly.

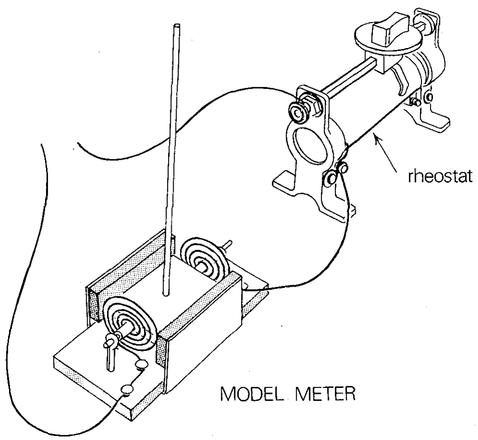
Take the ends of wire that lead to the spirals twice round under each rivet head as shown in the sketch. Then press the rivets into the base board.

The turns of the spiral must not foul each other or the supports or the magnets. The wires must be fixed rigidly under the rivets so that the spirals are not disturbed when the connections are made to the battery or supply.

To test your construction, give the armature a twist and make sure it swings back easily to a more-or-less horizontal position.

Then insert a drinking straw in the hole in the wood block so that it sticks up to act as a pointer.

Attach two magnadur slab magnets to the iron U-yoke, to provide the magnetic field. They will be held in place on the yoke by attraction. Opposite poles of the two magnets should face each other. Slip the yoke into place *under* the wooden base.



Connect the model to the low-voltage d.c. supply. When it is switched on, the pointer will probably swing right over.

Then put a rheostat (10–15 ohms) in series with your ammeter model and change the current. Also try reversing the current.

If you like, try the meter on a.c. Watch and listen.

* * * * *

Class Expt 98 Examining Commercial Ammeters

When pupils have made their model, they should look at a commercial ammeter, if possible one with the case removed so that they can see how its construction compares with that of their model.

It is worth while to keep any broken ammeters for this.

Electric motor Can the ammeter's motion be made to *continue*? It is certainly rotatory, but it ends when the two forces balance, the restoring force of the springs and the deflecting force produced by the magnetic field and the current.

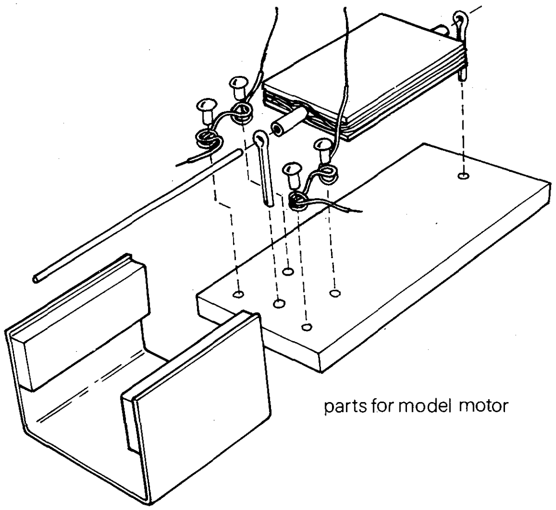
This leads us to develop the simple motor by removing the ammeter's springs and adding a commutator.

This motor will run easily on d.c. It will also run on a.c. if it is spun to the synchronous speed to begin with.

Class Expt 99 Making an Electric Motor

Apparatus

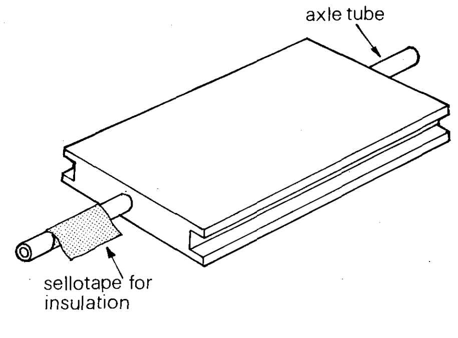
From electromagnetic kit, 16 sets of:	item 92
PVC-covered copper wire	92X
base	92J
armature	92H
steel yoke for slab magnets	92I
pair of magnadur slab magnets	92B
2 split pins	92K
knitting needle	92M
4 rivets	92L
valve rubber	92Y
sellotape	
16 low-voltage power units	104
16 wire strippers	84


parts for model motor

The motor is similar in construction to the ammeter except that a commutator and brushes replace the spiral ends of the armature coil.

The wood base has holes to receive split pins which serve as bearings for the armature; also 4 holes for rivets to anchor the lead-in wires and spirals.

The armature-former is a wood block with an aluminium tube as axle already fixed in it. A knitting needle put through the tube and supported by the split pins provides a convenient bearing with not much friction. Explain to pupils that the split pins can be turned so that the knitting needle jams in the eye of the split pin and is thus held firmly. The wood block has a channel in its edge for the coil.



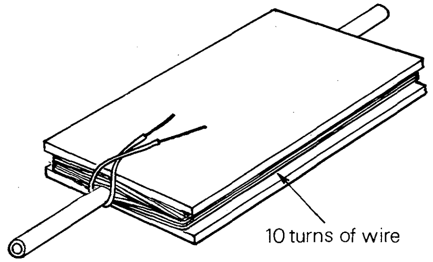
Pupils work in pairs. Each pair needs about $2\frac{1}{4}$ metres of wire.

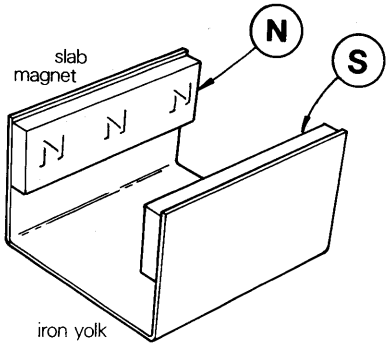
Procedure

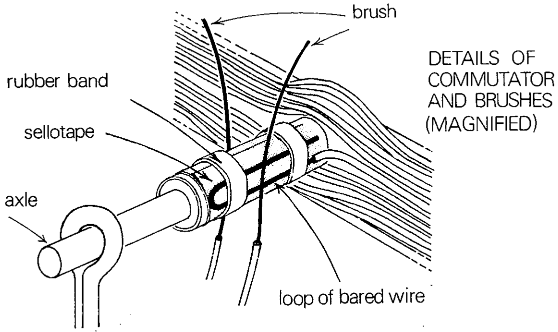
Discuss the need for commutator and brushes.

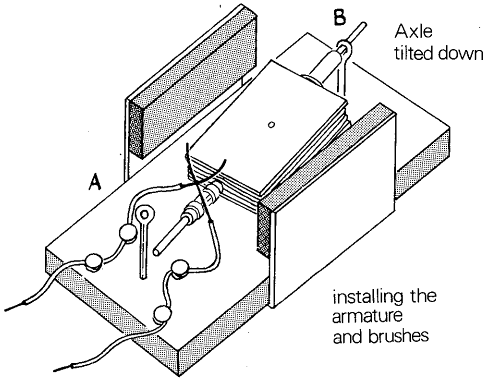
Pupils then follow these instructions:

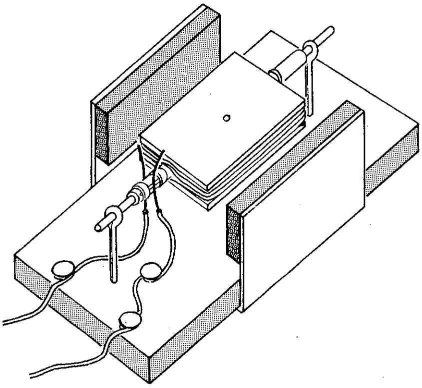
* * * * *











To make the commutator, insulate one end of the aluminium tube with sellotape. Then cut two short slices of valve-rubber tubing to make two tiny rubber bands. Slide the rubber bands over that end of the aluminium tube.

Bare an end of the wire, loop it as shown, and fix it in place with the rubber bands.

Wind about 10 turns on the wooden armature block. Make sure the coil begins and ends at the *same* end of the block. Cut off the wire, leaving enough to make the loop on the other side of the commutator. Bare that end and loop it. Slide the rubber bands back, place this loop on the sellotape on the opposite side of the tube from the first loop. Finally move the rubber bands back to retain both loops in position.

(A single rubber band may be sufficient to secure the tips of the looped ends. Looped ends are not strictly necessary. A straight end would suffice; but the loop provides contact with the brushes over a greater part of a revolution, with a consequent increase in power.)

Now make the brushes. These consist of two lengths of wire, which also serve as leads from the supply. Attach the brushes to the rivets in the base and the rivet heads hold them firmly. Bare the ends which will press against the commutator.

The brushes will not make good contact if you just bend them towards the commutator. Therefore proceed as follows:
(i) Cross the brushes as in the diagram.
(ii) Slip the commutator end of the armature under the brushes as you insert the other end into the bearing, B.
(iii) Lift the armature and complete the assembly as in C. That provides good contact and the brushes are lightly spring loaded.

The *wires* should now be vertical and *almost* touching each other. The supply should be off at this stage.

Finally, holding the armature in this position, pass the knitting needle through the aluminium tube and through the supporting split pins already fixed in the base.

Now the motor is ready. Apart from the slight friction of the brushes, the armature should spin freely when you twist it with your fingers. The brushes must make contact with the coil ends when the coil is *horizontal.*

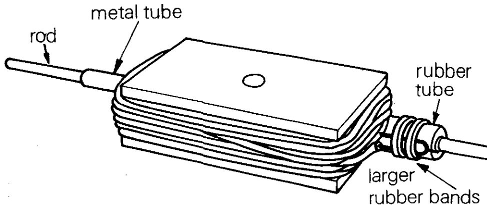
Put two magnadur slab magnets on the iron U-yoke to make the magnetic field.

Connect to the d.c. supply and start the motor.

★ ★ ★ ★ ★

Pupils may try their motor in series with a moving coil meter (one of their own or a commercial one). If the motor is a good one they will see the current increase when they load the motor lightly by pressing gently with a finger on the rotating aluminium tube.

Note. For those with poor manipulative ability, there is an easier way to make the commutator; it is not as good, because the friction torque is greater with a



commutator of larger diameter. In place of the sellotape, pupils slide rubber tubing over the aluminium tube to provide insulation. Then larger rubber bands are needed to secure the bared wire loops.

Showing the model motor at home? We hope that many pupils will want to take their own motor home to show it running. We wish they could take it home and keep it. The possession of something which, though in some ways only a toy, is in other ways a piece of scientific construction, accompanied by knowledge of its working, may be so valuable to a young boy or girl that the cost of materials seems trivial.

The Nuffield Physics Group would like to say 'by all means let any pupil who wishes keep his motor'. The motor will run on a simple battery—and the pupil should buy that for himself. The only serious cost in the materials taken home would be that of the magnets. We trust schools will at least allow the magnets to go home on loan for a weekend.* If magnets can be paid for and kept, so much the better for the good name of science.

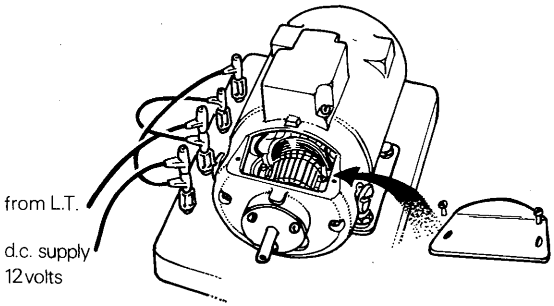
Commercial motor It would be a pity for pupils to leave the motor at this point and not see some real motors. They should look at a commercial motor—whatever is available and not completely shrouded, from 40 watts to several kilowatts—to see whether they can identify corresponding parts.

In any case, the lab should have a fractional horse-power motor—a commercial form and not a toy—to be used in demonstrations. Pupils should now see this in use, with the commutator open to view.

Demonstration 100 Commercial Motor: Fractional Horse-power Motor

Apparatus

1 fractional horse-power motor	item 150
1 L.T. variable voltage supply	59



Procedure

The fractional horse-power motor recommended for use elsewhere in the programme operates from 12 volts d.c., which is obtainable from the L.T. variable voltage supply. Connect the field and armature in parallel, to the supply.

The motor has a convenient plate on the end which can be removed to show the brushes, etc. Pupils should look inside to see whether they can identify the parts.

* The J. Willmer Home Experiments Endowment will reimburse any Nuffield Physics class for damage, or loss, of parts of the electromagnetic kit taken home on loan with permission from the teacher. (This includes lost magnets.) See details on page 53.

Loudspeaker Show a loudspeaker (permanent magnet, moving coil) and explain how it uses the catapult force. Pupils can make a model loudspeaker which will be sensitive enough to radiate a strong buzz when driven by a 1-volt a.c. supply. This does not take long and we hope that pupils will try it.

Class Expt 101 Model Loudspeaker *(OPTIONAL)*

Apparatus

From electromagnetic kit, 16 sets of:	item 92
iron yoke	92I
pair of magnadur magnets	92B
thin insulated copper wire, SWG 36	222/2
sellotape	
low-voltage a.c. supply	104 (a.c.)
16 sheets of stiff paper (A4)	
scissors	

Pupils work in pairs. Each pair needs $2\frac{1}{2}$ metres of thin wire. For the paper cone, 'extra strong bond' paper is suitable.

Procedure

Pupils follow these instructions.

* * * * *

Make a simple loudspeaker with paper and sellotape:

(i) Cut a circle of fairly stiff paper. Cut a 45° wedge out of the circle. Bring the cut edges together to make a shallow cone. Tape those edges together so that the cone will keep its shape.

(ii) Cut a strip of the same paper about 4 cm by 20 cm. Roll the strip up to make a tube about 3 cm diameter, and tape it to keep it like that.

(iii) Place the tube on the point of the cone and fix it there with several strips of tape.

(iv) Wind two dozen or more turns of thin insulated wire (SWG 36) round the tube.

(v) Support the cone by its edges.

(vi) Make a strong magnet with a gap in which the coil is to be placed. The proper shape of magnet would have a central North pole inside the coil with a ring of South poles outside it. Then the lines of the magnetic field would all go radially outward, all perpendicular to the coil, all crossing it the same way. And the catapult forces on the coil would be in the same direction on all parts of the coil. They would all push the cone out or all pull it in.

With the apparatus you have, you must make a rough substitute for that. Here are two good ways of making a suitable magnetic field. Use I or II.

(I) Use two C-cores side by side so that they form a 'W'. (You may tie the central pair of legs together if you like.) Make the paper tube wide enough to fit over that pair of legs.

Place slab magnets on the *inside* faces of the two outer legs. Make sure the slabs have the same poles pointing inward.

(That is *not* how you placed the slab magnets on an iron yoke to make a U-magnet. Then you had N and S poles facing inward to make a strong field across. Now you need N and N poles facing inward, with the central pair of core legs acting as SS poles.)

(II) Make a long magnet by placing 3 or 4 ticonal bar magnets head-to-tail in a line. Put the head of this long magnet inside the tube and coil. Then you have a N pole inside with magnetic field lines sprouting out across the coil's wires, like spokes of a wheel.

(vii) Attach the coil to a low-voltage a.c. supply. Can you make the coil broadcast a buzz? (To make your model broadcast music or speech from a record, you would need an amplifier and probably a small transformer.)

* * * * *

ELECTROMAGNETIC INDUCTION

In the history of electrodynamics, which grew up so quickly at the beginning of the last century, the discovery of the motor-force was a great event; but the discovery of the dynamo-effect (slightly earlier) seemed even greater but more strange: a very large jump ahead of other knowledge. Some traces of that historical background remain with us in our teaching; and we are apt to postpone discussion of electromagnetic induction, feeling that it is something that belongs in advanced teaching. Yet it is not difficult, and it follows the electric motor work very easily. So we urge teachers to take pupils on to 'power-station knowledge'.

Go straight ahead with the electromagnetic kit. Ask pupils to try turning their motor by hand, to see what happens when there is no battery there. They must add an instrument to show what happens; so, if they do not think of it themselves, suggest adding a galvanometer. Then they will make the great discovery.

Pupils with time to spare can convert their 'd.c. dynamo' to an 'a.c.' one. They replace the commutator by 'slip-rings', one at each end of the axle.

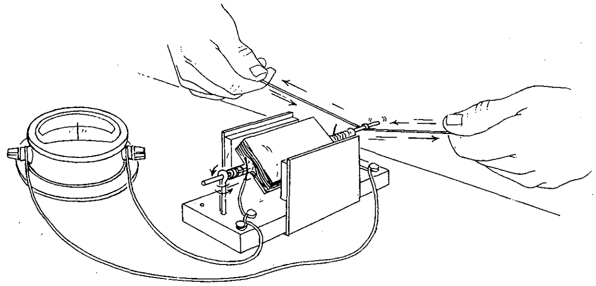
Or they may make a *temporary* a.c. dynamo (which will work for a few turns if they bring out a pair of leads of thin wire from the coil and let those leads twist up as they turn the coil).

Rules? We hope strongly that, neither before nor just after this, will pupils' attention be diverted to questions of left-hand or right-hand rules. Those of us who value those rules highly will be willing to postpone discussion if we see that the delight of young people making rapid progress with the electromagnetic kit as an experimental road for travel rather than a geography book's description to be learnt.

Class Expt 102 The Mysterious Machine: Model Dynamo

Apparatus

16 motors from electromagnetic kit (made in Expt 99)	item 92
16 galvanometers	180



driving the AC dynamo fast

Procedure

Pupils connect their motors' leads to the galvanometer instead of the supply. They spin the armature, and watch the galvanometer.

They should try reversing the direction of spin.

The armature can be spun with a finger on the aluminium tube. To run it faster, wrap a length of thread once round the tube, hold it taut, and pull it to and fro as illustrated.

Note. If the motor has run for an appreciable time, the brushes and commutator will be dirty and will have a high resistance. Strip the assembly down and scrape the brushes and commutator with sandpaper to clean them. Avoid finger grease. Taking these precautions may increase the galvanometer deflection several times.

Class Expt 103 Model Dynamo, a.c. Form *(OPTIONAL)*

Apparatus

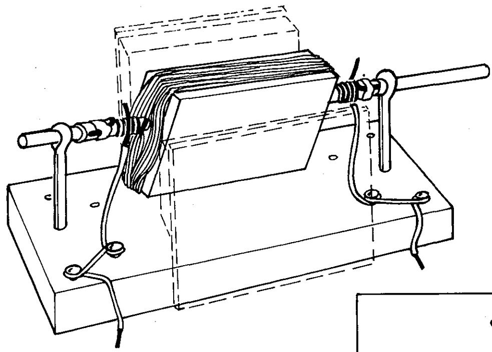
16 motors from electromagnetic kit (made in Expt 99)	item 92
16 galvanometers	180

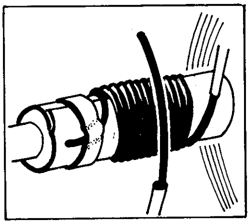
Procedure

Pupils may convert their 'd.c. dynamo' to an a.c. one. They follow these instructions:

* * * * *

Most modern power stations produce a.c. To make a model a.c. dynamo, you must change from your commutator to two 'slip-rings'.





Bring out the two ends of the coil's wire to *opposite* ends of the metal tube that carries the coil. Near each end of the tube put a wrapping of sellotape as insulation. Wind a *bare* end of the coil's wire tightly round the sellotape at each end of the tube.

Move one of the brushes to the other end; so that you have a brush at each end.

Then correct the brushes to a galvanometer. Try spinning the coil.

* * * * *

Discussion

That dynamo effect is surprising and puzzling. We ask pupils:

How can you simplify the apparatus to find out what is really happening? When you turn your motor and find you get a current, you have too many things all at once: the magnet, the coil, the motion, the electric current.

Try taking the magnet in one hand and the coil in the other. You had better use a straight bar magnet. Then you can poke it in and out of the coil, instead of the complicated arrangement of changing the coil. And you don't need a commutator.

'Real' dynamo As soon as pupils have made their model dynamo work, they should see a 'real' dynamo lighting a lamp—even if they saw that long ago in an 'energy circus'. Show a toy dynamo at work. If the school has a lifelike working model of a power station generator—all the better.

Bicycle Dynamo One of the simplest generators commercially available is the generator made for bicycles. Pupils should see one at work, and try it for themselves.

This machine's alternating voltage is induced in a coil which stays at rest while the field magnet revolves around it—as in the large generators in modern power stations.

The field is produced by an 8-pole circular permanent magnet.

For our teaching, the generator should have a gear system so that it can be driven very slowly and smoothly; then the output can be examined on a demonstration moving-coil meter.

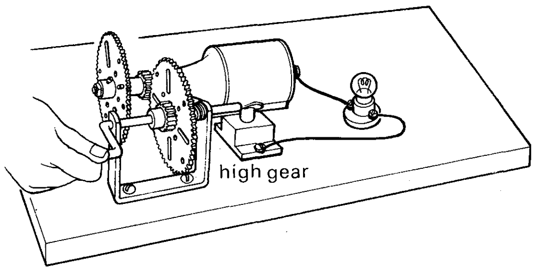
Pupil Demonstration 104 Bicycle Dynamo and Lamp

Apparatus

1 bicycle dynamo assembly including lampholder and lamp	item 103
spare lamp ($2\frac{1}{2}$ V)	92R

Procedure

Drive the dynamo, then leave it available on a side table for pupils to try. At this stage it should be connected to the lamp, so that driving it fast can do no harm.



(This is just to offer a real dynamo for a quick look. Explanations and investigations with a galvanometer (with slow motion) and with an oscilloscope should come later, in Expt 109.)

Other 'Dynamo' Experiments

After this introduction, pupils should try further experiments. They connect a wire to a commercial galvanometer and move the wire across the field of a U-shaped magnet. They wind a coil on one limb of a C-core and connect it to a galvanometer. They arrange an electromagnet and bring it near; then they clamp the electromagnet to the first core and switch it on and off—they have made a transformer.

Pupils try running their transformer by switching on and off the current through the electromagnet's coil, which serves as primary.

(Except for a very fast group, further work with transformers should be postponed to Year 4.)

Class Expt 105 Moving Magnet and Coil: Investigating Electromagnetic Induction

Apparatus

From electromagnetic kit, 16 sets of:	item 92
pair of ticonal magnets	92A
PVC-covered wire	92X
16 galvanometers	180

Each pair needs about $2\frac{1}{4}$ metres of wire.

Procedure

Pupils follow these instructions:

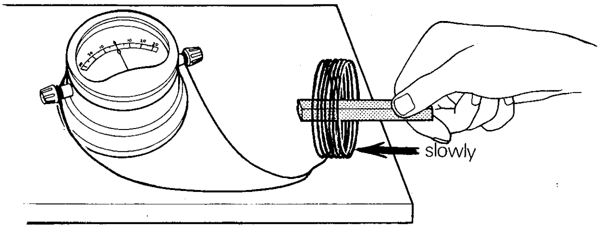
* * * * *

Take about $2\frac{1}{4}$ metres of insulated wire. Wind a hoop coil of many turns, big enough to put your thumb through. Have plenty of spare wire (say $\frac{1}{2}$ metre) at each end of the coil.

Connect the ends of the coil to a galvanometer. Try moving a small bar magnet (ticonal) towards the coil and away from it, *slowly*. Try moving it a little faster. Try moving it *through* the coil.

What else can you move instead? Try all the things you can think of.

* * * * *



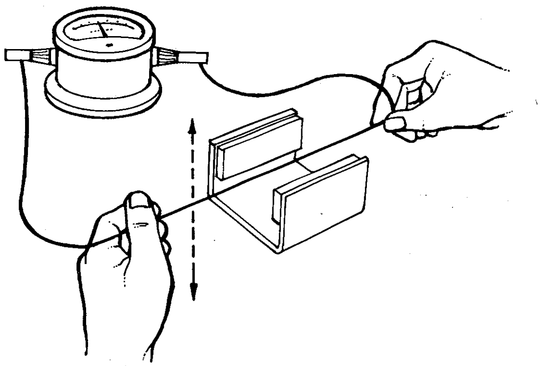
This seems clear enough to us, because we have heard of it long ago; but pupils need considerable time to disentangle the different versions of the same effect. We want them to enjoy finding out about this dynamo effect; so we should not bother them with rules and explanations—but we should encourage them by pointing out that they are doing the basic research for power stations.

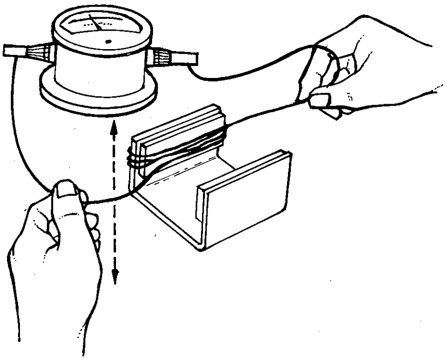
There is no need to go into the mathematical aspects of this work at all. Yet it will be apparent that rapid motion produces a larger effect than a slow motion; and that stronger magnets, and more turns of coil, produce greater effects.

Class Expt 106 Wire moving across Magnet Gap

Apparatus

From electromagnetic kit, 16 sets of:	item 92
PVC-covered wire	92X
iron yoke	92I
pair of magnadur slab magnets	92B
16 wire strippers	84
16 galvanometers	180





Procedure

(i) Single wire. Pupils attach two slab magnets to the yoke, with opposite poles facing each other. They connect long leads of wire (about $\frac{1}{2}$ metre) to a galvanometer, and try moving the wire across the field in the gap.

(ii) Several wires. (OPTIONAL) The effect with a single wire will be small, on the galvanometers available for class use; but it would be a great pity to break this sequence of class experiments with a demonstration using a sensitive galvanometer. It would be better to let pupils form their wire into a loose coil of several turns and try with that. Each pair will use about $1\frac{1}{4}$ metres of wire.

Class Expt 107 Loudspeaker as a Dynamo *(OPTIONAL)*

Apparatus

2 small loudspeakers	Optional item 183
connecting wire	

Procedure

Place the two loudspeakers well apart, in different rooms so that pupils listening in one room cannot hear someone talking in the other room by direct sound.

Connect the coil of one loudspeaker to the coil of another.

Explain that a loudspeaker is like a specially shaped electric motor.

'It uses catapult forces due to the varying current from a radio to drive a paper cone attached to its movable coil.

Just as a motor can act as a dynamo, a loudspeaker can act as a dynamo. It can produce varying currents if its cone is pushed in and out by sound waves.'

Someone should talk to one loudspeaker, the 'dynamo', with his mouth close to the cone. Pupils listen to the other loudspeaker, the 'motor'.

Three more dynamo-effect experiments

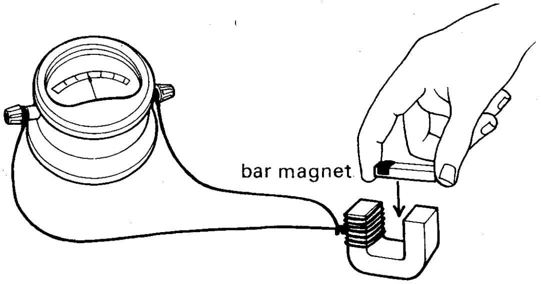
Pupils wind a coil on one leg of an iron C-core and try two experiments with it. These are described separately, although they follow quickly.

Class Expt 108a Dynamo Effect in Coil on Iron Core

Apparatus

From electromagnetic kit, 16 sets of:	item 92
PVC-covered copper wire	92X
C-core	92F
ticonal magnet	92A
16 galvanometers	180

Each pair needs about 2 metres of wire



Procedure

Pupils follow these instructions:

* * * * *

Wind a coil of about 20 turns on a C-core. Leave plenty of spare wire at each end. Twist the wires together where they leave the coil, to prevent the coil unwinding.

Connect the ends of the wire to a galvanometer. Bring a small magnet near.

Now you have a coil with an iron core. *Does the iron make any difference? Does the galvanometer show more, or less, or the same effect when you bring the magnet near?*

* * * * *

Class Expt 108b Dynamo Effect using Electromagnet

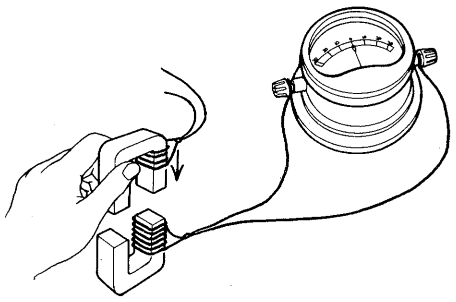
Apparatus

From electromagnetic kit, 16 sets of:	item 92
PVC-covered wire	92X
pair of C-cores	92F
16 galvanometers	180
16 dry cells‡	52B

‡ It is best to use dry cells for this experiment. Low-voltage power units could be used but the ripple on their d.c. output can lead to confusion.

Each pair will need about 4 metres of wire for the two coils.

Procedure



Pupils wind a coil of 10 to 20 turns on one arm of a soft iron C-core and connect the coil by long leads to a galvanometer. They wind 10 turns of wire around another C-core and connect the ends of this coil to a dry cell. This second core becomes an electromagnet when the current flows.

Pupils bring the electromagnet up to the first core and watch the effect on the galvanometer. They take the electromagnet away again watching the effect.

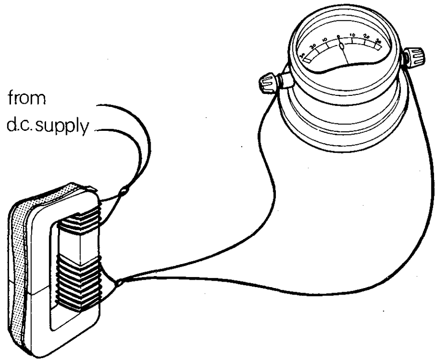
Class Expt 108c Dynamo Effect: Switching an Electromagnet

Apparatus

From electromagnetic kit, 16 sets of:	item 92
PVC-covered copper wire	92X
pair of C-cores	92F
16 galvanometers	180
16 dry cells	52B

Low-voltage power units could be used in place of the dry cells, but the ripple on the d.c. output will probably lead to confusion. There will be a deflection of the galvanometer even when the electromagnet is left switched on. Dry cells are therefore much better.

Each pair will need about 4 metres of wire.



Procedure

As a conclusion to the previous experiment pupils leave the two halves of the C-cores together—held if they wish by the clip provided. They switch the battery off and on as a way of 'removing' and 'restoring' the electromagnet.

Return to the bicycle dynamo and show its behaviour in greater detail.

Demonstration and Class Expt 109 Bicycle Dynamo (a.c.) and Milliammeter

Apparatus

1 bicycle dynamo assembly	item 103
1 demonstration meter	70
1 d.c. dial (2.5–0–2.5 mA)	71/4

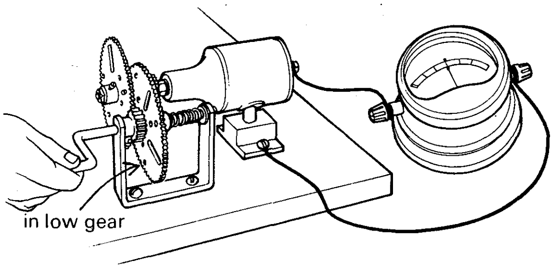
The dynamo is mounted on a base and geared so that it can be driven fast or slowly.

Procedure

Connect the generator's output (which is alternating) to the large demonstration meter with a d.c. dial 2.5–0–2.5 mA. Turn the handle with low-speed gearing so that the changing deflection is clearly visible.

Let pupils do this for themselves *using the low-speed gearing*. They should watch the pointer as they drive a little faster.

Also connect a pea lamp across the dynamo and drive it at high speed, using the other gears.



The demonstration meter with dial is suggested because it is clearly visible to the whole class.

If possible, leave the dynamo at the side of the lab for pupils to use for themselves.

A galvanometer with greater voltage sensitivity will give a better deflection (e.g., item 553). However, there is a danger of pupils using the high-speed gearing and the meter being damaged. So it may be better to confine this side-table experiment to lighting the lamp.

As the generator is driven faster, the motion of the galvanometer's pointer can be followed until it only vibrates over a small range. Then we need something that responds more quickly to rapidly fluctuating voltages. We need less mass, a stream of electrons instead of a coil and pointer. If pupils have seen an oscilloscope used with the mains, they are likely to suggest that now. In any case, offer it . . .

Introduction of oscilloscope Apply the output of the bicycle dynamo, running slowly, to the vertical input of the oscilloscope and run a horizontal sweep.

Let pupils compare the wave form of the dynamo's output with a sample from a transformer connected to the mains.

Switch from the bicycle generator to the transformer without changing the time-base at first, and let pupils themselves raise the problem of the change of frequency.

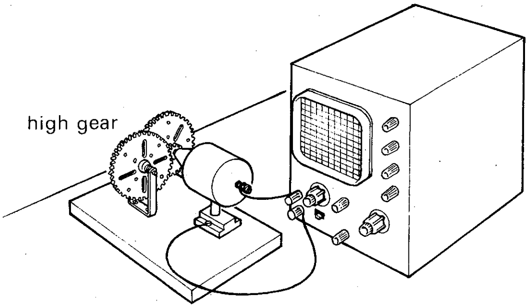
Demonstration 110a Bicycle Dynamo and Oscilloscope

Apparatus

1 bicycle dynamo assembly	item 103
1 oscilloscope	64

Procedure

Apply the output from the bicycle dynamo to the Y-plates (the vertical input) of the demonstration oscilloscope, with maximum gain on the Y-amplifier. Keep the time-base switched off, and drive the dynamo slowly. The spot will move up and down.



Switch on a slow time-base and centre the trace with the X-shift. The Y-gain should still be at maximum. Again drive the dynamo slowly. (A long persistence screen would be better here but is not essential.)

Gradually speed up the time-base.

Cut down the Y-gain of the oscilloscope to about 2 volts/cm and drive the dynamo at the high speed. With the time-base set at 10 milliseconds/cm pupils will see the wave form.

The wave-form is not sinusoidal: the bicycle dynamo was designed for efficient use and not for teaching purposes. Other generators can be found which give a more nearly sinusoidal wave-form, but there is greater value here in using a generator as familiar as the bicycle dynamo, because it is familiar.

Note. For details of the operation of the demonstration oscilloscope (item 64) see the Appendix.

Let pupils see how the wave form of the dynamo's output compares with a sample from a transformer connected to the mains.

Demonstration 110b Graph of Mains Voltage with Oscilloscope using Output from Transformer

This experiment should be a continuation of the previous one, 110a.

Apparatus

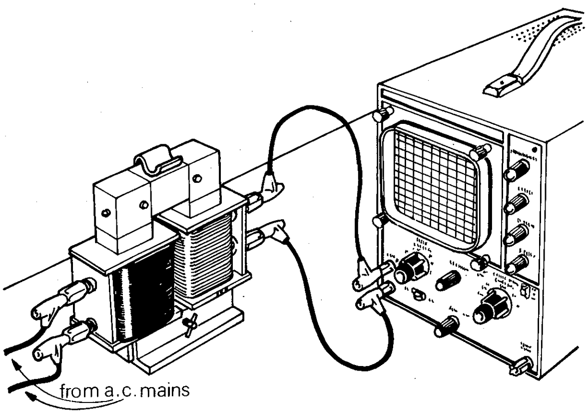
1 oscilloscope	item 64
1 transformer, 240 V to 6 V or 12 V‡	27 or 147

‡ Any transformer from mains to 6 or 12 volts will serve here; but one which makes its function clear would be much the best. If the demountable transformer, item 147, needed for Demonstration 111, has already been bought with a 12 000-turn coil, use that with a 300-turn secondary coil.

But, for schools now buying the demountable transformer, the 12 000 turn coil should be omitted as this would be the only use for it. Then either use a *home-made* secondary of 90 to 100 turns on the demountable transformer with a 3600-turn coil primary for the mains or use an a.c. power supply.

If the coils that fit C-cores for the a.c. powerline demonstration (Year 4) are available they would make a very good clear—though small—transformer for this.

If the demountable transformer is used, its core should be completed with the yoke.



Procedure

Set up the transformer. Connect the mains to the primary. There should be about 6 volts across the secondary.

Without changing the time-base on the oscilloscope from its setting for the bicycle dynamo, disconnect the dynamo; and connect the low-voltage output of the secondary of the transformer to the vertical input terminals of the oscilloscope.

Pupils will raise the problem of the change of frequency from the dynamo to the transformer. Then readjust the time-base.

A class oscilloscope This experiment with the cathode ray oscilloscope is our first extensive use of an instrument which is now so standard and commonplace in every research laboratory and engineering testing-room that we should do our utmost to continue with a class experiment.

There are small oscilloscopes designed for class experiments. If pupils crowd close they can see the small screen wall. Those small instruments are not very expensive and it should be possible to avoid having waiting crowds. If the class can be provided with one C.R.O. for every four pupils, that will be fine teaching and valuable modernization.

If this is to be a class experiment teachers may find it best to start with a demonstration using a large C.R.O. For class experiments, pupils should examine a low-voltage supply from the mains a.c.

Extra Expt 110c Class Oscilloscope
(OPTIONAL)

Apparatus

8 class oscilloscopes	item 158
8 low-voltage power units	104

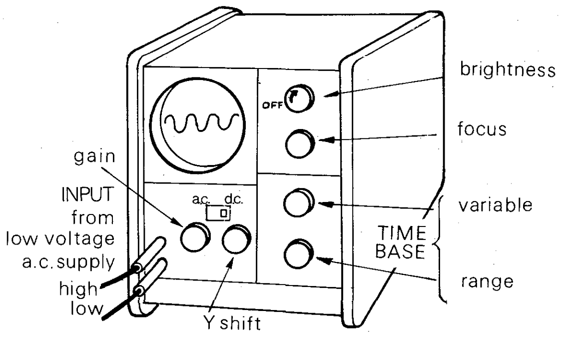
Pupils work in groups of four.

Procedure

Having seen the demonstrations on the large oscilloscope, pupils should now use small oscilloscopes themselves. They connect the low-voltage a.c. supply to the Y-input of their oscilloscope.

The time-base should be switched off at first, and then switched on to range 2. The gain-setting should be about 1.

For most of the pupils this will be a first experiment with their own oscilloscopes and they should have time to enjoy this first encounter. *This experiment should be open-ended.* Some will doubtless try doubling the supply voltage, some will change the oscilloscope gain, some the frequency of the time base.



Some pupils may also try the d.c. outputs from a low-voltage d.c. supply. Such supplies have rectifiers but, for economy, no smoothing. In that case the oscilloscope will show full-wave and perhaps half-wave rectification.

FURTHER WORK IN ELECTROMAGNETISM?

Except with a very able, fast, group, it is probably best to leave electromagnetism at this point, to be taken up again in Year 4.

Experiments have now brought pupils to the beginning of transformers and would lead to more work with alternating currents. Some pupils with special interests may want to continue now. If so, experiments with transformers will be found in *Pupils' Text 4,* starting with Expts 108a, b and c of this Year (to introduce the transformer concept with d.c.) and continuing with class experiments on the home-made transformer with a.c., the model power line with a.c., and rectification. In *Pupils' Text 5* there are interesting class experiments with very slow a.c.—1 or 2 cycles per second.

One more experiment now For now, we suggest a demonstration for delight, which also shows the fundamental action of a transformer in changing voltage. An open C-core is used and there is no secondary coil to begin with. The primary is connected to the a.c. mains. A long piece of *flexible* insulated wire is connected to a small lamp and then wound, turn by turn, round the other leg of the transformer.

As more and more turns are wound on, the lamp begins to glow, and then glows brighter and brighter. This shows very clearly the effect of intercepting more and more flux with the secondary and thus picking up volt after volt.

The Demountable Transformer and its Coils

There have long been demountable or dissectable transformers for teaching, usually in an outfit for illustrating all electromagnetism by lecture experiments.

Although we place most emphasis on pupils' own work in class experiments, there is occasionally an important experiment which might be dangerous in pupils' hands, or one that needs apparatus that is too expensive for multiple sets. One of these is a simple transformer with interchangeable coils, large enough to be watched by a whole class, to meet several needs in our Years 3, 4, and 5.

The core should be a laminated U, at least $11\frac{1}{2}$ cm wide by 12 cm high with a laminated I yoke that is easily removed, and restored. It should have a cross section at least 3 cm × 3 cm.

The arrangement for clamping the core to a baseboard and for clamping the yoke to the core (seldom necessary) should be as simple and unobtrusive as possible. Supporting clamps should not bulk large in the appearance of what is meant to be a clear 'skeleton' device.

The coils, which should be wound professionally and given good terminals, should have numbers of turns chosen to fit our needs economically. Those needs have changed a little. Originally, we asked for coils of 300 turns, 600, 600, 1200, 3600, 12 000 turns. Schools that already have those will find they meet all needs. Schools now planning to buy the transformer are advised to buy the following coils:

300 turns, 300, 600, 3600.

With two 300-turn coils (and only one 600) the 1200- and 12 000-turn coils will not be needed. For an inductance with slow a.c., the 12 000-turn coil is better replaced by the new 'high inductance coil' (designed for A-Level) on a pair of C-cores.

Demonstration 111 Winding a Transformer Turn by Turn *(OPTIONAL, but desirable, NOW)*

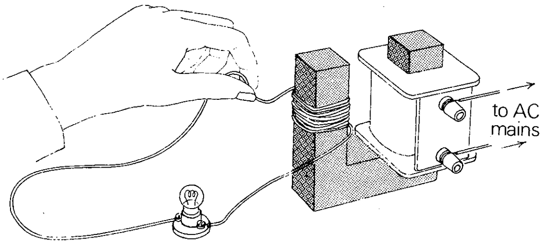
Although we suggest this as optional in Year 3, we hope teachers will show it, for sheer delight.

Apparatus

1 demountable transformer	item	147
with 1 coil of 3600 turns		147G
1 MES bulb ($2\frac{1}{2}$ V)		92R
1 MES holder		92T
spare lamp		92R
flexible, well-insulated wire (4 metres or more)‡		

The demountable transformer is necessary for this demonstration. It is large and impressive; and it has other uses in this Year: for a step-down transformer to show a.c. on an oscilloscope; its coils in a demonstration of magnetization curve; and one of its coils for magnetizing and demagnetizing magnets. So we trust it will be available now.

‡ For the flexible wire, one of the wires from twin lamp flex is much better than the PVC insulated wire.



Procedure

Place the 3600-turn coil on one leg of the laminated U-core of the demountable transformer. Connect it to the a.c. mains.

Connect the long flexible lead to the lampholder with the pea lamp.

Switch on the mains and wind the long wire *turn by turn* round the other leg of the U-core. As more and more turns are wound on, the lamp begins to glow and then gets brighter and brighter. At least 25 turns will be necessary for this.

CHAPTER 7

VOLTAGE AND POWER

Introduction to voltmeters; model transmission line; household electric supplies and safety

Before this Year ends, pupils should learn something about potential difference, not for an excursion into Ohm's-Law calculations but for simple empirical knowledge of power measurement. Some pupils will leave Physics at the end of this Year and we owe them especially some practical feeling for the use of voltmeters in a circuit and the meaning of volts, amps, and watts.

Introduction to Voltmeters

Energy-transfer When pupils consider a dynamo in a power station, they can see the changes of energy: *FROM* chemical energy in fuel *TO* heat *TO* mechanical energy in the driving machinery, *TO* some electrical form of energy which, as electrons are driven along the wires, is in turn converted *TO* heat and mechanical energy.

That would be an interesting chain leading quickly to the concept of p.d. or voltage, if pupils were already familiar with energy-transfer. Pupils who followed Nuffield Physics in Year 2 will have met considerable discussion and practice with such energy-changes. Pupils in Nuffield Combined Science will have met similar emphasis on energy-transfers but may have missed the questions.

Pupils from other programmes may have missed such discussions; and in any case they are likely to have missed our special insistence on WORK as a name for calculated energy-transfer (and not a name for mechanical or any other actual form of energy).

For the present, rather than embark on the full discussion of energy-changes which will come in Year 4, we suggest teachers should introduce voltmeters as empirical instruments now and show their use with only brief discussion of energy.

Energy units With a fast group, it would be good to remind pupils that a newton—still only defined as a FORCE unit provided by a spring balance—leads to a newton·metre of WORK which we name a joule. Then a volt can be described as a joule per coulomb. But that in turn asks for definitions of a coulomb and of an amp as a coulomb per second. Such a series of new quantities and names is likely to be burdensome rather than illuminating at this stage. So we do not advise it for this Year.

Introducing the need for voltage The bicycle dynamo, driven fast, will produce enough power to light a small lamp at, say, $\frac{1}{2}$ amp. But pupils would hardly expect it to run a mains lamp at $\frac{1}{2}$ amp. That raises the question of measuring the energy which an electric supply can transfer—described vaguely as ability to light lamps.

Some pupils will already be familiar with the use of the word 'volt' in this context. The bicycle dynamo provides only a few volts while the mains provide 240 volts. And the label at the bottom of a pylon may read 'Danger: high voltage. 132 000 volts'.

In this connection it is good to give the impression that 'volts bite'. However, insistence on p.d. being 'electrical pressure' can build up serious trouble for later stages when we want to define p.d. properly as energy-transfer per unit charge. 'Pressure' is not a safe analogue; yet describing p.d. as '*like* pressure' is helpful when pupils are making a first acquaintance.

Simple description of voltmeter as a 'cell-counter' In Year 4 we shall use voltmeters with a clear definition of the potential difference in terms of energy-transfer. But here, in Year 3, we suggest introducing voltmeters as empirical instruments which can count the number of cells in a battery. The following class experiment provides the introduction. We hope to convey the idea that the new instrument is a 'cell-counter'.

Class Expt 112 The Voltmeter as a Cell Counter

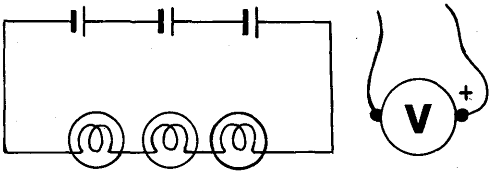
This could be done as a demonstration to save time, but the lasting value would then be much smaller for most pupils because voltmeters are mysterious and each pupil needs to get his hands on one.

Apparatus

From Worcester Circuit Board kit, 16 sets of:

3 U2 cells	52B
3 bulbs	52A
3 spring connectors with bulb holders	52D
spring connectors	52E
2 plug/croc leads	52I
2 croc/croc leads	52J
16 Worcester Circuit boards‡	52C
16 d.c. voltmeters, 0 to 5 volts	80
(cinemoid filter)	57J

‡ It is not necessary to use the actual circuit boards. Schools which do not follow Nuffield Year 2 and have no circuit boards certainly should not buy them for this. Any arrangement that enables pupils to connect up cells and voltmeter will suffice, though the circuit board is clear and convenient and saves time.



Procedure

Pupils follow these instructions:

* * * * *

Set up a circuit with three cells and three lamps all in series, as in the diagram.

Attach two long, flexible wires ('leads') to the voltmeter.

Switch on the lamps, and keep them running.

Connect the voltmeter leads to one cell, then across two cells, then across three. Record the reading of the voltmeter each time.

How many cells are needed to light one lamp fully?

How many cells to light two lamps in series fully? Three lamps in series fully?

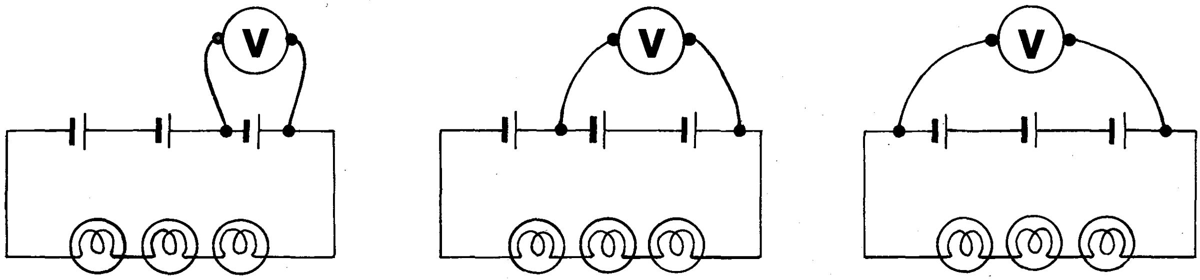
What does the voltmeter tell you? What does it count?

Is the voltmeter connected in series with the lamps or in parallel?

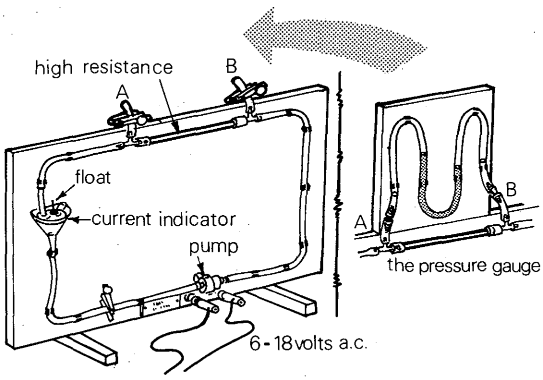
Is an ammeter connected in series with the lamps or in parallel?

What does an ammeter count?

* * * * *



Model water circuit As an illustration of our talk about current being the same all round the circuit, we suggested showing a simple water circuit. This model was first described in Year 2. At that stage it would have been a mistake to include a pressure gauge, but we shall suggest that in Year 4. If teachers like to show the water circuit now with a pressure gauge connected *across* the high resistance it may help pupils to see the use of a voltmeter.



Model water circuit: Description of Apparatus

CIRCUIT. A rectangular circuit of narrow transparent tubing, preferably plastic, on a vertical board. The tubing is filled with water.

PUMP. A small pump combined with an electric motor drives water round. One suitable make runs on 6 to 18 volts a.c. This corresponds to a battery.

TAP. A pinch clip at some point corresponds to a switch.

RESISTANCE. A section of capillary tube corresponds to a wire of high resistance in series in the circuit. Or that may be a section of ordinary bore filled with lead shot.

FLOWMETER. At a break in the side of the circuit where the flow is downward the water falls into a funnel and swirls round before continuing down. A small cork float indicates the rate of swirling, as a measure of the current. This corresponds to an ammeter.

PRESSURE GAUGE. A small U-tube with some coloured water in it shows the pressure-difference between the ends of the high-resistance section. It is connected *across* that section, and it must be placed *above* so that the coloured water in it is separated by air from the water flowing in the main circuit.

NOTES. (i) In earlier models, there was a suggestion of a *pair* of high-resistance tubes in *parallel.* That is confusing and should be avoided completely.

(ii) An alternative flowmeter is a home-made form of the commercial flowmeter known as a 'rotameter'. This is a vertical tapered tube with the wide end at the top, containing a ball or a small spinning top as indicator. As water flows up the tube it carries the indicator up to a height which depends on the speed of flow. The faster the flow, the higher the ball's (stationary) position. Commercial rotameters have carefully made tapered tubes and are expensive. We certainly do not suggest that any school should buy one; but it is easy to make a simple uncalibrated form by drawing out a piece of wide glass tubing to make a tapered pipe.

Demonstration 113 Water circuit

Apparatus

1 water circuit board	item 89
1 L.T. variable voltage supply	59

Preparation

Set up the board vertically. Connect the electric motor (which is incorporated in the pump) to the a.c. terminals of the L.T. variable voltage supply (*not* d.c.). The motor can take up to 16 volts. Fill the tubes with water by pouring it in at the funnel. A little fluorescein or a few drops of methyl orange can be added to make the water more visible.

The pump drives water round the circuit, the pump's pressure ('e.m.f.') being dependent on the voltage applied to the pump's motor.

Put some coloured water in the pressure gauge; but leave some air above that water in each leg.

Procedure

Show how the pressure gauge must be connected. Point out that it measures *differences* of pressure.

Demonstrate the change of water-current with pressure, by changing the supply to the pump motor.

Power Transmission: Model Transmission Line

Some pupils may continue to experiment with voltmeters; but before that all should use a model transmission line as a class experiment in the electrical work of this Year. The low-voltage experiment is followed by a *demonstration* with a high-voltage supply, done with one of the pupil's models. (That supply could be the 240-volt a.c. mains if a d.c. supply is not available, since no meters are used.) It is important to change to high-voltage lamps of approximately the same wattage.

Together the two experiments show something important about voltage and efficiency.

(The same 'power line' will be used with alternating current in Year 4; but will be all the better for a first trial with d.c. in this Year.)

Pupils do *not* need a clear understanding of potential difference for this—in fact this experiment may serve as the best introduction to the concept, since it shows the practical importance of voltage.

For the low-voltage class experiment we suggest 12-volt lamps, run from a 12-volt car battery. As our programme continues through this year and the next two years, such accumulators, which have probably proved useful already, will be necessary for several important jobs.

We advise every school following our programme to have at least four accumulators (or the Nife cells). The cost and care of these may be a considerable burden; but we live in an electrical age where pupils should be able to draw upon visible, steady supplies of direct current at a few volts.

When we change to a 240-volt supply, the lamps ought to be of about the same wattage. These should be ordinary bulbs like those the pupils meet at home. The best choice would be

25-watt lamps. If the 240-volt d.c. supply cannot supply 50 watts for the two lamps, 15-watt lamps must be used instead.

No meters are needed. The importance of these experiments lies in the clear change from a highly inefficient line to a highly efficient one. Teachers who have not tried this experiment will be amused by the impressive contrast.

Class Expt 114a Model Transmission Line, d.c. (6 volts)

Apparatus

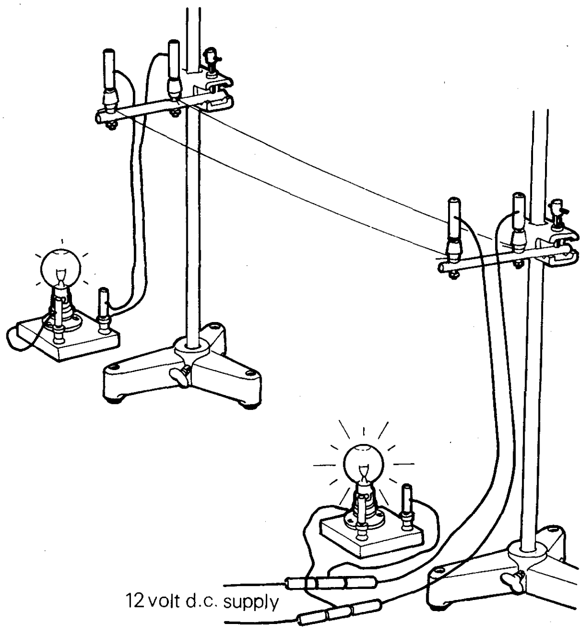
8 pairs 'power-line' terminal rods	item 99
16 $1\frac{1}{4}$-metre length bare Eureka wire (SWG 28)	98
16 retort stands and bosses	503–505
16 lampholders (SBC) on bases	74
16 lamps (12 volt, 24 watt)	72
4 (or more) 12-volt batteries	176

Pupils work in groups of 4.

Preparation

It will save much time and avoid confusion if the pylons and 'power lines' can be set up beforehand. Otherwise assembling the apparatus may bulk larger in later memory than the very important exhibit of power transmission and the need for high voltage.

For each group of pupils, two dowels form the 'power-line' terminal rods. They are held horizontally in bosses at a height of 30 to 50 cm above the bench and 1 metre or more apart. Two lengths of high resistance wire (Eureka SWG 28) are stretched between the terminals to form the power line.



Procedure

Pupils follow these instructions:

* * * * *

Set up the experiment sketched. Use a 12-volt battery (or similar power supply) as your 'power station'. Run wires from the 'power station' to the terminals on a pylon nearby.

Run two thin wires from that pylon to the second pylon at a 'village' far away. Those wires are your model 'power line'.

At the 'village', connect a 12-volt lamp to the 'power line'.

Switch on. How well is the 'village' lit?

Install an extra lamp at the 'power station' end. That is the station engineer's lamp to read his meters by. How does that lamp compare with the lamp at the village?

* * * * *

Before any discussion, offer a demonstration with a high-voltage transmission line.

Demonstration 114b Model Power Line, with High-voltage Supply

Apparatus

As for one of the pupil groups:

1 pair 'power-line' terminal rods	item 99
2 $1\frac{1}{4}$-metre lengths bare Eureka wire (SWG 28)	98
2 retort stands and bosses	503–505
2 240-volt, 25-watt lamps‡	
1 H.T. power supply	15
2 lampholders on bases‡	74
1 switch	224

‡ Ideally the lamps should be SBC so that they can be used in the same lampholders as in the previous experiment. Otherwise BC lampholders will be necessary.

Procedure

Set up the 'power line' as in the class experiment but with the two 240-volt lamps instead of the two 12-volt lamps. For the 'power station', use the 240-volt H.T. power supply.

Install a switch.

Switch on and let the lighting speak for itself.

NOTE. Remember that there will now be a p.d. of about 240 volts between the two bare wires of the 'power line'. Therefore this second experiment must be a demonstration.

Voltmeters Some pupils may have seen a voltmeter introduced in Year 2: but the impression gained then would probably be vague. Now voltmeters are growing in importance. They will be essential in Year 4, with an energy-transfer definition of p.d.

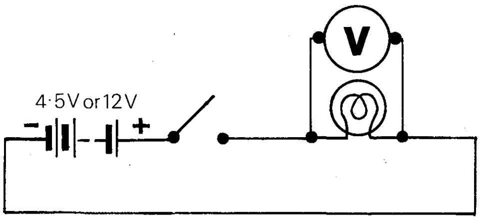
If time permits, pupils should have quick introductory class experiments now. Those who continue to Year 4 will profit from this early look. Those who will leave physics at the end of this Year deserve to make some practical acquaintance —if only to make voltmeters seem reasonable and useful instead of a mysterious step-brother of an ammeter.

Class Expt 115 Using a Voltmeter *(Advanced extension, OPTIONAL NOW)*

AIM. This is a quick experiment with definite instructions, to let pupils connect a voltmeter correctly. This is a rare case where it seems better to avoid a mistaken start; just tell pupils directly, without explanation, what to do.

Apparatus

There should be a voltmeter for every pupil or pair of pupils. The apparatus must depend on the number of pupils or pairs trying this experiment and the number and ranges of voltmeters available.



If voltmeters reading to 12 volts or more and suitable ammeters are available (items 178 and 179, for Year 4), use 12-volt 24-watt lamps in SBC lampholders (as in the power line experiment) with 12-volt batteries.

If only voltmeters with range 0–5 volts are available, use 3 U2 cells and 3 small bulbs all in series—as in the previous experiment with a 0–1A ammeter inserted.

Procedure

Pupils follow these instructions.

* * * * *

First make your lamp(s) light as you have done before. Then add a voltmeter to the circuit. You may take it for granted, just for now, that a voltmeter has to be connected like a pressure gauge. Connect it 'across the lamp(s)'—as electrical engineers would say—to measure the 'voltage' being applied to the lamp(s).

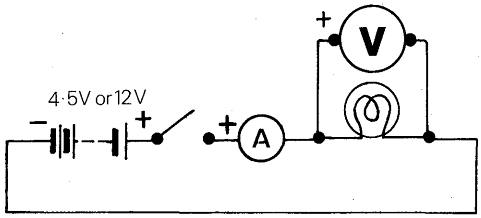
This experiment is just for practice; to learn how a voltmeter is used. If you want to measure power, now insert an ammeter in the circuit.

* * * * *

Class Expt 116 Using a Voltmeter to measure Power *(OPTIONAL NOW)*

Pupils continue with the circuit of the previous experiment (115).

They insert an ammeter. They read their ammeter and voltmeter.



To calculate the rate of energy-transfer from electrical form to heat and light in the lamp, pupils must know what a voltmeter measures and what an ammeter measures. *Pupils' Text 3* provides this knowledge, by assertion at this stage, and gives a sample calculation. Therefore this should only be offered as an extension now for those who will accept the assertion.

Mains, Fuses, Earth wires

Pupils' Text 3 has a section on safety and earth connections in house wiring.

CHAPTER 8

ELECTROSTATICS

A stream of electrons, charges, forces and fields

We suggest only a brief qualitative look at charges at rest: their general behaviour and the forces they exert. Also a look at some patterns of electric fields.

Since this chapter comes at the end of the year none of its work is essential now.

However, those pupils who will proceed to Years 4 and 5 will profit from an early look at field patterns and a simple knowledge of forces on charges in a field. That will prepare for the very important treatment of Millikan's experiment in Year 4.

Electrostatics

Electrostatics has a varied history in teaching: sometimes emphasized for historical value, or for its simple experiments, or as a necessary basis for making atomic measurements and models; sometimes neglected as wayward and puzzling experimentally and not really necessary for atomic physics at an elementary level.

In our programme some new equipment has made electrostatics experiments more reliable, and emphasis on modern physics has made *simple* knowledge of electric forces and fields essential.

In Year 3, however, a long series of electrostatics experiments with a Nuffield kit seems unnecessary—pupils would consider it unconnected with the electromagnetism they have been learning in the lab. So we suggest postponing, or even omitting altogether, class experiments on forces with rods and suspended samples, ice pails, and charging by induction.

Yet pupils should see now some simple demonstrations of electric forces and fields.

We suggest introducing those by the fine-beam tube. Pupils will see a stream of electrons made visible and an electric field used to deflect the stream. That gives pupils a glimpse of evidence for electrons with a negative charge. The deflecting force is made by charges driven on to plates by a battery.

From that beginning, a simple discussion of charges, forces, and fields can run quickly.

Balloons charged by rubbing will show forces. And pupils should at once see the charges being installed by other methods. If an E.H.T. power supply is available, pupils should see it pumping up stores of charge on to short strips of metal-coated plastic.

If a Van de Graaff machine is available they should see that doing the same thing.

We want pupils to see that power supplies which drive a current produce the same kinds of charge as electrostatic machines—not two different types of + and − electricity. So, if the school has an E.H.T. supply and a Van de Graaff, it is worth while to use both for each of the following demonstrations: charged balloons; charged metal-coated strips; electric fields with a paper arrow and with semolina. But only the Van de Graaff does well for smoke clearing.

Apparatus for Electrostatics

Changes in school organization have raised serious problems in the provision of Nuffield physics equipment. When the Programme was first constructed and apparatus for it was listed, we assumed that most schools trying the Programme would teach all five Years in succession. Therefore apparatus essential for, say, Year 4 would be available in the school for a first look in Year 2. So we did not feel embarrassed in asking schools to buy such apparatus for Year 2 classes.

We relied particularly strongly on such availability for multiple use in topics prominent in the 'spiral approach'—i.e. topics to be treated with increasing sophistication in several successive Years.

Now, however, Years 1 and 2 may be taught far away from Year 3; and there may be further moves between 3 and 4 or between 4 and 5. Since there is no universal pattern of such rearrangements, we cannot specify a grouping of Nuffield equipment that will fit all schools economically. Instead, we list apparatus and kits as necessary where we feel the experiments form an essential part of the programme.

We list some experiments 'optional now' to avoid overcrowding or boredom in Year 3. But we also use that description to save a Middle School from buying apparatus that is not strongly needed until a later Year, which may be in a different school.

The new difficulties of apparatus for reorganized schools are acute in the case of electrostatics. We do not consider electrostatics very important in Year 3; yet there are things that we wish pupils could see—particularly pupils who will leave physics at the end of Year 3.

So, for electrostatics equipment, we make the following suggestions:

HIGH-VOLTAGE SUPPLIES. Both the E.H.T. power supply and the Van de Graaff machine are only used for a few suggested demonstrations near the end of the Year. If the school has both, or proposes to buy both for use in later Years, *both* should be used in the experiments now listed.

If the school was neither and decides to buy only one of those, *we recommend the E.H.T. supply.* It is not so flamboyant but it has more uses in later stages.

E.H.T. POWER SUPPLY. As described in *Guide to Apparatus*, this should give a variable d.c. supply up to about 5000 volts. The case should be earthed through the third wire of its mains connections; and there should be an earth terminal on the front. The output, both + and −, should be independent of earth, so that either end can be connected to the earth terminal.

The E.H.T. supply is essential now if we are to show that 'electrostatic' charges are the same kind of thing as charges driven on to conductors by a battery or its equivalent. Without the parallel demonstrations with the E.H.T. supply, electrostatics will remain a detached study.

The E.H.T. supply will have important further uses in Years 4 and 5.

CHARGING BALL. For some electrostatics demonstrations, it is helpful to have a metal ball (2 cm or more in diameter) with a 4 mm rod fixed on it to go into either + or − socket of the E.H.T. supply. A large insulated ball ('charge conveyor') can be brought up to that metal ball to pick up charges easily and convey them to other apparatus.

VAN DE GRAAFF MACHINE. As this is the input generator for many modern accelerators, the school model shows pupils an important contemporary device.

In our use, the machine is at best a source of plentiful charges at very high voltage; and at worst a mysterious, charming toy. In Year 3 it can help to show that 'electrostatic' charges do the same things as charges from supplies that drive currents; but the only demonstration for which it is *essential* is that of clearing smoke.

If the school decides to buy one, we strongly recommend a *hand-driven* machine. This should be less expensive than a motor-driven one; and, from the point of view of good teaching, the presence of an *electric* motor is unwise.

Accessories. The set of accessories offered with a Van de Graaff machine is quite unnecessary and unreasonably expensive. We urge schools not to buy it. One can make what is needed from a cheap plastic tumbler and a few expanded metallized polystyrene balls.

Home-made machine. It is possible to make a small simple form of the machine from household components. See the construction sheet for details.

A Wimshurst machine can be used as a substitute; but its action appears more complex to pupils, and it would be a pity to spend time explaining. Old machines with glass disks are often temperamental; but, if the glass is replaced by Perspex or another plastic, the machine's performance will be magnificent—but as mysterious as ever.

We do not advise any school to buy a Wimshurst for Nuffield physics.

CHARGE CONVEYOR. This should be a large light ball (polystyrene 5 to 15 cm diameter, or a balloon). It must be made conducting by antistatic spray or Aquadag.

It should have a long insulating handle (60 to 100 cm) so that one can stand far away from the apparatus and thus avoid producing unwanted induced charges. The new plastic metre rulers from manufacturers of metric teaching apparatus make excellent handles.

KIT FOR CLASS EXPERIMENTS. The Malvern Electrostatics Kit is an excellent collection of simple apparatus which avoids the old troubles that arose from leakage on damp days. However, work with it would carry pupils out on a side branch in busy Year 3. Instead we suggest a few simple *demonstrations*. These will require only two kit items, easily obtained separately:

a few metallized expanded polystyrene balls (51C)
a reel of very fine nylon suspension (51E).

Then the whole kit will be needed in Year 4 or Year 5 for class experiments to introduce the electroscope which plays an important part in Year 5.

FINE-BEAM TUBE. We suggest this as an interesting introduction to the brief treatment of electrostatics in Year 3. It also gives pupils a glimpse of 'electrons'. So we regard it as essential now. It will be used again in Year 4, and for measurements in Year 5.

If the school already has a Leybold fine-beam tube, that will be excellent for use in Years 4 and 5 with the stream bent into circular orbit. Without a magnetic field, it has room for only a short beam in our demonstration here; but even that is worth showing to pupils individually. It is not suitable for the optional demonstration of magnetization at the end of this Year.

If the school does not yet have a fine-beam tube, we recommend the Teltron one with two guns. The green glow that marks the path of the stream is easier to see; though sometimes it does not focus quite so sharply. The straight-ahead gun provides well for the demonstrations now and for the magnetization demonstration in this Year. The other gun provides a good stream for the circular orbit in Years 4 and 5. The magnetic field coils for the latter use are unfortunately small but the economy in cost is welcome.

Policy suggestions for Electrostatics

{**Stories of electrons** Pupils seem to find it easier to understand or describe electrostatic phenomena if we, and they, tell romantic stories about electrons. All have heard of electrons, and many have heard a good deal about the way electrons behave, running freely over metals, etc., and even hurtling round unrealistic sharp orbits in atoms.}

{Some teachers like to use their pupils' common knowledge and enthusiasm for electrons in explanations of electrostatics. Others consider it bad science to embroider the experimental facts with stories about electrons of which the simple experiments give no hint whatever.}

{The policy which we suggest in this programme is one of compromise: that we should accept pupils' familiar knowledge and speak of the behaviour of electrons in describing electrostatic phenomena, but the teacher should warn his pupils—and should keep the same warning in his own thoughts—that at this stage electrons are only an interesting concept. They make it easier for us to think about the things we see. Scientists have always enjoyed imagining material models. (See also the 'Note on Teaching Electrostatics with Electrons' in the General Introduction.)}

{**Electrons moving** Pupils may bring up a question about which charge moves in a current: do the positive charges move one way or the negative charges move the opposite way, or do both kinds move in the two directions? We must be honest, and say that nothing in the experiments pupils are doing (or in many of the experiments that we ourselves know about) makes any distinction between these three possibilities.}

{Therefore, on strict principles, we should be wise to follow Einstein and Bohr, and not put unwarranted details into our descriptions. Newton too had some feeling in that direction when he wrote '*Hypotheses non fingo*'—'I will not *feign* hypotheses'—though he also made speculative guesses.}

{Yet pupils 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 agnostic view to them, we should put it gently; but we should insist on keeping an open mind.}

{We should always be wary about decorating descriptions of the *microscopic* world with unnecessary details. In being cautious, we shall be following the practice of the modern physicists who make most progress in knowledge of atomic and nuclear structure: they try to avoid 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 young child's idea that a 5p piece has a 1p coin and two 2p coins rattling round inside. In general, we know that transferring our *vocabulary* from the man-sized world to the microscopic world may lead to paradoxes and mistakes.}

{**Driving electrons along a wire** Pupils may ask what makes the electrons run along a wire. (We should not quarrel with their wording, though a more sophisticated question would be 'What makes the great random motion of electrons in a metal wire keep up a small drifting motion in one direction when a battery is connected?) We can say that the battery has piled up *electric charges* on its terminals, + and − ; and those produce forces which extend to the wire and push or drag electrons along the wire. We may say the battery produces an *electric field* along the wire.}

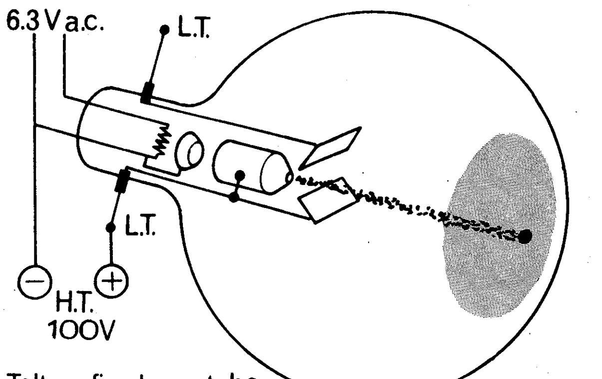
Pupils are now going to learn about charges and fields. For a good start, show a stream of electrons in a fine-beam tube.

Demonstration 117 The 'Naked Oscilloscope': Fine-Beam Tube

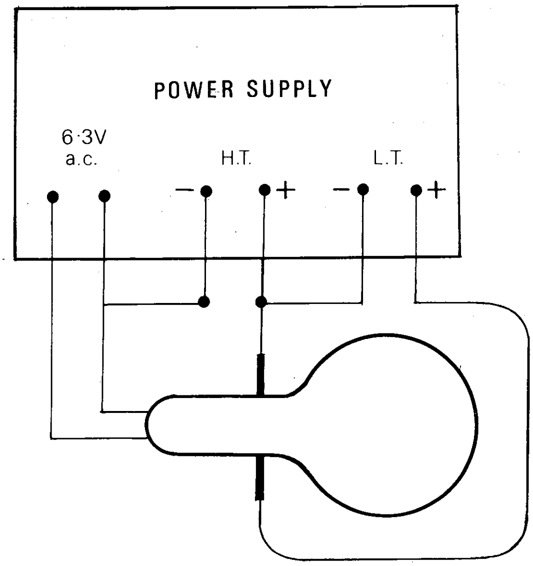
The Teltron fine-beam tube with two electron guns meets our suggestions better than other designs previously recommended; so the instructions below refer to the Teltron tube; but if the school already has a tube of another make that should certainly be used.

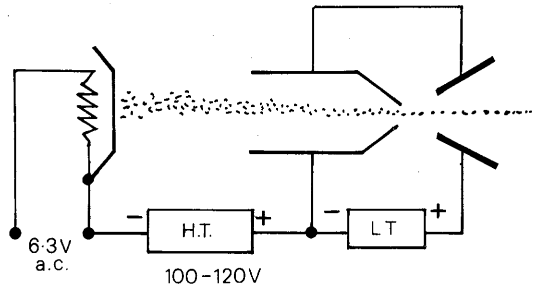
Apparatus

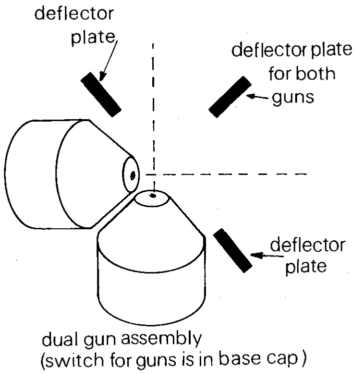
1 fine-beam tube and base	items 235/140
1 H.T. power supply	15
1 L.T. power supply	59



Teltron fine beam tube







Tube Connections

Heaters. The sockets at the back of the base cap are for the cathode heaters. Connect them to a 6.3 volt (a.c.) supply. The socket marked − must also be connected to the *negative* terminal of the H.T. supply for gun voltage. The two-way switch on the cap puts one gun or the other in action.

Gun voltage. One of the side terminals on the tube leads inside the tube to the muzzles of both guns. Connect that to the *positive* of the H.T. power supply, 100 to 200 V d.c.

The deflecting field. Just outside each gun muzzle there is a pair of plates for deflecting the beam by an electric field.

One part of each pair is attached directly to the gun muzzle which supports it. The other plate of each pair is connected inside the tube to the second side terminal on the tube.

Connect that side terminal to the *positive* of a variable L.T. d.c. supply. To complete the connections to the deflection plates, connect the *negative* of the L.T. supply to the gun muzzle (the + of the H.T. supply).

A small p.d. of 1 or 2 volts between these plates will usually make the beam focus more sharply.

When the beam is to be deflected visibly by an electric field, increase that p.d. to 20 or 30 volts.

Procedure

For pupils to 'see' an electron stream, use the gun which fires straight along the axis of the tube, to the fluorescent screen.

Heat the cathode, then turn on the H.T. gun voltage and let pupils look at the tube closely in a half dark room. For many, this will be their first glimpse of a 'visible electron stream' and they need time to enjoy looking; and then an explanation.

If the beam fails to make a clear spot on the screen try two cures:
(i) vary the small p.d. applied to the deflecting plates.
(ii) clean accumulated charges off the screen by sweeping the beam up and down it and across it.

Explanation *(as in Pupils' Text 3)*

* * * * *

At one end of the tube there is a little rocket-shaped 'gun'. In that gun a starting plate is heated by a tiny electric grill.

The plate has a special surface that lets electrons loose rather easily. Electrons boil off that plate. They are speeded up in the gun by a large voltage between that starting plate ('cathode') and the gun muzzle ('anode').

Electrons come out at high speed through a tiny hole in the cone-shaped muzzle.

(We can calculate their speed from some measurements. It is more than 5 000 000 metres per second!)

The electrons continue at that constant speed to the end of the tube and make a bright spot where they crash against the mineral screen.

You can see that this is like an oscilloscope tube, but naked so that you can see inside.

The tube in a cathode ray oscilloscope has an electron gun just like that: but here the stream from the gun muzzle is made visible. This glass globe has been pumped out to a very good vacuum to remove air, which would soon slow electrons down by collisions. But then a *very little* helium gas is let in, because the helium atoms give out a green glow when hit by electrons.*

So you can see the path of the electrons made visible as a thin line of glow.

Look at that carefully. You are seeing the path of electrons flying through thin helium, almost a vacuum, all by themselves, with no wires there.

* * * * *

* A similar tube of another make has hydrogen, which makes a faint blue glow, instead of the green glow of helium.

Note to Teachers

If, as we suggest, the fine-beam tube is shown as an *introduction* to electrostatic charges and forces, the deflection of the beam cannot be used yet to show that electrons in the stream are negatively charged.

Nor can we explain that the gun voltage accelerates the electrons.

Pupils have yet to seek that 'unlike charges attract', or that the electric field between + and − plates drives negative charges towards the + plate.

But we need not worry. Pupils will gain from a second look after demonstrations with balloons, etc. Then we can discuss the evidence from the deflection.

For now, show the beam being deflected when a p.d. of 20 to 30 V is applied to the deflecting plates; and promise a discussion later.

Programme Then show forces between charges with charged balloons, etc. (*Pupils' Text 3* gives a description of dynamos and batteries 'pumping' charges on to balloons and metal objects, where they exert static forces on each other.) Then show field patterns.

After that return to the fine-beam tube, for pupils to see it in the light of new knowledge.

Demonstration 118 Electric Charges and Forces

Apparatus

For 118a

1 E.H.T. power supply (5000 volts)	item 14
1 megohm resistor	216
1 demonstration meter	70
1 d.c. dial, 2.5–0–2.5 mA	71/4

For 118b and c

1 E.H.T. power supply	item 14
2 strips of metal-coated Melinex‡	214
2 Perspex rods	217
2 retort stands, and bosses	503, 505
sellotape	

For 118d

2 strips of plain Melinex‡, not coated	215
1 Perspex rod	217
1 retort stand and boss	503, 505
sellotape	

For 118e and f

4 balloons, inflated	
1 reel nylon thread	51E

For 118g

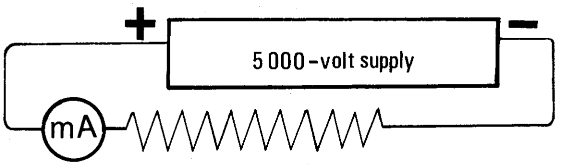
E.H.T. power supply	item 14
1 balloon, inflated and suspended (from *118f*)	
1 balloon, inflated, *conducting*	
1 long Perspex rod (60 cm or more) or *plastic* metre rule	
sellotape	

For 118h

1 Van de Graaff machine	item 60/1

‡The strips should be about 12 cm × 2 cm. They must be flexible. 25-gauge Melinex is suitable. For parts *b* and *c* it must be metal-coated on both sides.

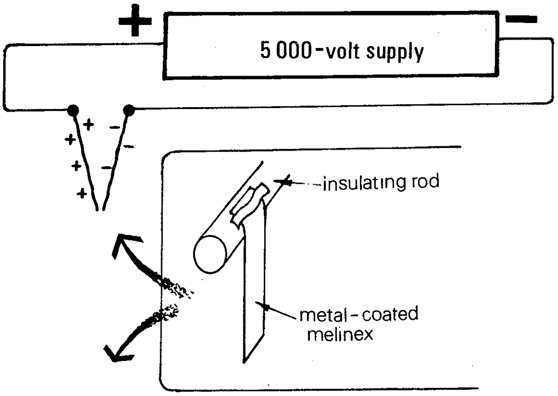
For part *d* the strips must be of plain flexible non-conductor (Melinex, or strips of polythene film cut from a sandwich bag).



Procedure

118a. A current, driven by power supply. Connect the E.H.T. supply to 2 megohms and the demonstration milliammeter. Simply point to the current.

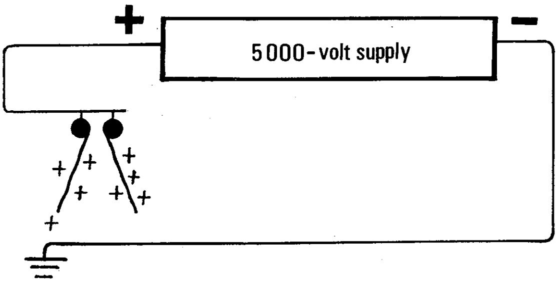
118b. Charges at rest, provided by power supply. Hang two strips of metal-coated Melinex from horizontal insulating rods on stands. Place the stands just far enough apart to prevent the strips touching when they attract each other.



Carry leads from the E.H.T.'s + and − terminals (neither of them earthed) to the strips, and touch them momentarily.

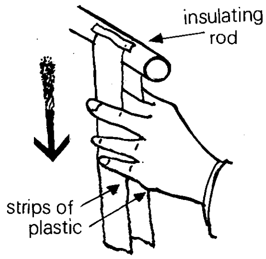
118c. Charges of the same kind, provided by power supply. Earth one terminal of the E.H.T. supply. Connect the other terminal momentarily to each strip in turn.

Move the stands nearer, so that the repulsion is more marked.



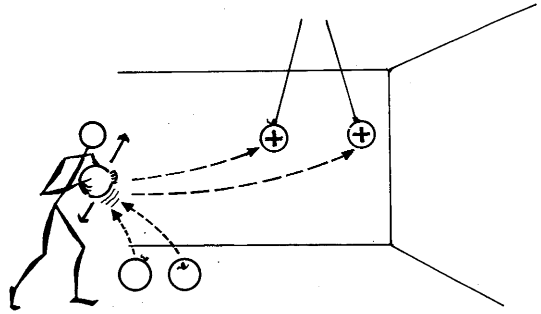
118d. Charges made by 'friction'. Tape two strips of uncoated flexible plastic to an insulating rod (Perspex) in a stand. Run *dry* fingers down the pair of strips, with one finger between them.

Note. If the strips are already charged, they are easily discharged by waving a lighted match nearby.

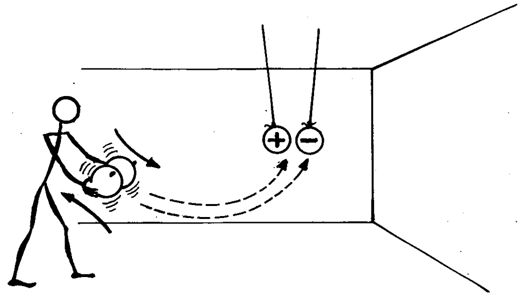


118e. Charging balloons by 'friction'. Hang up two inflated balloons by long nylon threads. The balloons must be well above the table or floor, and far from any metal supports.

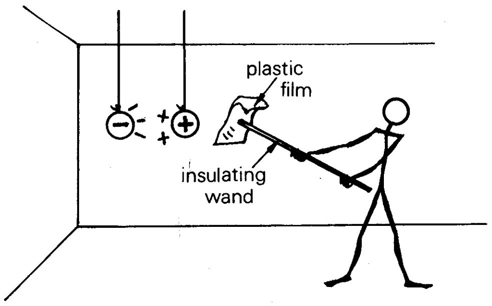
Charge the balloons with like charges by rubbing each in turn against a wool jacket or pullover. Stand well away and let pupils see the effect of like charges repelling.



118f. Unlike charges. Hang two more balloons a small distance apart. Rub them against each other. In practice, this produces *unlike* charges on the two balloons (but the charges are unequal in size).

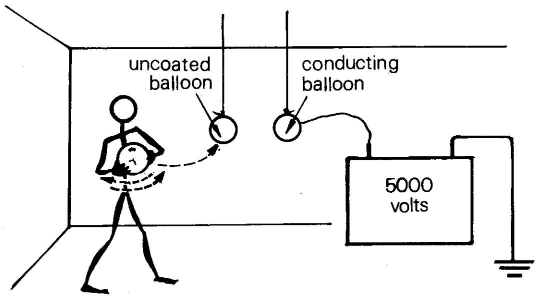


Hold these oppositely charged balloons apart by their threads. Gently release the threads. Pupils look for attraction.



Crumple a piece of plastic, such as a sandwich bag; rub it on wool and bring it near each of those balloons in turn. (There is a competition between the effect of the charge on the crumpled plastic and induced charges on one's earthed hand; so it would be better to hold the plastic on a long insulating rod.)

118g. Different methods of charging: the hybrid experiment. Charge one balloon by 'friction', the other by a 5000-volt power supply.



The E.H.T. supply will not put large enough charges on two balloons for the forces to be noticeable. However if one balloon is charged by rubbing on wool and a second balloon is charged from the E.H.T. the mutual forces will be appreciable.

The second balloon must be made conducting. Spray it with anti-static aerosol spray. (Some aluminium aerosol sprays will make a conducting coating, or the balloon can be painted with Aquadag mixed with wetting liquid; but anti-static spray is best.)

Attach the conducting balloon to a long insulating handle. Make sure that the handle is not itself already charged, accidentally, by friction. To remove such charges, wave a lighted match or candle nearby.

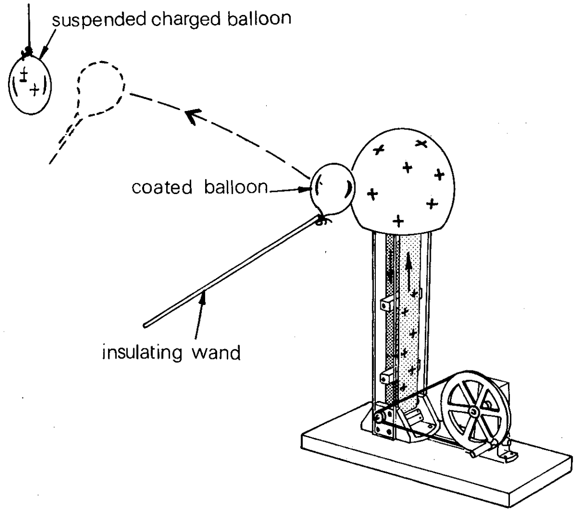
Suspend the uncoated balloon by a long nylon thread. (It may be one of the two balloons already used.) Rub it on wool to charge it.

Earth the positive terminal of the E.H.T. supply. Bring the coated balloon on its long holder up to the negative terminal of the E.H.T. supply and thus charge it. (It is easier to do that if a small metal ball is attached to the E.H.T. terminal so that it stands out.)

Carry the coated balloon with its charge across to the suspended balloon. Pupils look for forces.

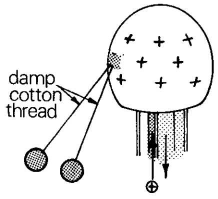
Then earth the negative terminal of the E.H.T. instead and charge the coated balloon from the positive terminal. Bring it near to the suspended balloon. Pupils look for forces.

118h. Van de Graaff machine used to charge objects. If a machine is available show it. *Pupils' Text 3* has an account of its working.



(i) Run it and charge the coated balloon on its insulating handle by contact with the globe at the top of the machine. Carry the coated balloon across to the suspended balloon that has been charged by rubbing.

(ii) Show the repulsion between two strongly charged light balls. These should be metal-coated polystyrene balls. Hang them by threads of *cotton* which will be conducting unless it is very



dry. Tape the upper ends of the two threads to the *side* of the Van de Graaff globe and run the machine.

'Conclusions' We hope pupils will extract some generalizations; but there is no harm, in this case, in helping them to summarize:

There are two kinds of charge, labelled 'positive' and 'negative'.

Negative charges can be obtained from the negative terminal of the E.H.T.; or they can be obtained by 'friction', for example on a balloon rubbed with wool.

Positive charges repel positive; negative charges repel negative; positive and negative attract.

There are not two different types of electricity, 'electrostatic' and 'current'. Positive charges are the same whether they come from friction or from a current supply. Similarly for negative charges.

Fields in our Programme, now and in Years 4 and 5

{Pupils have now met three kinds of field, gravitational, magnetic and electric.}*

{*Magnetic fields*. Pupils find these utilized in ammeters and in electric motors and loudspeakers. These also play a vital part in the working of generators and transformers.}

{By now, pupils should know how magnets behave in a magnetic field and what happens to a wire carrying a current across a magnetic field. In Year 4 they will see a beam of electrons shot across a magnetic field in the fine-beam tube, as a preparation for measuring e/m in Year 5.}

{*Gravitational field strength*. We have mentioned gravitational fields. When we say 'the Earth pulls with a force of 10 (or 9.8) newtons on every kilogram of matter' we are stating a *field strength* without calling it that. In Year 4 we shall use the concept of a gravitational field strength (measured in newtons per kilogram) to simplify problem-solving and clarify the distinction between weight and mass—and in Year 5 we shall discuss universal gravitation.}

{*Electric fields*. In Year 4 we shall use *gravitational field strength* to suggest measuring *electric field strength* (in newtons per coulomb) because we make use of that concept in treating the Millikan experiment.}

{*Millikan experiment*. In Year 4 we shall discuss the Millikan experiment (and possibly a large model, provided a film of the real experiment is also shown and discussed.)* Perhaps some pupils will try the real experiment themselves.}

{*That is a very important experiment in our programme, the only one that gives any real indication that electricity comes in small atomic charges.* All the other experiments in electrostatics and with electric currents and even those with electron streams in a vacuum, can be understood equally well on the basis of believing that electricity is a continuous fluid and that currents are continuous streams of some 'juice'—in the case of electrons in vacuum it must be 'negative juice'.}

{It is only when we come to Millikan's experiment that we are forced to believe in atoms of electricity. So, if we want to do justice to the

---

* From Relativity we know a more complicated story about electric and magnetic fields, but we should not raise this with pupils. It is probably better to insist that electric fields and magnetic fields are 'entirely different kinds of thing'.

Yet, in fact, a moving magnetic field generates an electric field; and a moving electric field generates a magnetic field.

In relativistic physics, when we carry a small electric charge and go exploring among fields, we think that our test charge will see no magnetic field due to any other charges that are at rest relative to it.

If any other charges are moving relative to the test charge, an observer *staying with the test charge* will see magnetic fields in the neighbourhood. But since magnetic fields only exert forces on moving charges we may see no *catapult* force on the test charge. We may have to think that only an outside 'stationary' observer who sees the test charge moving *and* other charges moving relative to it will describe the events in terms of magnetic fields. A trained observer may be able to describe everything in terms of electric charges, electric fields, and relative motion.

This is certainly not something to take up with pupils. But it makes us consider electric fields as very important things.

* We should miss the point of the programme if we showed a gross model without showing a film of the real experiment. A Nuffield film of the experiment is available.

electrons which we have introduced so early and talked about so confidently, we must try to do justice to that great experiment—not just showing it as an obscure wonder but giving pupils some genuine understanding of it.}

Present programme For this Year 3 we suggest only brief preliminary teaching of electric fields, with a look at the field between parallel plates charges + and −.

Electric Fields show Possible Forces

Explain that all round an electric charge there is an electric field, which is *ready* to pull on unlike charges or push away like charges.

The force that a field exerts is not there until we put a charge there for the field to push or pull on.

A little needle of damp paper held in an electric field will develop + and − charges on its ends because the field pulls and pushes those charges along to the ends. They were *in* the paper before; but, being equal amounts of + and −, they cancelled each other's effects until the field dragged them apart.

Then the field tugs the charged ends of the paper needle and pulls it round until it points *along the field*. So we can map the electric field with the needle. (That is like the way we mapped a magnetic field 'sailing due north by the compass'.)

Show the paper needle exploring the field between two balls charged + and −. Then show grains of semolina in oil mapping various electric field patterns. (The grains become temporary dipoles, like the paper needle.)

Pupils' Text 3 also mentions a charge moving to-and-fro sending out waves along its field: the prediction of electromagnetic waves.

Demonstration 119a The Electric Compass Needle *(OPTIONAL NOW)*

Apparatus

1 E.H.T. power supply	item 14
and/or Van de Graaff machine	60
2 polystyrene balls, 2.8 cm	3B
Aquadag	201
2 Perspex rods to hold balls	217/1
2 retort stands and bosses	503–505
1 Perspex rod (about 69 cm) with paper vane	217/2

(Metal balls are equally good, but they should be large: diameter at least 5 cm.)

Preparation

Paint the polystyrene balls with Aquadag or spray them with antistatic spray to give them a conducting surface. Support each on a horizontal insulating rod (e.g. Perspex). On each ball, sellotape a small piece of aluminium foil to serve as an electrode to take a crocodile clip which carries a wire to the supply.

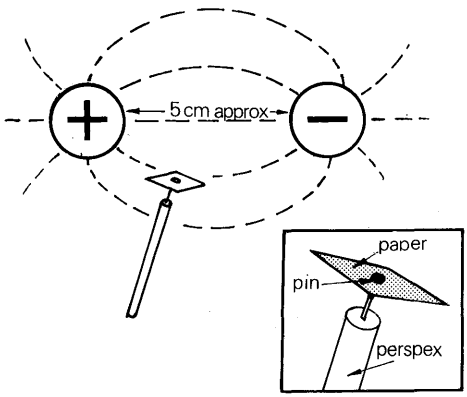
Make a small paper vane, like a compass needle, about 4 cm long. Attach it to a long Perspex rod with a pin as pivot.

Procedure

Place the two balls 8 cm apart, centre to centre.

Connect the balls directly to the 5000-volt supply's + and − terminals—both left floating.

Make sure the paper vane is free to rotate. Hold it by the long rod in the space between the balls. It will set along the field lines, because it develops induced charges in the field—rather like the behaviour of iron filings of soft iron in a magnetic field. Paper is hygroscopic enough to ensure conduction in most cases. If necessary, breath on the paper.



Start with the vane near one ball, move it, steering 'straight ahead by the compass' to map a line of force of the electric field. Show several such lines in quick succession.

Ask the pupils where they have seen a magnetic field of similar shape.

With a Van de Graaff pupils may see the same field pattern but corona discharge may mar it.

Demonstration 119b Electric Field Patterns *(OPTIONAL NOW)*

AIM. To show electric fields in much the same way as magnetic fields are shown by iron filings.

Apparatus

1 E.H.T. power supply	item 14
and/or Van de Graaff machine	60/1
1 electrode unit	149
semolina	
castor oil	
crystallizing dishes	528

If both E.H.T. power supply and Van de Graaff generator are used in turn, pupils will see that 'electrostatic' charges make the same field-patterns as the charges provided by a power supply designed to drive measurable currents, as a battery does.

The electrode unit consists of pairs of electrodes to be mounted in a glass dish of liquid.

The electrodes can be made from aluminium sheet or purchased complete with a dish. If care is taken with the insulation, this unit is easily improvized.

Procedure

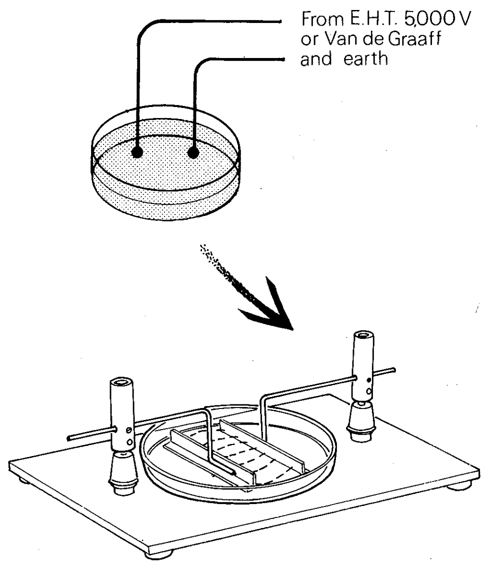
Fill the dish to a depth of about 6 mm with castor oil.* Immerse a pair of electrodes in the liquid.

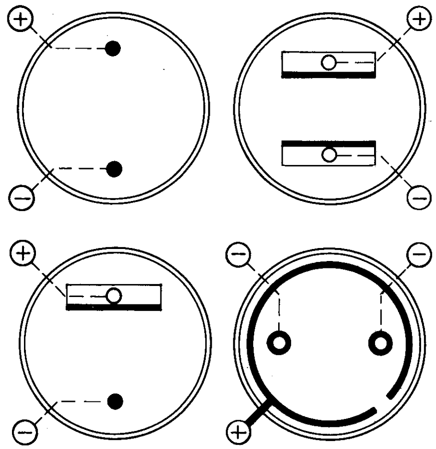
Sprinkle a little semolina over the surface. A thin piece of glass tubing drawn out to give a fine pointed stirrer is helpful in distributing the semolina evenly. It is better to start with too little semolina and increase the quantity later, than to start with too much.

Connect the E.H.T. power supply to the electrodes and adjust it to give 3000 to 4000 volts. When the voltage is switched on, field lines will be clearly visible.

Try electrodes of different shapes. For example, one can be a 'point' electrode while the other is a plate; or two point electrodes can be used.

Also show the field with two parallel plates quite close together.





* Carbon tetrachloride, suggested previously, has proved unnecessary. Plain castor oil suffices.

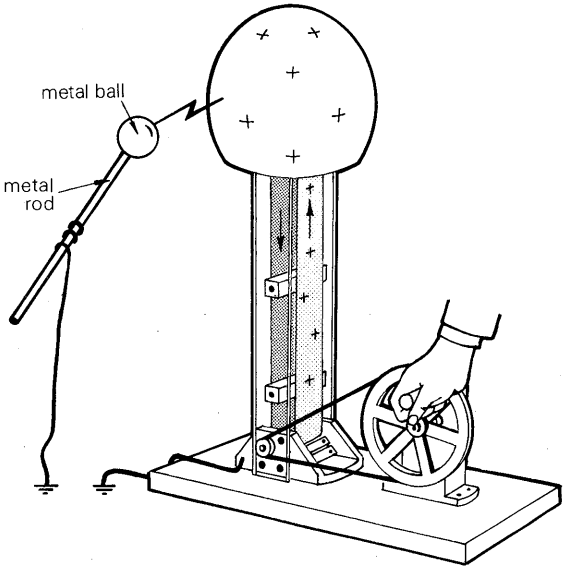
Strong Electric Fields

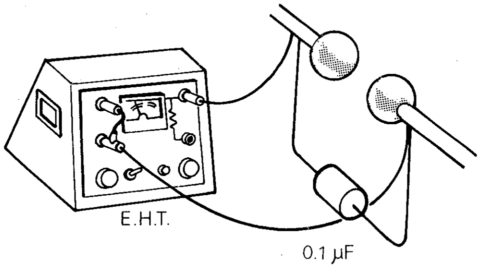
Demonstration 120 Van de Graaff Machine and Electric Sparks *(OPTIONAL NOW)*

If a Van de Graaff machine is demonstrated, pupils will certainly see it making large sparks. This is not the time for a discussion of sparks—that will come in Year 5—but *Pupils' Text 3* gives a short description of a spark involving a chain reaction of collisions which release more and more electrons.

Apparatus

Van de Graaff machine (or Wimshurst) item 60/1





Procedure

Run the machine and show it making sparks.

Compare that with the E.H.T. supply. A p.d. of 5000 volts can make a corona discharge and 'electric wind' from a needle point; but it is not very impressive. The 2-millimetre spark between metal balls connected to the E.H.T. is also unimpressive, unless a capacitor is connected across the gap. (0.1 microfarad charged to 4500 volts will store 1 joule. For comparison with the snap of the spark, note that a mousetrap stores about 1 joule when its spring is set.)

Demonstration 121 Clearing Smoke *(OPTIONAL)*

Apparatus

Van de Graaff machine	item 60/1
1 transparent plastic cup	
several small light balls	51D
drawing pin	
aluminium foil	
Aquadag or antistatic spray or metal spray	201

The 'accessories' offered with Van de Graaff machines are expensive and unnecessary. Instead, a thin plastic tumbler, used for parties, will serve.

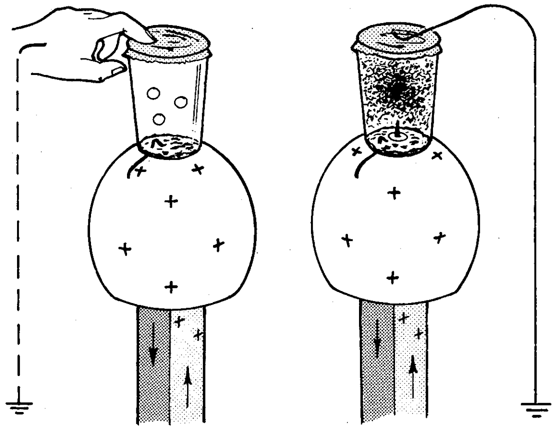
The balls should be of expanded plastic foam. They need not be round, but they must be coated to make them conducting.

Preparation

Make the balls conducting with antistatic spray (or aluminium spray, or Aquadag).

Drill a hole in the bottom of the cup. Run a bare wire through the hole to make contact with the Van de Graaff's sphere.

Place a small piece of foil at the bottom of the cup, to make contact with the wire. Place a metal lid of foil on top of the cup.



Procedure

Place the cup on top of the machine's sphere. Connect its lid to earth.

a. Jumping particles. As an introduction, put the coated balls in the cup and run the machine. There will be a strong vertical electric field inside the cup. The balls pick up charge from the base or lid of the cup, and are driven up and down, changing charge at each impact.

This might be regarded as a model of the motion of ions in electrolysis, but the changes of charge make it a confusing illustration. Its use here is simply to show large particles being driven by the field, as a preliminary to showing smoke.

b. Smoke. Place a drawing pin, point upwards, in the cup. This will ensure a strong local electric field, and 'electric wind' to stir the smoke.

Fill the cup with smoke and run the machine.

Tell pupils this can be used to remove industrial smoke. A wire is strung inside a factory chimney and a high voltage applied between the wire and the chimney walls.

Demonstration 122 Fine-Beam Tube: Second Look

Apparatus

as in Demonstration 117

Procedure

Run the beam along the axis of the tube, as before. Again let pupils look at it closely.

Apply a deflecting electric field by connecting 20 to 30 V d.c. to the plates just outside the gun muzzle. Trace the connection from the L.T. negative: it runs to the gun muzzle *and* the lower plate. Therefore the upper plate is positive.

Now ask, in terms of pupils' new knowledge of forces and fields, what the deflection tells us about the *sign* of the electric charge on the things in the stream.

Promise that later (in Year 5) pupils will see the investigation carried further, with a magnetic field to show that electrons have a very small mass, only a fraction of an atom's mass.

Also discuss the gun. Must the gun muzzle be + or − relative to the cathode where the electrons start?

As a puzzle, ask what would happen if we connected an a.c. supply to the deflecting plates. Try it, making sure the a.c. supply is isolated from earth and other supplies in use.

Postpone magnetic field deflection. It is tempting to show this. If we do that, we have one great reward: pupils will see the catapult field in action. But we shall meet one serious trouble: the problem of circular orbits, for which we are not yet prepared. We urge teachers to postpone that to Year 5.

Looking ahead. *Pupils' Text 3* comments on atoms and electrons with a promise for Years 4 and 5.

CHAPTER 9

A FRUITFUL THEORY

A simple theory of magnets to show what a theory can do

At the end of this year, we suggest a brief return to magnetism to leave pupils with an example of the use of theory to guide experimenting and to provide new language to aid scientific discussion.

This is an almost unique example of a theoretical treatment that is within the compass of understanding of young people and yet shows the power of theory to build scientific knowledge.

We hope that this discussion and the final test will not be omitted or postponed. It is placed here as an important stage in pupils' learning about theory.

The programme was originally planned for pupils progressing from Year I to Year II to III, IV, V without changes of school; and Energy was discussed in Years I and II and treated at length in Year IV. But now many pupils may enter Year 3 without the introductory studies of Years 1 and 2; and some will not continue to Year 4. Therefore, although we suggest the same topics as before for Year 3, we have added to *Pupils' Text 3* a supplementary chapter on Energy and Power with this explanatory heading:

This is an extra chapter about energy. If you learnt about energy and work in Nuffield Physics Years 1 and 2, or in Combined Science, you need not read this chapter—unless you like it as a reminder. The final section on Power is new, but it is 'OPTIONAL NOW'.

That is placed at the end of *Pupils' Text 3* for use at any stage in this Year.

SIMPLE MAGNETIC THEORY

Pupils have looked at the fields of bar magnets, felt the forces exerted by one magnet on another, and have seen what we call 'poles'* marked by clusters of iron filings or indicated by field patterns.

Return to magnets and ask pupils if they can make a magnet with only a North pole and no South pole. This is to lead, by experiments and imaginative thinking to a theory of magnet structure. It will be the simple nineteenth-century form without elaboration into modern domain theory. But it will enable pupils to learn some uses of theory.

AIM. Thus, our aim now is NOT to cram in a few more facts concerning magnets but to let pupils enjoy a taste of theory.

* In some teaching programmes the idea of magnet poles is condemned as fiction and all mention of them is avoided. Yet young pupils will *see* the phenomena that led to the idea of poles in earlier times; and our teaching of beginners is made easier by free use of the concept and its name.

That the concept is artificial should be no bar—entropy, Bohr orbits, chemical bonds, virtual images, infinitely thin rays of light, absolute zero, are all of them artificial or unreal, each in its own special way or sense, yet very useful in building knowledge and guiding experiments. Sometimes—as in the case of neutrinos and perhaps quarks and possibly gravitons—we may see the artificial status revoked by experimental discovery.

It is *inconvenient* to use magnetic poles—whether real or imagined—in advanced electromagnetism. Then poles seem unnecessary and *fields* will suffice. But that should not prevent us using the concept at the present stage. And the set of experiments here will themselves provide a gentle warning.

Experiments on Breaking Magnets—Description of Equipment

'Bar magnets'. These must be long thin rods which a child can snap into shorter pieces by using fingers alone —without tools such as pliers. They must be of material which can be rendered 'glass hard' and which will make a good permanent magnet in that state.

The best material is 'drill rod' (about $1\frac{1}{2}$ mm diameter). That is steel that can be hardened fully. It is hardened by heating it cherry red and plunging it into water. (The usual advice is 'oil is better'; but in fact water is better for this.)

These rods should be supplied already glass hard, but when buying them it is necessary to test a few samples to make sure the hardening is sufficient. If any bend instead of snapping, the consignment should be refused.

The rods will be broken into much shorter pieces in the experiment, so each class will need a new supply. Nevertheless, there should always be a rod for each pupil (plus a few spares) because a pupil deserves to have the personal experience of snapping.

(There are some possible substitutes for drill rod. Steel knitting needles can be hardened and magnetized, but they are no economy. Hacksaw blades are unsuitable; they will need pliers for snapping; also, some brands do not harden and magnetize well. Main-springs from watches and small clocks will serve in an emergency —but when needed in quantity they are no economy. The only economical and successful substititute is piano wire ($\frac{1}{2}$ mm or more diameter) cut into 15-cm lengths. The whole length of each piece must be heated cherry red and quenched in water. Since these make very thin magnets they are much less impressive.)

Magnetized rings. These are small flat rings stamped out of thin steel and hardened so that a child can snap one in two by using fingers alone—without tools such as pliers.

The hardening is done by heating the rings cherry red and quenching them in water.

The rings should be supplied already glass hard, but when buying them it is necessary to test a few samples to make sure the hardening is sufficient. If any bend instead of snapping, the consignment should be refused.

The magnetizing is done in the lab by a special process: see below.

The steel from which the rings are stamped must be a type which will take glass-hardening and will magnetize well. The steel used for Belvoir spring washers is suitable. A suitable thickness is 0.25 mm. A suitable size is: external diameter about 2 cm, internal diameter about 1 cm.

Home-made rings are unsatisfactory—they often show uneven magnetization. It would be possible to use Belvoir ring washers and harden them in the lab.

There should always be a ring for each pupil. This test of theory is important and deserves personal experience.

Magnetizing and demagnetizing. The rods will need magnetizing before pupils receive them. And, as a result of accidents, one may occasionally need to demagnetize a rod or a ring.

Arrange a large hollow coil, with plenty of space for rods and other magnets inside, to run on d.c., with a switch to change to a.c. for demagnetizing. In the case of a.c., it is good to include a variac.

With d.c., push the rod or other bar magnet through the coil while the current is on. (Or, if the magnet is very short, place it in the coil and turn the current on for a fraction of a second.)

With a.c. bring the magnet to be demagnetized slowly up to the coil and through it; and draw it very slowly away. (Or, if the magnet is short, just place it inside the coil and reduce the current to zero with a variac —not by sudden switching, which will often leave the bar magnetized.)

The glass-hard rods of $1\frac{1}{2}$ mm drill rod need 600 ampere-turns for satisfactory magnetization. Use a coil from the demountable transformer kit: either the 300-turn coil with 2 amps from a 4-volt d.c. supply or the 2400-turn coil with $\frac{1}{4}$ amp from a 20-volt d.c. supply.

For demagnetizing use the 300-turn coil with about 6 V a.c. or the 2400-turn coil with about 25 V a.c.

Note. Commercial 'magnetizing coils' are unnecessarily expensive; but it would be well worth while to mount a home-made coil on a board, with switches and signal lamps. Such a coil should be long enough to take the full length of the steel rods inside.

For the magnets used here, we strongly recommend magnetizing by this method, because the simpler methods of stroking or touching with a strong magnet are apt to divert attention, and they are seldom used in professional practice.

MAGNETIZING THE RINGS. The rings are to be magnetized, before class, with circular magnetization, so that no poles are seen. For that, use the circular magnetic field of a current in a straight wire. Even a small ring should have at least 100 amps through a wire running up through its centre.

To magnetize a ring, take a short piece of very thick copper wire, pass it through the ring, and connect the wire momentarily to a car battery. A considerable number of rings can all be threaded on the wire and magnetized at the same time.

To ensure even magnetization with no poles, the wire must pass through the centres of the rings. Therefore it is best to make a special holder for rings: a wood dowel of diameter slightly less than the internal diameter of the rings, with the short-circuiting copper wire running through a hole drilled in the dowel along its axis.

Class Expt 123 Breaking a Magnet

Ask pupils: 'Can you get a magnet with a North pole at one end and no South pole at the other end or anywhere else?' Suggest: 'Try breaking a long thin magnet in half'.

Apparatus

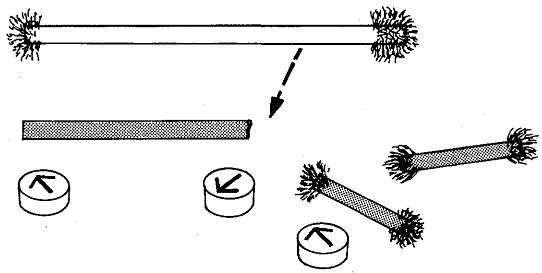
From magnetization kit:	item 122
32 hardened steel rods	122A
16 pepper pots of iron filings	92W
32 sheets of paper	
24 plotting compasses	92D
For magnetizing:	
1 L.T. variable voltage supply	59
1 coil (300 or 2400 turns)	147D or 128

Procedure

Pupils follow these instructions:

* * * * *

Try breaking a long thin magnet in half.



(i) Before you break your magnetized steel rod, try it with iron filings to see where its poles are.

(ii) Also bring each end of the rod near a small compass needle so that you know which pole is North-seeking.

(iii) Then snap the rod in half and again look for poles. Try further snapping and testing.

* * * * *

Tell pupils that the way their magnet behaves on breaking seems to be true of all magnets. There is never a single pole without the opposite one—unlike electric charges.

Starting from that, help pupils to construct a simple theory:

Imagine you continue to cut up a magnet into smaller and smaller pieces. If you always found little magnets as the result, you might pretend those little magnets were there already inside the big magnet before you started.

Sketch a picture of basic* magnets in a completely magnetized bar. Develop this in several stages: start by drawing small rectangular magnets, then change to small compasses as symbols, then omit the round box of each compass and simply show a symbolic arrow.

---

* The term 'basic magnets' is intended to evade the mistake in early theories of calling the domains 'molecular magnets'. We should tell pupils in passing that there *is* some such structure inside a magnet, though the full story is more complicated.

We now know that the basic magnets are not individual atoms of iron, but are large groups of atoms with all the atoms in a group orientated magnetically the same way. Some of the groups point magnetically in one direction; other groups other directions. The groups are called domains. The domains are far bigger than molecules. They may be big enough to see, or they may be much smaller than that.

We know that domains are there in unmagnetized magnetic materials. We can see their boundaries with a microscope when we pour very fine iron filings on the surface of a sample. The filings collect at the boundaries where the different domains meet, because there are 'exposed poles' there as in the magnetic method of testing an iron casting for flaws.

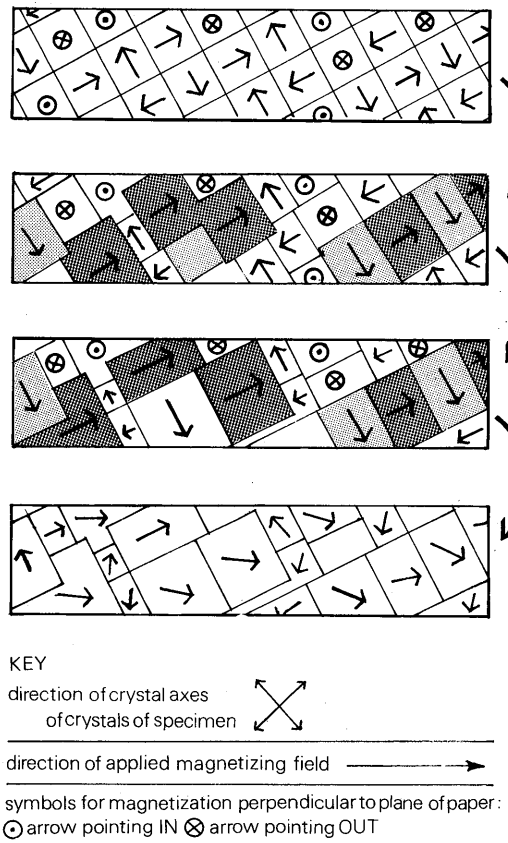
In unmagnetized iron the domains are small, and are oriented equally in several directions. When we apply a magnetizing field, we do not drag the magnetization of the domains round to the new direction, but rather we encourage 'favourable' domains—those whose natural direction of magnetization is near to that of the field—to grow at the expense of shrinking 'unfavourable' ones—domains magnetized 'the wrong way'. Thus the bar as a whole becomes more and more favourably magnetized along directions near to the general direction of the field. (We might compare that to a country growing and spreading its political boundaries, at the expense of neighbouring countries.)

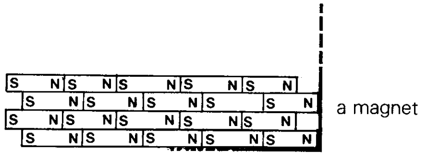
In the later stages of magnetizing, the domains are large and many of them 'favourable'. But their magnetism will still lie along directions that fit 'crystal axis' directions. Then, as saturation is approached a strong magnetizing field may wrench the favourable domains' magnetization round nearer to the direction of the field itself.

With iron powder on the surface of a steel sample under a microscope, we can see the domain boundaries moving as we increase the magnetizing field. (A film of that would be very interesting for faster pupils. However, the only film available at present—of transparent domains of special material—is too difficult to understand.)

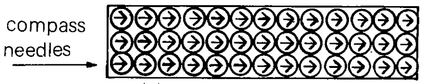
The domains make their conquest of territory in a rather vacillating way, with little vibrations of growth and shrinkage. A loudspeaker fed by an amplifier connected to a search coil round a specimen which is being magnetized gives a hissing sound which is really a rapid succession of small clicks. The clicks used to be considered signs of complete domains switching their direction of magnetization; but experiments have shown that there are far too many clicks; clicks just show minor oscillations of domain boundaries.

With pupils at this stage, we need not go into details of domains. Our simple account will preach the moral of fruitful theory, if we just discuss 'basic magnets'.

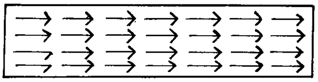




crude picture

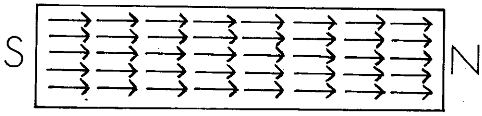


model

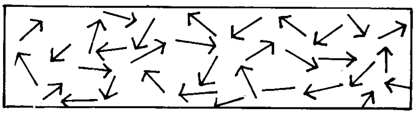


simple picture

Pupils should use the simple arrow form in answering questions.



magnetized bar



demagnetized bar

Suggest that we might imagine the basic magnets to be already there inside a bar of steel or iron, *even when it is not magnetized.* They would be disarranged, all pointing in different directions—or rather they would be arranged in small closed chains ('family groups') pointing head to tail.

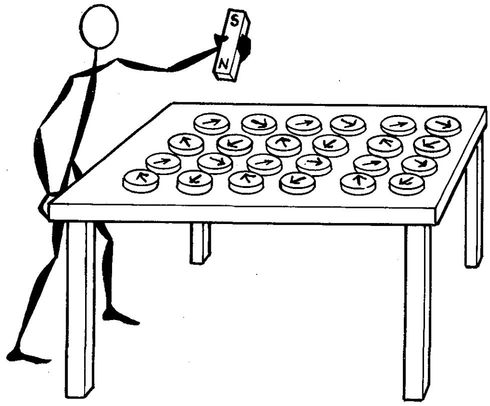
In sketching that it is best to show cyclic groups of basic magnets. (A two-dimensional sketch is far from true, but a three-dimensional one is harder to understand at this stage.)

Show a crude teaching model in which basic magnets are represented by plotting compasses.

Expt 124 Giant Model of a Magnet

Apparatus

plotting compasses	item 92D
bar magnet	50/1



Procedure

Arrange as many compasses as possible in a regular crowd to fill a rectangle on the bench top, as a model of a bar magnet.

To 'magnetize' the model draw a large magnet once over the compass needles from end to end of the crowd.

To 'demagnetize' wave the large magnet arbitrarily over the model, taking the magnet slowly farther and farther away while waving it.

This model, which illustrates an early, simple theory of a magnet (but does not do justice in detail to the modern domain theory) is so important that pupils should see it clearly at close range—not at a distance on a remote high lecture bench. Pupils should be encouraged to take turns in small groups to try it. Before pupils try the model, warn them not to bring the large 'magnetizing' magnet very near the compass needles. (However, if some compass needles are given reverse magnetization, it is easy to cure that—see note below.)

If the compass needles are mounted in transparent cells, a crowd of them can be shown on an overhead projector. But that type of compass is expensive. A projection model can be made cheaply by pushing points of sewing needles through a thin sheet of Perspex, as pivots for compass needles from cheap plotting compasses. Install a transparent lid over the array to avoid losses in storage.

This has the advantage of providing a large picture for a demonstration, and the disadvantage of being more 'special' than a crowd of ordinary compasses.

NOTE. If compass needles acquire reverse magnetization, demagnetize them, then remagnetize them by placing in a coil in which a direct current is turned on momentarily. There is a 50% chance of magnetizing them the 'right' way at the first try. (There *is* a 'right' way, because the needle must be pivoted off centre to allow for the vertical component of the Earth's field.)

'Our theory of basic magnets inside a big magnet is just a picture, a thinking-model, to help us think about magnetism and discuss experiments with magnets. Having made the picture, we can ask our theory some questions.'

Question A

Is there a limit to the strength of magnet that you can make out of a steel bar? (There is probably no limit to the strength of electric current you could drive through a wire, provided you could cool it to prevent it melting.) Given a steel bar, can you make as strong a magnet as you like out of it, supposing you have a suitable magnetizing coil?

We hope to elicit:

There *is* a limit, when all the basic magnets have been lined up in the direction of the field.

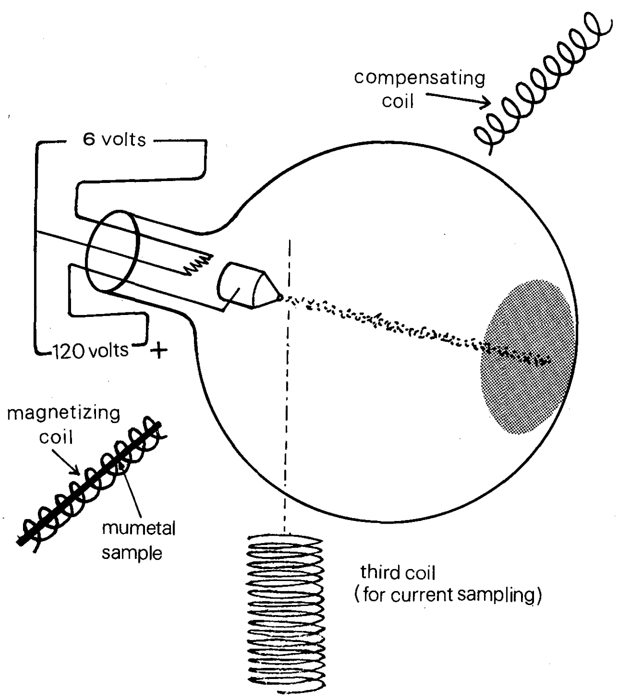
Give the theory a pennyworth of praise for success. But explain that physicists already knew from simple experimenting that there is such a limit. And engineers designing transformers etc. have always kept it in mind, because it is important for their designs.

So it would be unwise to welcome this prediction as a tremendous triumph. Nevertheless it is an achievement and we should show pupils the experimental fact, either by a graph—given in *Pupils' Text 3*—or, if possible, by Demonstration 125.

Demonstration 125 Magnetization of Soft Iron—Magnetization Curve and Saturation *(OPTIONAL)*

This can be a very satisfying illustration; and it is easy to set up and run once it has been tried. Ordinary oscilloscope tubes are unsuitable, because they have magnetic shielding firmly installed; but a demonstration tube could be used.

Here the Teltron fine-beam tube is suggested. It shows the magnetization curve well; but, with the coils available, the sample must be magnetically very soft. A short bar of *mumetal* is easy to obtain and shows saturation clearly. The bar should not be longer than the coil.

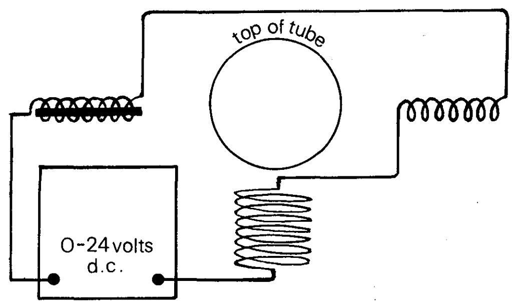


Apparatus

fine-beam tube (double beam form) with stand	item 235/140
2 similar magnetizing coils, each 300 (600) turns	147D, (E)
1 coil for current sampling, 600 (1200) turns	147E, (F)
1 short mumetal rod	202
H.T. supply	15
L.T. variable voltage supply (preferably smoothed)	59

The coils suggested belong to the demountable transformer kit which should be available for three uses in Year 3. If the school is buying the coils now, we advise 300, 300, 600 turns—and the 1200-turn coil will never be needed. If the school already has the coils, the ones in brackets will do equally well. (If home-made coils are to be used instead, the magnetizing coils should be long, and so should the sample; then the sample's field will not vary so strongly across the globe—400 turns in a 15 cm length would be suitable. The current-sampling coil may be more compact.)

The two magnetizing coils and the current-sampling coil are to be connected in series.



Arrangement

We wish to make the electron beam plot a graph with magnetization of the sample (plotted upward) against magnetizing field (plotted along).

Place a magnetizing coil, with axis horizontal, at one side of the tube, so that the field will fill the middle region of the tube. It should be 10 to 15 cm from the glass of the bulb. Place the mumetal sample completely inside the coil.

Then when the current flows in the coil the sample's magnetic field will deflect the beam upward.

But the coil's own field when a current is flowing in it will deflect the beam also. To remove the latter deflection, place an equal coil on the *other side* of the tube to carry the same current. Connect that so that its magnetic field deflects the beam in the opposite direction, *down* instead of *up*.

To adjust the coils for that compensation, run a current through them with no sample. Move one coil until the spot on the screen moves as little as possible when the current is turned on or off.

To move the spot sideways to indicate the magnetizing field (or the current that makes it), place the third coil (600 or 1200 turns) below the tube with axis vertical. Connect it in series with the other pair. After a preliminary trial with the sample, adjust the height of the third coil to give a suitable horizontal range.

The voltage for the coils should vary from zero to 25 V d.c.

Procedure

Start with the spot in the centre of the screen, with no current and no sample. Show that the spot moves across to the right as the current is increased. Simply state that the X-deflection shows the magnetizing field.

Disconnect the coil which is responsible for the horizontal motion. Insert the mumetal sample in one magnetizing coil. Show that as the current is increased the spot moves upward. Simply state that the Y-deflection shows the magnetization of the sample.

Now make the spot plot the graph, by giving the spot both deflections.

Magnetization Cycle (Extra Option). The demonstration can be run with an a.c. supply to show a hysteresis cycle—also to show demagnetization as the alternating current is slowly reduced to zero. The best sample of hard steel for this is a bundle of hacksaw blades, but it is necessary to test them, since some alloys do not respond well.

Question B

Does the theory tell you what will happen when you cut a magnet in half?

Sketch the answer to this, taking care not to let the line of your cut chop any of the basic magnets in half. Then one might say:

Yes, the theory tells us that we shall just find new poles. Isn't that wonderful?

Ask for opinions on the last statement. One might then say strongly:

It isn't wonderful at all. It is no credit to our theory whatever. Our theory has merely given us back the story we put into it. We found that out by experiment ourselves and used it as a basis for building our theory!

Question C

Suppose you have a bar magnet with poles at the very ends, just on the end faces. What is likely to happen to those poles?

We may elicit the answer that the like poles at an end will elbow each other away, so that we should expect to find the pole regions of a bar magnet spreading from the ends round the corners to the last part of the length. This agrees well enough with what one sees. It suggests the usefulness of keepers.

We could ask about heating, hammering, twisting a magnet, and might demonstrate some effects. However, modern magnet materials are so good that we cannot say that magnets become demagnetized if one drops them or hammers them a little.

Satisfaction? So far, our theory's answers to questions have been pleasant little examples, but hardly enough to justify the fabrication of this picture; and we say so to the pupils. Explain that we shall now come to a use of theory which goes far beyond that.

Question D

Can a ring of steel be magnetized even though it shows no sign of any poles?

State the problem more fully:

Here is a ring of steel. I believe I have magnetized it—I have done special things to it which I think should have succeeded in magnetizing it. Yet I can find no poles. You see no clumps of iron filings hanging on the ring when I dip it in filings. I find no sign of a big magnetic field near it. When I put this compass needle nearby it is not affected.

So I find no poles, no field and yet I thought I had magnetized it.

Here is my question for theory: *is it possible that, in any reasonable sense of the word, this ring is magnetized?*

Give pupils time to think about that. Leave it for several days rather than spoil it by giving an answer. Coax and encourage by making it clear that there *is* some kind of sensible comment to be made and then leave it. When a pupil has thought of the answer he is likely to be pretty sure that he is right—that the basic magnets in the material may be arranged head to tail all the way round the circle.

As soon as a pupil brings us the answer ask the next question.

What could you do to test whether that idea is true of this ring?

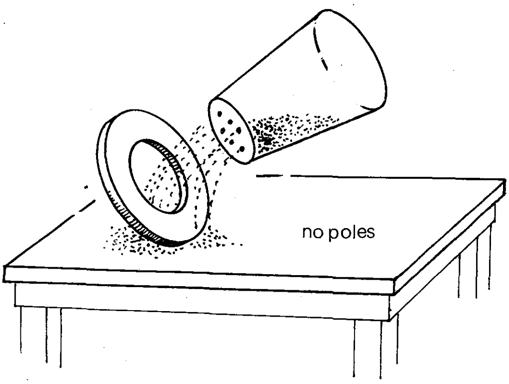
Again, the pupil who guesses right is pretty sure he is right. (He should crack the ring in half.)

Then provide rings for the experiment, *at least one for each pupil.*

Class Expt 126 Is the Ring Magnetized?

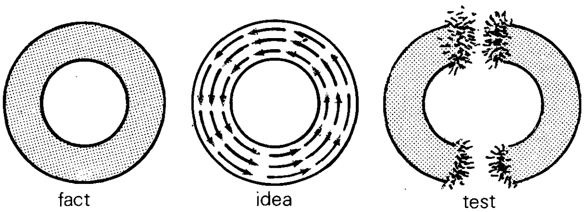
Apparatus

From magnetization kit:	item 122
32 rings (already magnetized)	122A
16 pepper pots of iron filings	122B
32 sheets of paper	



Procedure

Each pupil tries his ring with iron filings and finds no poles—if the ring has been magnetized carefully. Then he snaps it in two with his fingers and again tries it with filings.



Then discuss with pupils the help our simple theory has given.

Here is theory producing surprising help: it enables us to make sense in talking about magnets, in a way that we couldn't have done if we had no theory.

If you had no theory and were asked if the ring could be a magnet without any poles or field, anyone would say 'No poles, no magnet'. But here with theory as your guide you have yourselves guessed at a very sensible possible meaning; and we have tried it.

Theory is doing a wonderful job for you by providing *extra language*, by giving a new meaning for the word *magnetized.*

That meaning is very important to electrical engineers, because they use rings of iron for the cores of transformers; and they are certainly interested in magnetization of this kind.

This story loses most of its point, particularly with young pupils, if we just tell them about the ring and do not let them try the experiment. At all costs let them do a real experiment. After that emphasize theory's contribution to language.*

When pupils see the rings and test them and snap them they need not know what has been done to them to 'magnetize' them. But after that we should remember that the pupils in this programme are in a position to understand, even to guess, the method of magnetizing.

We might well ask a question about this and reward the answer by magnetizing another ring.

The pupil who asks how we could possibly know that the ring was not *already magnetized*, before we did that, will go far.

* Providing new language for scientific communication is an important aspect of theory but there are few examples that can be made clear and cogent in elementary teaching. That is why we hope the magnetized ring example will be included in this Year—and its importance for language advertised.

Another example, in Chemistry at a later stage: 'How many different di-chlor-benzenes are possible?' That is a talisman question to distinguish between learning mechanically by heart and learning for understanding. Its sequel is 'If you are given one of them, how can you tell by *chemical* methods, which one you have?'

APPARATUS APPENDIX 1

Operating instructions for the demonstration and class oscilloscopes

Operating instructions for the demonstration oscilloscope

The details and operating instructions given here refer to the Telequipment S51E cathode ray oscilloscope, which was the instrument used in our trials. For other instruments, these details should be read in conjunction with the maker's instructions.

Procedure

The oscilloscope controls are as shown in the diagram.

Note that the Y-shift and Time-base Variable controls are the red knobs on the front panel.

To prepare the oscilloscope for use, plug into the mains supply and set the controls as follows:
Brightness to OFF
Focus to the mid-position
X-gain fully anticlockwise
X-shift to the mid-position
Trig control to +
Time-base: time/cm control to 1 mS
Time-base: variable control fully clockwise
Stability control fully clockwise
Trig level control fully clockwise
Amplifier: volts/cm control to 0.5
Y-shift to the mid-position
Input switch to d.c.

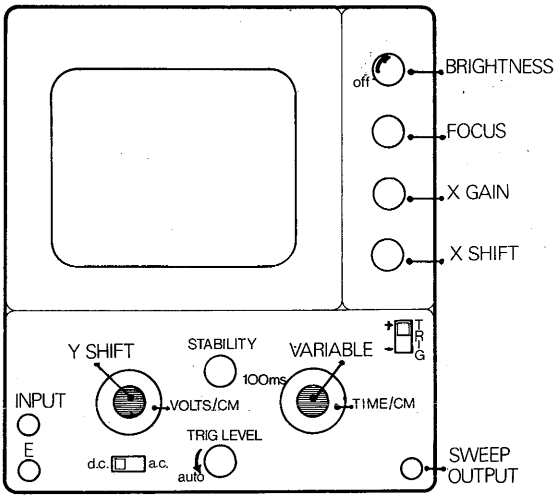
Switch on by means of the Brightness control. After 1 minute for warming up, turn 'Brightness' clockwise until a trace appears and set the control so that the trace is clearly visible but not excessively bright.

If no trace appears, leave the 'Brightness' in the fully clockwise position, and adjust 'X-shift' and 'Y-shift' until the trace appears. This is best done by rotating 'X-shift' backwards and forwards whilst slowly advancing 'Y-shift' from the fully anticlockwise position. When the trace is found, reduce 'Brightness' to a convenient level.

Now centre the trace with the 'X-shift' and 'Y-shift' controls; and adjust 'Focus' to give a sharp trace.

Turn 'Stability' slowly anticlockwise until the trace *just* disappears. Finally, rotate 'Trig Level' anticlcockwise and switch it to the Auto position. The trace (which reappears when 'Trig Level' is rotated) may dim when this is done, but will brighten again when an input is applied.

The oscilloscope is now ready for use; but it is important to be familiar with the function of the various controls. Experience is best gained by applying a 50 Hz signal and then exploring the action of the various controls (except 'Stability' and 'Trig Level' controls, which are set by the above procedure.



A practice routine for those unfamiliar with such instruments is as follows:

Connect 2 to 4 volts a.c. (50 Hz) to the input and E terminals
Change volts/cm back to 5
Turn the variable time-base control (red knob) fully anticlockwise; then forward to the calibrated position (fully clockwise)
Change time-base to 100 μS; then return to 1 mS
Change Trig + to Trig − (If the sine curve trace is not inverted by this change, turn the stability control very slightly anticlockwise until it is.)

Practice will bring increasing confidence. The tube and its supplies are robust and will not be hurt by extreme changes of controls.

Details regarding the use of 'Stability' and 'Trig Level' controls are given in the makers' handbook. For most experiments—and all those in this programme—the 'Trig Level' can be left at AUTO. To obtain a steady trace, the 'Stability' should be turned as far as possible counter-clockwise without losing the trace. This setting may vary a little with different time-base speeds.

To avoid screen damage, do not use excessive brightness. With the time-base off, do not leave the spot in a fixed position longer than necessary.

Esso-Nuffield Film Teachers may find it helpful to see the film for science teachers '*Oscilloscopes and slow* a.c.' in which the operation of this oscilloscope is demonstrated. This film is only suitable for teachers and is not intended for showing to pupils. It is available on free loan from Esso Petroleum Company, Public Affairs Department, Victoria Street, London SW1E 5JW.

Further details

Use of X-input

First switch off the time-base by turning the Variable control fully counter-clockwise to the OFF position.

Then connect an a.c. input to the X-input and E sockets *on the back of the oscilloscope case.* (*Note.* The E socket on the back and the E terminal on the front are connected internally.)

The X-GAIN control will give a variation of 2:1 in the amplification. The spot will be deflected horizontally to the full screen width by a.c. voltages of 3 to 6 volts r.m.s. The sensitivity varies from 2 V/cm to 1 V/cm.

(There is no direct connection between the X-input socket and the cathode ray tube; so d.c. inputs will give only momentary deflections.)

Use of Z-input

If a sine-wave or square-wave input is connected between the Z-input and E sockets *on the back of the case*, the brightness of the trace will be varied.

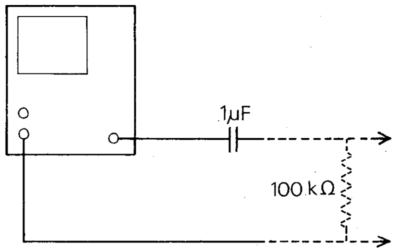
With sine-wave inputs, at least 20 V r.m.s. will be needed at 50 Hz. This reduces to 1 V r.m.s. at 20 kHz. It is necessary to dim the trace for the variation in brightness to be noticeable.

With square-wave inputs, 30 V peak to peak is necessary at 50 Hz. This reduces to 2 V peak to peak at 20 kHz. The variation in brightness is much clearer with square waves and with low frequencies—sudden increases or decreases in brilliance can be seen.

Use of Sweep output

When the time-base is switched on, a p.d. corresponding to the X deflection may be taken from the 'sweep output' and E terminals on the front. The potential of the 'sweep output' terminal varies from about +40 V, when the trace is on the left, to about +20 V when the trace is on the right.

The current taken should be kept small, unless distortion of the time-base is permissible. As a rough guide, the time-base will not be affected if a 0.1 μF capacitor (to block the d.c. component) is connected in series with the sweep output and the load resistance is not less than 100 kΩ. At some sweep speeds, much more current may be taken. To see if the load circuit is distorting the time-base, unplug it momentarily.



The sweep output may be used to trigger any transient effect repeatedly so that a steady pattern occurs on the tube. An example of this is the velocity of sound measurement.

It is also interesting, and helps pupils to understand the operation of the time-base, to connect the sweep output of one oscilloscope to the Y-input of a second oscilloscope.

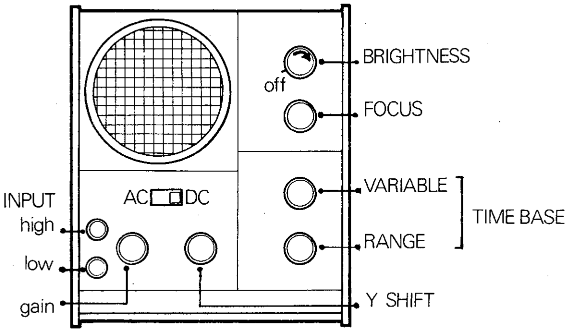
Operating instructions for the class oscilloscope

The details and operating instructions given here refer to the Telequipment Serviscope Minor cathode ray oscilloscope, which was the instrument used in our trials. For other instruments, these details should be read in conjunction with the maker's instructions.

Procedure

The oscilloscope controls are as shown in the diagram.

To prepare it for use, plug into the mains supply and set the controls as follows:
Brightness to OFF
Focus to the mid-position
Y-shift to the mid-position
Y-gain to 1 division/volt
A.C.–D.C. switch to D.C.
Time-base range switch to 2
Time-base switch to OFF



Brightness and focus
Switch the oscilloscope on by means of the brightness control. After allowing a quarter of a minute for the oscilloscope to warm up, turn the brightness control clockwise and move the Y-shift control gently about its central position until a trace appears. Then adjust the brightness and focus controls until a clear, sharply focused trace is seen.

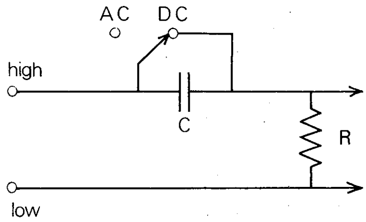
With the time-base switched off, do not allow the spot to be very bright.

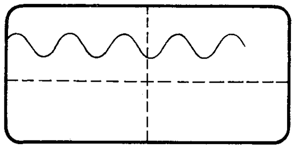
If it is impossible to obtain a sharp focus when the brightness control is near maximum, turn the brightness control anticlockwise until a sharp focus is obtained.

Input
The input terminal labelled 'low' should normally be connected to the part of a circuit, if any, which is at earth potential. As the terminal is not directly connected to earth it does not matter if it is connected to a point which is above earth potential.

The input terminal labelled 'high' is sensitive and should normally be connected to the part of the circuit which is above earth potential. If that terminal is touched, the spot will often show considerable deflection on account of a.c. potentials of the body of the person touching it. This is not normally seen with a.c. voltmeters because they have much lower internal resistance.

The 'Gain' control is roughly calibrated; the markings are not intended to be precise. For accurate readings of voltage, the calibration should be set with a moving-coil voltmeter connected in parallel to the terminals. The numbers on the 'Gain' control indicate approximately 'scale divisions per volt'.





A.C.–D.C. switch
The switch should normally be set to D.C., even when the oscilloscope is used for a.c. In the A.C. position there is a capacitor in series with the input and this will separate the a.c. component from a wave-form such as the one in the sketch. The A.C. position of the switch should be used only for this purpose.

When the oscilloscope is used for pure a.c., setting the switch to 'A.C.' will cause a smaller deflection at very low frequencies because C and R modify the signal fed to the tube. This is another reason for not using it except for the purpose indicated above.

Time base
When the time-base is switched off the spot is automatically centred. There is no X-shift control.

When the time-base is switched on, the *speed* of the spot is determined by the setting of the 'Range' and 'Variable' controls. However, the *frequency* of repetition of the time-base is not much increased at the higher speeds and the time-base is often interrupted by slow changes of the input voltages. For these reasons it is better to have the time-base off when the oscilloscope is being used as a d.c. voltmeter.

When an alternating voltage is connected to the input, it automatically triggers the time-base and makes a very steady trace.

Esso-Nuffield Film. Teachers may find it helpful to see the film for science teachers '*Oscilloscopes and slow A.C.*' in which the operation of this oscilloscope is demonstrated. This film is only suitable for teachers and is not intended for showing to pupils. It is available on free loan from Esso Petroleum Company, Public Affairs Department, Victoria Street, London SW1E 5JW.

APPARATUS APPENDIX 2

Suppliers of Solid Carbon Dioxide

Suppliers of Solid Carbon Dioxide

IMPERIAL CHEMICAL INDUSTRIES LTD supply rectangular blocks of dry ice through their 'Merchants'. A block may be collected from a Merchant's Depot or in most cases the Merchant can arrange for delivery by road transport or rail To find the address of the nearest Merchant, consult any of the following ICI Sales Offices:

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Telephone: 0642 553601

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Telephone: 0232 27741

ICI, Britannia House, 50 Great Charles Street, Queensway, Birmingham, B3 2LU
Telephone: 021 236 7070

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Telephone: 0274 29530

ICI, Severnside, Hallen, Avonmouth, Bristol, BS10 7SJ
Telephone: 02752 3601

ICI, 15 Park Place, Cardiff, CF1 3TR
Telephone: 0222 22731

ICI, 4 Blythswood Square, Glasgow, G2 4AB
Telephone: 041 248 5020

ICI, Cunard Building, Liverpool, L3 1EQ
Telephone: 051 236 8000

ICI, PO Box 19, Templar House, 81–87 High Holborn, London, WC1V 6NP
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ICI, Sunley Building, Piccadilly Plaza, Manchester, M60 7JT
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There are Depots in Aberdeen, Belfast, Birmingham, Bradford, Edinburgh, Glasgow, Great Yarmouth, Grimsby, Guernsey, Hull, Leicester, Liverpool, London, Londonderry, Manchester, Nottingham, Shepton Mallet, Southampton, Tyneside, Wellingborough.

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The following Sales Offices will give the address of the nearest supplier:
(Main Office)
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Telephone: 061 236 5151

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(Scottish region)
14 Manor Place, Edinburgh, EH3 7DD
Telephone: 0675 62695

There are Factories, Depots and Agencies in: Alloa, Aberdeen, Bath, Birmingham, Birtley, Bootle, Dagenham, Edinburgh, Glasgow, Grimsby, Hammersmith, Hull, Liverpool, London Docks, Manchester, Pontypridd.

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This volume contains the work for the third year of Revised Nuffield Physics. The main titles of the sections are 'Waves', 'Optics', 'Light and colour', 'Motion and force', 'Gases', 'Electromagnetism', 'Voltage and power', 'Electrostatics', and 'A Fruitful theory' (a simple theory of magnets), together with a chapter on 'Energy and power' for pupils who have not followed this material in earlier years of the Nuffield programme.

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