Physics

Teachers' guide **Unit 7**

Magnetic fields

Nuffield Advanced Science

copy 2

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Nuffield Advanced Science

Nuffield Advanced Physics team

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Physics Teachers' guide Unit 7

Magnetic fields

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Foreword

It is almost a decade since the Trustees of the Nuffield Foundation decided to sponsor curriculum development programmes in science. Over the past few years a succession of materials and aids appropriate to teaching and learning over a wide variety of age and ability ranges has been published. We hope that they may have made a small contribution to the renewal of the science curriculum which is currently so evident in the schools.

The strength of the development has unquestionably lain in the most valuable part that has been played in the work by practising teachers and the guidance and help that have been received from the consultative committees to each Project.

The stage has now been reached for the publication of materials suitable for Advanced courses in the sciences. In many ways the task has been a more difficult one to accomplish. The sixth form has received more than its fair share of study in recent years and there is now an increasing acceptance that an attempt should be made to preserve breadth in studies in the 16–19 year age range. This is no easy task in a system which by virtue of its pattern of tertiary education requires standards for the sixth form which in many other countries might well be found in first year university courses.

Advanced courses are therefore at once both a difficult and an interesting venture. They have been designed to be of value to teacher and student, be they in sixth forms or other forms of education in a similar age range. Furthermore, it is expected that teachers in universities, polytechnics, and colleges of education may find some of the ideas of value in their own work.

If the Advanced Physics course meets with the success and appreciation I believe it deserves, it will be in no small measure due to a very large number of people, in the team so ably led by Jon Ogborn and Dr Paul Black, in the consultative committee, and in the schools in which trials have been held. The programme could not have been brought to a successful conclusion without their help and that of the examination boards, local authorities, the universities, and the professional associations of science teachers.

Finally, the Project materials could not have reached successful publication without the expert assistance that has been received from William Anderson and his editorial staff in the Nuffield Science Publications Unit and from the editorial and production teams of Penguin Education.

K. W. Keohane
Co-ordinator of the Nuffield Foundation Science Teaching Project

The Teachers' guide

This volume is intended to contain whatever information and ideas are required for the day to day teaching of the Unit. Not every teacher will need all of it all of the time; sometimes the summary and the list of experiments will come nearer to meeting the need.

The main text contains, on the righthand pages, a detailed suggested teaching sequence, which teachers can adopt or adapt. The facing lefthand pages carry practical details, suggested questions, references, and background information for teachers in the form of a commentary on the text. This commentary also indicates aims of the teaching, and points out links with other parts of the course.

At the end, there are some appendices containing material needed on occasion only, and lists of apparatus and teaching aids for the Unit. These include details of books and articles referred to in this *Guide*.

Introduction

More perhaps than most others, this Unit is a compromise between the many good things which can be got out of the study of its subject. Electromagnetism can be used to illustrate a wide variety of the features of physics and of practical engineering. It can be used to show the power of the tools of mathematical analysis at work in calculating fields. It can be used to show how concepts can be built up into complex logical structures and to illustrate the interplay of definition and fact. It can be used simply to develop an understanding of principles, like the principle of electromagnetic induction, which are needed elsewhere. It can be used as a way of showing the importance and use of the field concept, and, in particular, of the way in which vector fields are handled. It can also be used to illustrate how a host of practical machines may be devised, based on a few principles only. It can even be used as an introduction to relativity.

What is certain is that not all these things can be attempted at once. We have chosen to lay the emphasis squarely on the usefulness of electromagnetism, not just because the subject is a splendid vehicle for displaying the variety of uses of a few ideas, but because its uses involve so much of that creative ingenuity and flexibility of mind that characterize the engineer. This is not the design of the entire Unit, but it is its mainspring.

Part Three therefore ends with a discussion of induction motors, which has been much influenced by Professor Laithwaite's books, *The engineer in Wonderland* and *Propulsion without wheels*. It tries to catch something of the creative intelligence that shines through those books. The work leading up to that point handles some of the ideas in a way that engineers will recognize as akin to their own methods, especially on those occasions when they want answers quickly and choose not to worry too much about deeper theoretical matters. The flux from currents in wires is treated as if it were like the flow of water or of electric current, the amount of flow being decided by the 'push' it is given (ampere-turns) and the 'resistance' to its flow (reluctance). We suggest this approach because, in the context of the work being developed, it is the *easiest* way, and also because it is the *practical* way, relating closely to such things as iron-cored transformers.

This Unit, then, like Unit 1, *Materials and structure*, and Unit 6, *Electronics and reactive circuits*, but unlike, say, Unit 5, *Atomic structure*, is directly about engineering problems and their solution. Reluctance, like feedback in Unit 6, is a concept of more use to an engineer than to a physicist. We make no apology for abandoning the physicist's point of view in some parts of three Units in the course; it is well enough represented elsewhere, and to look at things in only that one way would be to ignore the variety of interests among students.

Much of the Unit, however, follows well trodden paths. Part Two contains a careful development of electromagnetic induction, which, while being treated with as practical a slant as possible and emphasizing ideas which will be of value in Part Three, turns mainly (as it must) around rates of change, turns, flux, and the idea of linking. Here the engineer's and the physicist's interests largely coincide.

Because to want everything, and to want it now, is as fruitless in teaching as it is elsewhere, other aims, usually embodied in the teaching of this subject matter, have been sacrificed to a greater or lesser extent. The integration of an equation for the field of a current element, to give the fields of coils or wires, is a fine opportunity to show the power of mathematics. We have not taken that opportunity. Instead, the fields of current distributions are treated mainly as something to be investigated by careful, quantitative measurement. The results of such measurements are compared with the rules they might obey, serving to illustrate the act of comparing data with theoretical relationships. This is no less valuable an exercise than using the tools of analysis, and has the additional virtue of emphasizing that the magnetic field is a measurable thing.

Electromagnetism is complicated. Were it not so, we would have preferred to pass as rapidly as possible to its uses, as was done in Unit 6 for a less difficult area of subject matter. Because electromagnetism *is* complicated, Part One has been given over to a simple preliminary approach to the magnetic field via the force on a current. This has the advantages that a B-field is actually measured in the first lesson or so, and that the discussion can rapidly move to a set of applications of magnetic fields – accelerators and mass spectrometers – which are simple and useful (though they do not illustrate the engineering virtues that the later uses reveal).

Some teachers may feel that our fears are unfounded, and that electromagnetic induction is easy enough for that to be a reasonable starting point, given their students' background. Some might be more radical, and begin with the magnetic circuit around which something magnetic behaves as if it flows, being driven by current turns wrapped round the circuit. They would then develop ideas of induction and of practical uses of induction alongside each other. We have no way of knowing which of such lines of attack would be the 'best'. The design of this Unit is to be regarded merely as one fairly plausible way of putting the ideas together in a sequence.

Other aims have played a part in leading us to suggest some of the approaches at various points. The work on accelerators and mass spectrometers is treated as an exercise involving reading, so that students may develop skill at extracting information from books and articles, and presenting it coherently. (Part One of Unit 5 is treated in a similar way for the same reason.) Further reading on electromagnetic machines, such as linear motors, could be used to widen the scope of this work.

The work on electromagnetic induction is proposed as a series of demonstrations, because the interlocking of the relevant factors is complex enough for it to be hard to see how to expect results from students left entirely to themselves. But the demonstrations are, we suggest, best done by *students*, not by the teacher. This will not necessarily improve the quality of demonstrations, but it may involve each student in the work, in a way that sitting back and watching the teacher working hard is less likely to do. As a counterbalance, once the rules have been presented, students are asked to invent their own individual transformer experiments. Here the apparatus is simple, but the possible scope is wide, and the task becomes one of thinking what to do, rather than, as in the demonstrations, how to do a known thing.

The Unit also contains four long experiments, each intended to occupy a single pair of students for several sessions. They need to be planned in conjunction with other long experiments in other Units. These long experiments are indicated in the list on page 7.

Of the two vector fields, B and H, only B is employed in this Unit.

Summary of Unit 7

Time: up to six weeks.
(Numbers in brackets refer to suggested experiments, listed on page 7.)

Part One
Forces on currents

Time: up to two weeks.

This Part forms a simple introduction to the B-field as producing a force on a current-carrying conductor. It includes, when necessary, revision of earlier work on the shapes of magnetic fields as mapped by iron filings. It then goes on to show how knowledge of the force on a conductor and on a charge which is moving can lead to new effects, and the invention of uses for the force. The latter involves students being asked to do some more reading on their own.

Suggested sequence

The existence of electromagnetic forces (7.1), indicating the existence of a 'magnetic' field. Revision of shapes of fields (7.2). Measurement of a B-field (7.3), and a rule for the direction of force, current, and field. Argument from $F=BIL$ to $F=Bqv$ for the force on a moving charge. A new effect (Hall effect) arising from forces on moving charges (7.4); use of the effect to compare B-fields, and to investigate charge transport in a conductor (7.5). Charge to mass ratio for electrons (7.6). Uses of bending particles into curved paths: reading about mass spectrometers and accelerators.

Part Two
Electromagnetic induction

Time: up to two weeks.

This Part begins with electromagnetic induction, and ends with transformers and inductors. A motor made into a dynamo carries the argument smoothly over from Part One. Most of the time then goes on a series of demonstrations of aspects of the law of induction, given by students, in which the many complications are explored rather thoroughly. Then the work moves to more individual investigation of transformers. Much of this work lays foundations for Part Three, especially those experiments which relate to magnetic circuits.

Suggested sequence

Introduction to induction effects, making a motor into a dynamo (7.8). A plausible explanation of induction in a moving wire. Demonstrations to test aspects of the moving wire type of induction, and others to suggest that there is also a different sort of induction, by changing fields (7.9). Induced voltage as rate of change of flux.

Demonstrations showing the influence of area, turns, rate of change, orientation, and iron, and others concerning the two sorts of induction and flux as a conserved quantity in a region of space (7.10). Investigations of transformer action: choice of things to investigate, including flux and current turns; flux and the shape of the iron circuit; voltage ratios, current ratios, and turns ratios; and the phases of voltages or currents (7.11). Self induction (7.12).

Part Three
Flux near currents

Time: up to two weeks.

Measurements made with tools discussed in earlier work show how the B-field varies in simple (and in less simple) ways close to solenoids, coils, and wires. Rules for fitting the variations to mathematical relationships are tried. Having found that the flux in a solenoid is large when the solenoid is fat, and small when it is long, the flux is treated as if it were like the flow of water in a pipe (where the rate of flow sometimes obeys a similar rule). Flux in iron cores, explored in Part Two, is seen to behave rather like a flow too. Then the flow idea is used to introduce the idea of reluctance, which is itself put to use to predict the $1/r$ variation of field around a long straight wire. Ampère's circuital law can be developed out of these arguments.

Finally, the engineering problem of making a motor without brushes is used to show how, with ingenuity and skill, the engineer can deploy the ideas developed in the Unit to invent a variety of useful machines.

Suggested sequence

Quantitative investigation of B-field around current distributions (7.13). Flux as being like the flow of something. Flux in a solenoid compared with flow in a pipe, and flux in iron compared with flow in a circuit of pipes. Reluctance. Ampère's circuital law, seen as a relation between flux in a closed tube, the reluctance of the tube, and the number of current turns encircled (7.14). The field of a long straight wire (from 7.13). The definition of the ampere, and the value of μ_0. Absolute measurements (7.15). Making a motor without brushes: eddy currents, and the force direction given by Lenz's rule; ways of moving fields without moving magnets, various forms of induction motor (mainly two phase and shaded pole; 7.17).

Choosing one's own path

We hope and expect that teachers will find their own ways of using the material in this Unit. The detailed teaching programme laid out in the following pages represents as good a way of handling the material as we have been able to find in the light of experience in the trials, but should not be thought of as more than a possible, fairly well tested way of achieving the aims we decided upon. No doubt others can and will do better.

But teachers will know that it is the detail that counts in successful teaching, and so the *Guide* is full of particular teaching suggestions and practical details. We hope that these will help those who are uncertain how to handle either new material, or old material taught in a new way for unfamiliar aims.

The summary and list of experiments will, it is hoped, assist those who have taught the course a few times and no longer need to refer to all of the detailed teaching suggestions, as well as those who feel confident that they can make up their own teaching programme out of their previous experience. We also hope that the summary will provide an overall view of the work suggested. Such a view is necessary for keeping a sense of perspective and direction both when one is immersed in particular detailed teaching suggestions and comments, and when students lead the teaching off in an unpredictable direction by contributing their own ideas.

It seems fair to add that the summary, taken on its own, could mislead. It cannot easily indicate the aims of pieces of work in any precise way, or find words to express the relative seriousness or lightness of particular episodes. Nor should a phrase one might find in a current examination syllabus always be taken here to imply the same work as it would imply there.

Experiments suggested for Unit 7

* Long experiments.

Part One

Forces on currents

Time: up to two weeks.

The time needed will depend a good deal on students' previous knowledge and experience. Those who have been through the full Nuffield O-level Physics course will have met most of it before, at least in passing, and will be able to go quite quickly.

Those who have done little previous work on magnetism will need more time, especially with the simpler experiments. It may be best, in such a case, to omit the reading suggested about mass spectrometers and accelerators, so as to move on to the more practical concerns of later parts. Part One is essentially introductory: the major work of the Unit is on electromagnetic induction and on machines that use electromagnetic induction, in Parts Two and Three.

Introducing work on electromagnetism

We hope that teachers will start the work of this Unit in such a way as to set it in perspective.

Electromagnetism is a better subject than most for stimulating a sense of wonder, for electromagnetic effects are often surprising. It is also a good subject for showing how engineers, having found ways of thinking about and of controlling these effects, can use imagination, ingenuity, and uncommon sense to invent new and useful ways of applying them.

On a long view, electromagnetism is a remarkable chapter in the history of science and its uses. It started with a surprise – Oersted's discovery that the magnetic field goes round the current – and it has never ceased to produce novelties. In physics, Faraday discovered electromagnetic induction, and also persuaded people to take the idea of a field as a physical 'something' rather seriously. Maxwell did just that, and predicted radio waves. Einstein was puzzled by Maxwell's theory, and by how electromagnetic effects could depend upon *motion*; the outcome was the theory of relativity.

In applied science, fifty years after Faraday's discovery, Edison had contrived the generation and supply of electrical power to houses to illuminate them at night. Soon afterwards, Tesla invented the induction motor, now the electrical work-horse of industry. Even today, new forms of electric motor remain to be developed, especially various forms of linear motor. The growth in the use of radio waves, since Hertz produced them and Marconi sent them across the Atlantic, has been phenomenal.

Too often the study of electromagnetism begins with the remark that, having studied forces between charges at rest, the next step is to study forces between charges in motion, as if that were something quite to be expected! Then this is followed by work which, while illustrating the virtues of the physicist, Faraday, conceals or diminishes those of the engineer, Tesla.

Individual teachers will find various ways of setting the right tone from the start. We have suggested a number of experiments, which follow, around which some general picture of the work to come can be developed. There are plenty of alternative experiments; we have selected some we like, which make a useful point.

Demonstration

7.1 Electromagnetic forces

7.1a Forces on currents

59 l.t. variable voltage supply

50/3 magnet Eclipse Major

1053 aluminium cooking foil

1040 clip component holder *2*

503 retort stand base

504 retort stand rod

505 boss *2*

1005 multi-range meter

1000 leads

The magnetic field

'The electric conflict acts in a revolving manner.'

H. Oersted, quoted by J. C. Maxwell, Collected scientific papers, *Volume 2, page 317.*

'How the magnetic force is transferred through bodies or through space we know not:—whether the result is merely action at a distance, as in the case of gravity; or by some intermediate agency, as in the case of light, heat, the electric current, and (as I believe) static electric action.'

M. Faraday, Experimental researches in electricity, *Volume 3, article 3075.*

'The engineer can find himself every bit as much in a Wonderland as did Alice. Every time he makes something new – perhaps even only in a new shape – he does not know what it will do, and surprises await him with every new machine. Like Alice, he, or she (for I believe engineering can be just as attractive to girls as it is to boys), is in a world where he does not understand why things happen, but with care he can learn to control them.'

E. R. Laithwaite, The engineer in Wonderland.

Magnetic effects are quite astonishing, and enormously useful. This Unit is about both these aspects, especially the latter.

Why say that magnetic effects are astonishing? Surely one ought to marvel simply at the feel of the repulsion between a pair of Magnadur magnets held in the hands. To realize that there are magnetic forces between charges in wires only when those charges *move* ought to be to realize that here is a strange phenomenon, especially if one notices that to be moving or not is a relative matter. To find, as Faraday did, that a current in one wire will make a current in another nearby, but only when the first current *changes*, ought to suggest that electromagnetism contains many deep puzzles.

Electromagnetism is not stranger than other things – say gravitation – but its strangeness is of a very striking kind. Its usefulness is beyond question: our civilization depends upon transformers, motors, and dynamos, not to mention electromagnetic waves. To make a good, powerful, efficient motor demands knowledge and skill. To make an entirely new kind of motor – perhaps one which has a rotor entirely without electrical connections to a supply, but which nevertheless carries currents, so solving the problem of worn out brushes – demands insight and imagination as well.

Demonstration

7.1 Electromagnetic forces

7.1a Forces on currents

A long strip of aluminium foil can be used to show quickly that there are forces on a conductor carrying current if a magnet is nearby, as in figure 1 *a*. The force is in an odd direction: it pulls the foil sideways.

7.1 b Forces on an electron beam

61 fine beam tube
62 fine beam tube base
15 h.t. power supply
92X reel of 26 s.w.g. PVC covered copper wire
503 retort stand base
504 retort stand rod *3*
505 boss *6*
59 l.t. variable voltage supply
1064 low voltage smoothing unit
50/1 pair of cylindrical magnets
1000 leads

7.1 c Forces on induced currents

59 l.t. variable voltage supply
1058 coil with 120+120 turns
503 retort stand base
504 retort stand rod (mild steel)
92P aluminium ring
92Q aluminium ring (split)
1078 gramophone motor
1000 leads

7.1 a Forces on currents

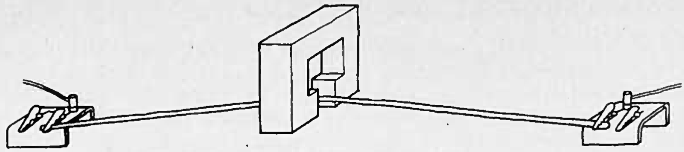
Lay a 1 m length of foil, about 10 mm wide, loosely on the bench holding its ends in crocodile clips on the clip component holders. Pass about 2 A d.c. through it, and lower the Eclipse Major magnet over the foil. Turn the magnet, as in figure 1 *a*, until the foil is lifted up between its poles.

To show forces between currents, clip two foil strips between clip component holders which are themselves held by bosses to a retort stand, as in figure 1 *b* and *c*.

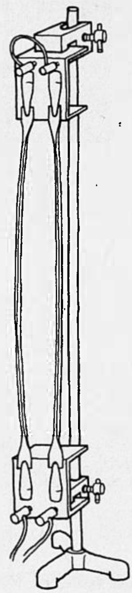
Twist the foils until they lie face to face about 10 mm apart. It is simplest to show the force between oppositely directed currents first, joining the terminals at the top, and connecting those at the bottom to a power supply via a multi-range meter (10 A range). Raise the voltage of the supply until the current is at least 8 A. The experiment works as well with a.c. as with d.c., of course, so the d.c. terminals, if used, need not be smoothed. The force is not large, but the foils should bow apart quite visibly.

To show forces between similar currents, connect the foils in parallel as in figure 1 *c*. The foils should bow inwards.

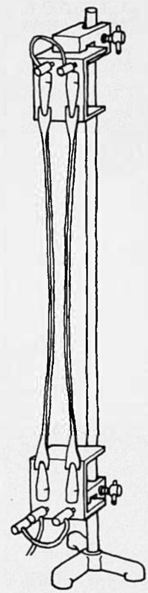
The effectiveness of the demonstration depends on getting the slackness of the foils just right. It is helpful to crimp the last few millimetres of each foil so as to be able to adjust their slackness. The foils should hang almost straight, but with enough slack to move 10 or 20 mm at their centres.



Force on a current lifts a loose length of foil
a



Currents in opposite directions repel one another
b



Currents in the same direction attract one another
c

Figure 1
Forces on current-carrying strips of foil.

If a current runs up one foil strip and down another close by it, as in figure 1 *b*, the strips of foil push one another apart. This time there is no magnet. The experiment can be used to discover what the class recalls of O-level work. They should know that a current has a magnetic field, and they may recall that it goes around the current. Each current's field acts on the other current. One might ask why it could be very dangerous to pass, say, 10 000 A in a small coil in an attempt to make a very strong electromagnet. (The coil would be liable to explode, quite apart from the problem of removing the energy dissipated in it.)

If the currents run beside each other in the same direction, the foils are pulled together.

The important thing is not to establish such rules as 'like currents attract, unlike currents repel', though these may be handy from time to time, but to enlarge the students' experience and discover how much revision will be needed.

7.1 b Forces on an electron beam

Wind a large square coil of PVC covered copper wire, putting 10 or more turns round pegs (or bosses) supported on retort stand rods as in figure 2. Such a coil, about 0.2 m square, is required for an experiment in Nuffield O-level Physics, and may already have been constructed. (See Nuffield O-level Physics, *Guide to experiments III,* experiment 83.) The magnetic field board can also be used.

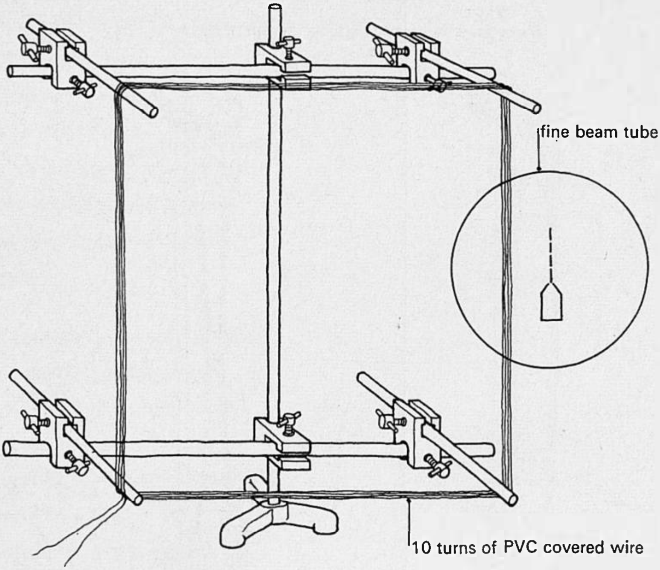


Figure 2
Electron beam deflection.

It is best to smooth the d.c. supply to the coil. A current of 3 A is suitable. Place one side of the coil hard up against the fine beam tube, and turn the tube so that the beam points parallel to these wires. The beam deflection is small, but can readily be noticed if the current in the wires is switched on and off. A darkened room is essential.

To show the effect of the beam direction on the deflection, it is best to have the axis of the tube horizontal and parallel to the axis of the coil. Then, if the tube is rotated, the beam can be put into various orientations, all of which are perpendicular to the field of the wire at the beam.

Students who have never seen the beam bent into a circle by a uniform magnetic field could see that now, or later on (see page 30).

7.1 c Forces on induced currents

Figure 4 shows the apparatus for the jumping ring experiment. The coil is rated at about 2 A, but will carry 5 A for a short time without harm, from an a.c. supply at about 12 V. To show that there is no effect with steady d.c., the d.c. supply must be smoothed. (At 5 A the smoothing may be poor.) If retort stand rods in the school are made of aluminium alloy or of stainless steel, a length of mild steel rod will need to be bought. The ring can be made to float about 50 mm above the coil, rising to about three times that height when the current is first switched on. A split ring does not move at all.

To finish the demonstration on a more practical note, the gramophone motor can be shown running on the mains a.c. supply, or on a suitable low voltage supply if the motor has been adapted for use at low voltages. It is an advantage to have a second motor which can be taken apart, to show the rotor by itself. (A low voltage motor will probably be demountable.)

7.1 b Forces on an electron beam

An electron beam near a wire carrying a current is deflected, suggesting perhaps that the force on a current-carrying conductor arises from forces on charges moving in it.

With a quick-thinking class there is much to be said for trying different orientations of the beam, as in figure 3. If the current is parallel to the beam, the effect on the beam is like an 'attraction' or 'repulsion'. But if the beam is sent at right angles to the current, it is still deflected. All these deflections may be brought together in one description if one supposes that the beam deflects in a corkscrew fashion around a direction itself at right angles to the current – the direction of the field produced by the current.

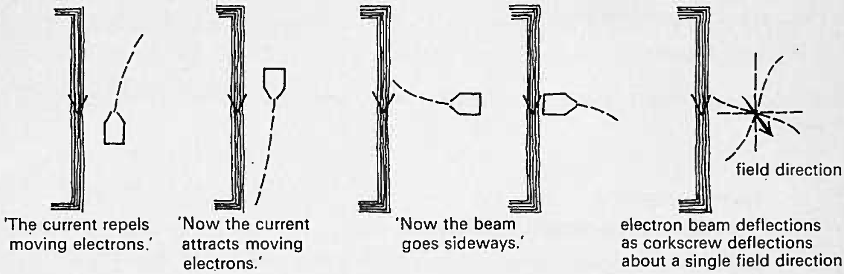


Figure 3
Deflections of a beam pointing in various directions.

7.1 c Forces on induced currents

This demonstration is not only a pretty sight which may startle some students, but also contains within it nearly all the physics of this Unit. A coil at the base of a steel retort stand carries an alternating current as in figure 4. When the current is switched on, an aluminium ring placed over the stand rises into the air and hangs suspended over the coil. If pushed down, it rises to its former height again.

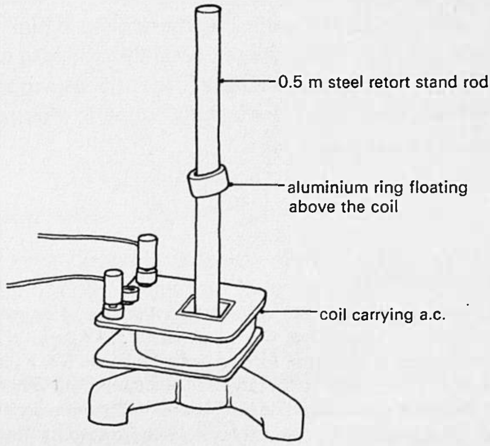


Figure 4
The jumping ring.

'Magic'

It does not matter if these first demonstrations seem something like magic to the class, as long as they capture some interest. There will be plenty of time later for making sense of the various things seen quickly now. In any case, electromagnetism is a subject full of surprises.

Students' book

Question 1 is for revision of vectors. See also Appendix D.

Revision experiments

7.2 Shapes of magnetic fields

92 Westminster electromagnetic kit

104 low voltage power unit

84 wire strippers

For details, see Nuffield O-level Physics, *Guide to experiments III*, experiments 80a, b, c, d, f, g, l, m, 83, 84, and 85.

Demonstration

7.3 Measuring magnetic fields

1036/1	wide current balance
70	demonstration meter *2*
71/1	dial for demonstration meter, d.c. dial, 1 A
71/2	dial for demonstration meter, d.c. dial, 5 A *2*
59	l.t. variable voltage supply
1064	low voltage smoothing unit
541/1	rheostat (10–15 Ω) *2*
92B	Magnadur magnets *3 pairs*
92I	mild steel yoke *3*
108/3	roll of tickertape (plain)
529	scissors
1030	high inductance coil
176	12 volt battery
1054	copper wire, 14 s.w.g., bare, 1 m
1079	flat solenoid
1000	leads

7.3a Force direction rule

The wide current balance is used to detect vertical forces on one of its arms. It rests on a pair of razor blades, through which current is supplied. Current does *not* flow down the second arm of the balance, which is bridged with a piece of insulator. As suggested in figure 5 *a*, a pin stuck through the insulator can pass between a slot cut in a stop, so that the balance cannot tilt very far. The balance is stable if it is bent a little about the pivot, as shown. The less it is bent, the more sensitive it is. Small pieces of wire or paper tape can be used to make the balance level when no external force acts on it.

A student asked to push the ring down will find that it has become hot, which may suggest that current is flowing in it. A split ring neither rises nor becomes warm, and so provides a simple test of the interpretation.

If the coil carries a steady direct current, there is no effect, either. Only when the magnetization of the retort stand is changing is there a current in the ring, and when there is a current, it is repelled by the current in the coil at each instant. One might deduce that the currents in coil and ring flow in more or less opposite senses at any one moment.

The class may recognize this arrangement as a relative of the transformer. This Unit will contain much about currents produced by changing magnetic effects, and about forces on currents. A device which uses such currents is the gramophone motor, which could be shown now without any explanation of its action, except to point to the absence of connections to the rotor.

Revision experiments

7.2 Shapes of magnetic fields

Experiment 7.1 and discussion around it should have given some idea of how much the class remembers about the shape of magnetic fields. For the work to come, what is important is the orientation of the field near magnets, wires, and coils; rules about the sense of the field can wait.

The present experiment should contain enough to remind students about the shape of magnetic fields, and the use of forces on currents in making meters or direct current motors. The amount needed will vary from zero to a substantial commitment.

Demonstration

7.3 Measuring magnetic fields

An electric field is measured by finding the ratio of the force on a charge to that charge. A gravitational field is measured by finding the ratio of the force on a mass to that mass. How might a magnetic field be measured? The suggestion, 'Find the ratio of the force on a current to that current', is sensible, but the magnetic force seems to be in a less easily predictable direction than the forces produced by gravity or by electric charges.

7.3a Force direction rule

Fortunately, iron filings give a good impression of the orientation of a magnetic field, so that it is quite easy to find out which iron filing field direction goes with particular current directions to produce some force direction or other. A copper frame of wire swinging on razor blade pivots is a convenient device for finding which orientation of field produces an upward or downward force. Figure 5 shows some of the things that can be tried: a magnet, a coil, a fairly straight wire, and a solenoid. The shape of the field inside the solenoid can be shown by putting iron filings on a flat

A current of 5 A is suitable for the current balance, but should only be passed when a test is being made, or the edges of the razor blades will overheat. Even so, the blades need regular replacement.

Figures 5 *a* to *g* show things to try. The 1080 turn coil, in *c* and *d*, requires 1 to 2 A. The straight wire, in *e* and *f*, can be a length of 14 s.w.g. copper shorted momentarily across a lead acid battery (or, better, across a Nife cell). The solenoid, in *g*, should carry at least 2 A.

The Magnadur magnets are convenient for settling the force direction rule. Having found that the force is, say, upward when the magnet is placed with the current in a known sense passing at right angles to the field, a compass needle can be used to find the sense of the field between the magnet's poles.

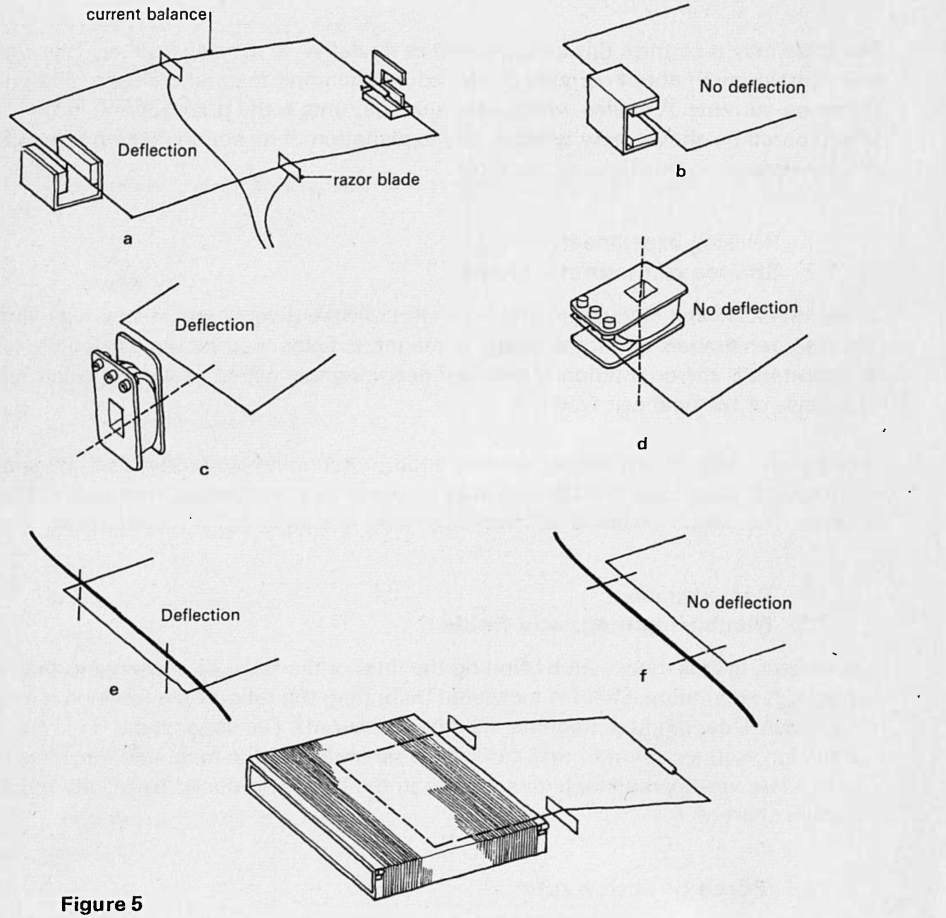


Figure 5
Directions of forces on currents.

Learning the force direction rule

The lefthand rule, or one of its many equivalents, is a useful thing to know, for practical purposes. Students should certainly know that there is a rule, and that it involves three directions rigidly related to one another. But examination questions should be set in such a way that a student who has temporarily forgotten which finger represents what does not suffer.

sheet of card inside it; the field shape to be expected from the others should have emerged in experiment 7.2.

The lefthand rule

'The seashore crab is a politician. Threatened with danger from above, he looks straight ahead and runs away sideways.'

All the experiments suggest that the force is at right angles to the current and field, and is greatest when these are at right angles (though a sceptical class may want to resort to the fine beam tube to show that the force is always at right angles to the current, as is indicated by the perfect circle or circular helix the beam makes in a uniform field).

The sense of the current is a matter of convention: from positive to negative. The sense of the field is also a matter of convention: along a compass needle that points North in the Earth's field alone. These two directions and the force direction together make a combined set of directions in space which can be turned around to predict one of them, given the other two. Coloured milk straws stuck in a block of wood can be used to represent this association of three directions; a more portable system is the left hand held with thumb, forefinger, and second finger mutually at right angles, assigning the directions as follows

motion (force) – along thumb

field – along forefinger

current – along second finger

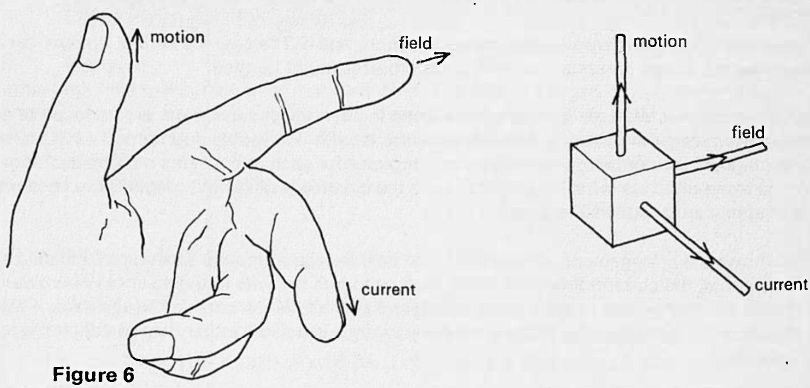


Figure 6
Force direction rule.

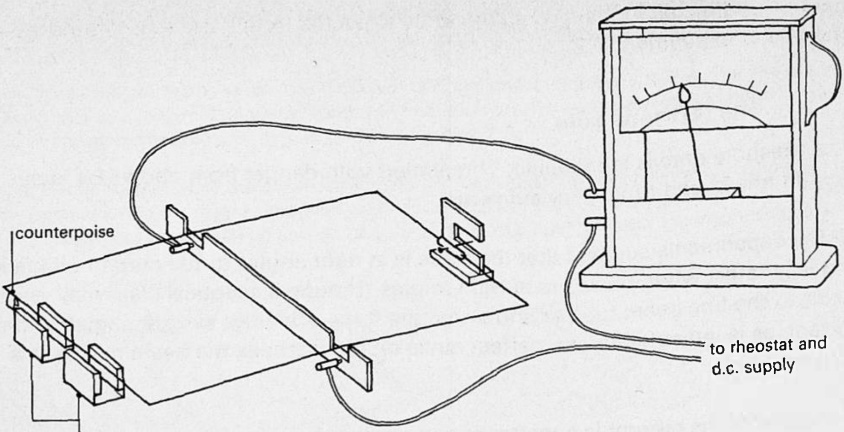


Figure 7
Measuring a magnetic field.

7.3b Measuring a magnetic field

Set up the current balance in series with a smoothed low voltage d.c. supply and a 5 A demonstration meter. Position the magnet so that the wire passing through it lifts when current flows, so that the other arm of the balance, carrying a pin restrained by a stop, falls. Have ready a paper tape or wire counterpoise which can be put onto the wire that passes through the magnet (so avoiding any need to balance moments), cut to a length which will suit a current of 1 to 2 A.

Raise the current until the balance just swings over, the pin going from the top of its stop to the bottom. If the balance is sensitive, the range of current over which the beam tilts is very small. This technique avoids the tedious business of trying to make the balance hang still and level.

Add one more equal counterpoise, and raise the current again. The balance should tip over at twice the previous current. Larger currents and more counterpoises might be tried.

Add a further magnet, selected to produce the same force at the same current, and reduce the current. The balance should now tip over at the original current, with the double counterpoise still on it. If two identical magnets cannot be found, make a counterpoise for each at the same current, and show that the two counterpoises are what is needed to keep the balance level if both magnets are used together. A third magnet can be added if required.

Figure 9 shows the arrangement for measuring the field in a flat solenoid. The current balance slides into the solenoid, the current directions being such as to pull the wire in the solenoid downwards. A counterpoise of wire or paper tape is hung on the arm of the balance outside the solenoid. It may be easier to adjust the current in the balance until the balance is poised, rather than to adjust the counterpoise.

The solenoid and the current balance should have independent, smooth d.c. supplies and meters, 0–1 A and 0–5 A respectively, though both can be driven from the same power pack.

Students may doubt that the field in the solenoid is uniform across its width: the point is examined in the next experiment.

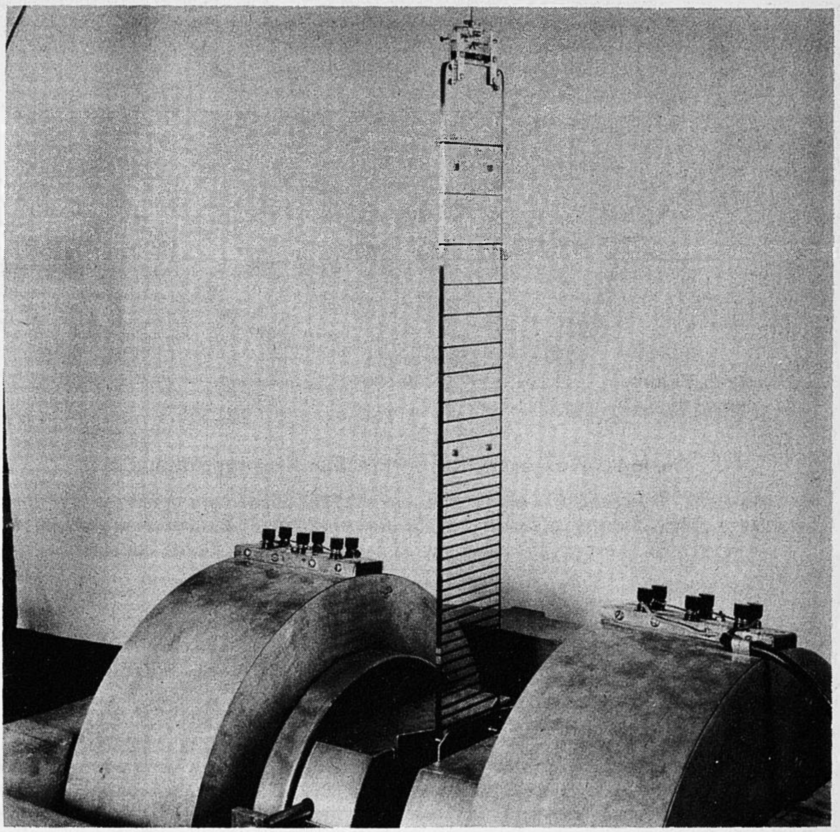


Figure 8
Accurate high field measurement of magnetic field. The field in the gap of the powerful electromagnet is being measured by hanging in it a coil wound on the edges of a glass plate suspended from a balance (not shown). The lines across the plate are threads wound round the plate to keep the coil in place along its edge.
Photograph, U.S. National Bureau of Standards.

7.3b **Measuring a magnetic field**

With one yoke and its Magnadur magnets placed around the wire of the current balance so as to produce an upward force on that wire, it may seem reasonable to say that the strength of the magnet will be indicated by the size of the force. (An Eclipse Major magnet gives a bigger force, and is stronger.) But the force depends on the current. If the current is doubled, so is the force, so the ratio of force to current would be a fairer measure of the magnet's strength. If a second, equally strong magnet is placed alongside the first, the force again doubles: a wire twice as long is in the magnetic field. So the strength of the field should be measured by F/IL, where a force F is found acting on a length L of wire carrying current I, if the field and current are at right angles.

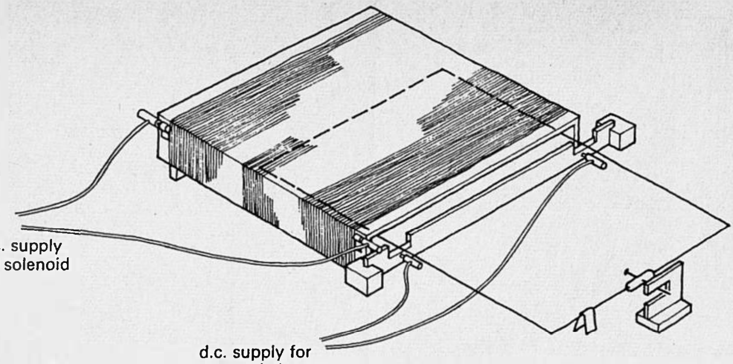


Figure 9
Measuring the field in a solenoid.

The logic of experiments to show that *F* is proportional to *IL*

Experiment 7.3 presents $F = BIL$ as simply as possible, but perhaps opens the way to some doubts about the logic of the situation, since the meter (measuring I) is a device very similar in principle to the current balance. The logic is explored more fully in Appendix A. Some students may appreciate it.

Students' book

Questions 8 and 9 concern forces on currents. Figure 8 appears in question 9. See also questions 13 and 14.

The ampere

So far as experiment 7.3 is concerned, an ampere is the current in a meter which shows one ampere, and which has been calibrated elsewhere. Later in this Unit, when sense can be made of it, the SI definition of the ampere is mentioned. It could be mentioned now, but is more likely to baffle than to help at this stage.

Textbooks: $F = BIL$

The selection of textbooks suggested in the *Teachers' handbook* has favoured those which use $F = BIL$ against those which offer an approach based strongly on electromagnetic induction, or on the interactions of magnetic poles. See particularly Bennet, *Electricity and modern physics*, Chapter 5.

A measure of the field in the gap of the Magnadur magnet can be obtained at once, if the counterpoise used on the current balance is weighed; the simplest (if rough) method is to measure the width of the magnet and to suppose that the field is uniform across the magnet and falls to zero rapidly outside it.

The Magnadur magnets may produce a force of perhaps 3×10^{-3} N (mass of paper tape about 0.3 g) on a current of 2 A flowing through a field extending over about 50 mm. If the proportionality

$F \propto IL$ is written $F = BIL$

then B represents the strength of the magnet's effect on the wire. In this instance, it is equal to about 3×10^{-2} N A^{-1} m^{-1}. B inside a coil will often be smaller; B in the gap of a very powerful magnet might be as much as of the order 1 N A^{-1} m^{-1}. Figure 8 shows the force on a current method being used for an accurate measurement of the field in such a magnet.

A second measurement of a magnetic field may not come amiss, and it will be helpful later on to have shown early that the B-field inside a solenoid is proportional to the current in the solenoid. So one may now put the current balance inside the flat wide solenoid, as in figure 9, and measure the force on it of at least two solenoid currents.

In general, the equation $F = BIL$ becomes $F = BIL \sin\theta$, if field and current make an angle θ with one another.

The *B*-field

In this course, no one who calls B the magnetic field will run into any difficulty, but this is not its usual name. For reasons that will appear later, it is often called the *flux density*. The name 'B-field' is neutral and will therefore often be used in the course.

The unit N A^{-1} m^{-1} is worth using fairly often to start with, to remind oneself that B is measured by the ratio of a force to the magnitude of the thing acted upon, as is an electric or a gravitational field. It is used often enough to have a contraction, T, for tesla; this unit being named after the engineer who invented one form of induction motor. (B is also called the magnetic induction, as well as the flux density, in many books. Whatever name is used, B means the same to everybody, fortunately.)

It may be noted that B has strange new properties not shared by gravity or electricity. The force is only there when the charges move and it depends on how fast they move (the size of the current). The force is at right angles to the field direction, not along it. Suppose one asked why the magnetic force has these odd properties – would this be a fair question? One could as well ask why electric forces act along the line joining the charges. Any new law may raise such queries, though the oddity of the rules for magnetic forces suggests them rather readily. It happens that the strange rules for magnetic forces can be explained; that is, they can be linked up with other ideas. The key is relativity and the changes it predicts for things seen from a moving standpoint. Part of Unit 8, *Electromagnetic waves*, will hint at the nature of this explanation.

Students' book $F = Bqv$

Question 15, taken from Nuffield O-level Physics, *Questions book V*, leads students through an argument from $F = BIL$ to $F = Bqv$. The argument is summarized in the text opposite, but it may be best to let students try it at home or on their own, saving teaching time for any discussion of difficulties that is needed. See also questions 10, 11, and 12.

Vector notation

Mathematicians have an elegant way of compressing the rules about the direction of the force F and its magnitude into one expression. They write,

$$\boldsymbol{F} = \boldsymbol{IL} \times \boldsymbol{B} \quad \text{or} \quad \boldsymbol{F} = q\boldsymbol{v} \times \boldsymbol{B}$$

where $\boldsymbol{IL}$ and $\boldsymbol{B}$ are vector symbols, and **x** is read as a new kind of product. This vector cross-product **x** yields a vector which is mutually perpendicular to both $\boldsymbol{IL}$ and to $\boldsymbol{B}$. The order of the terms is important, $\boldsymbol{IL} \times \boldsymbol{B}$ being in the opposite direction to $\boldsymbol{B} \times \boldsymbol{IL}$. In the order given, the notation embodies the lefthand rule. The magnitude of $\boldsymbol{IL} \times \boldsymbol{B}$ is $ILB \sin \theta$.

A few students may appreciate the elegance and compactness of the notation, and it may help them later on to have seen it in passing now.

Demonstration

7.4 The Hall effect, and using it to measure magnetic fields

1012	semiconductor Hall effect demonstration
1003/3	milliammeter (100 mA)
1033	cell holder with four U2 cells
1001	galvanometer (internal light beam)
92 B	Magnadur magnets *1 pair*
59	l.t. variable voltage supply
1064	low voltage smoothing unit
541/1	rheostat (10–15 Ω)
1079	flat solenoid
1038	Hall probe and circuit box
1003/5	ammeter (10 A)
1000	leads

7.4a The Hall effect in a semiconductor

The semiconductor Hall effect apparatus is supplied with a slice of semiconductor having connections already made to it for current and Hall voltage leads. The Hall voltage leads need to be provided with a potentiometer (usually built into the apparatus) to offset any ohmic p.d. across the specimen's width, arising from the Hall voltage connections not being exactly opposite one another.

A current of the order of 50 mA is suitable, and the maximum current for the specimen should not be exceeded, being supplied by dry cells, adjusted using the rheostat and monitored with a milliammeter, as in figure 11.

The galvanometer detecting the Hall voltage across the specimen may be a 0–100 μA meter, or, better, an internal light beam galvanometer. The latter should be tried first on its least sensitive range.

The force on a moving charge

The magnetic force seems to be a force on charges that move. How does the force depend on the speed of movement? Does it depend on the magnitude of the moving charge?

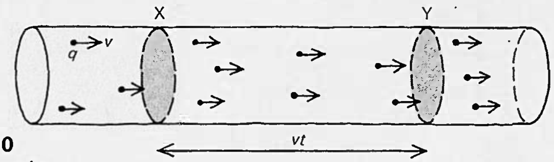


Figure 10
Charges moving in a wire.

Figure 10 is an imaginary, simplified picture of the inside of a wire, down which carriers, each with charge q, might travel at speed v. Suppose some number N of them pass place Y in time t, coming therefore from the region XY, length vt. Then,

the charge passing Y in time $t = Nq$

the current passing Y $= Nq/t = I$

the length XY over which these charges are spread $= vt = L$

the force on the N carriers is $F_N = BIL = BNqv$, the time t cancelling when substitutions are made for I and L.

The force on one carrier is less than that on N carriers by a factor N, and is

$$F = Bqv.$$

As with $F = BIL$, a factor $\sin\theta$ is needed if the field and velocity make an angle θ with one another.

Demonstration

7.4 The Hall effect, and using it to measure magnetic fields

The idea that there is a force on a moving charge can be put to immediate use, in predicting a new effect; the Hall effect. This effect will prove very useful for measuring magnetic fields later in the Unit, and is widely used in industry for that purpose.

7.4a The Hall effect in a semiconductor

What would happen to positive charges carrying a current and so moving through a slice of conductor, as in figure 12 *a*, if a magnetic field were applied at right angles to to the slice, as in figure 12 *b*? (The carriers would be pushed sideways.)

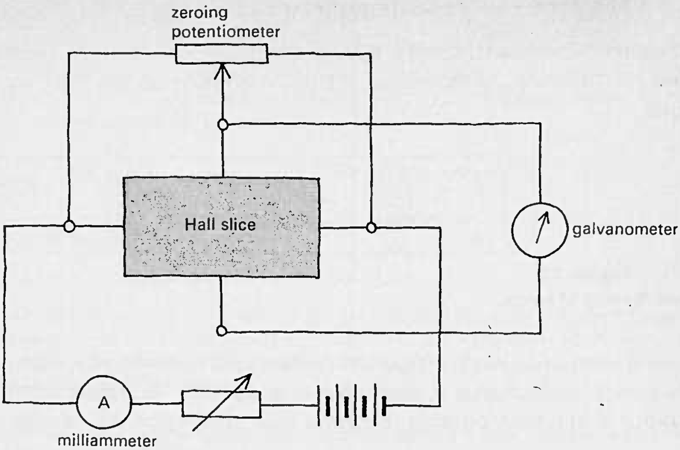


Figure 11
Semiconductor Hall effect demonstration.

Before applying the magnetic field, the galvanometer is zeroed using the potentiometer. A Magnadur magnet can then be placed over the specimen, and a small Hall voltage should now appear. Another magnet placed suitably orientated under the specimen increases the field and the Hall voltage.

When the experiment is repeated with the n-type specimen, it is worth while practising the changeover so that the experiment is repeated exactly as with the p-type specimen, with the minimum of fuss. The current direction should be the same, the galvanometer connections should be the same, and the magnets should be used the same way round.

n-type and p-type germanium

It may help students to have some information about the two sorts of doped semiconductor. In pure germanium, very few electrons are free to carry current. n-type material is made by adding a small proportion of foreign atoms which yield extra conduction electrons. p-type material is made by adding foreign atoms which accept electrons, having the curious effect of creating mobile 'missing electrons' which behave just like positive charges. It is a very difficult matter to explain why such 'positive holes' do, in p-type materials, behave like moving positive charges.

Students' book

Questions 19 and 20 are about the Hall effect.

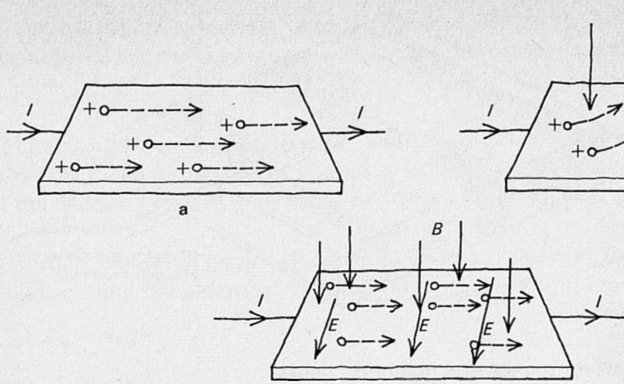


Figure 12
Forces on positive charges moving in a conductor with a transverse magnetic field.

Can the carriers get out of the back edge of the slice? (Not unless there is a wire there.) What will happen if charged carriers become densely crowded along the back edge? (They will push the others back into line as in figure 12 *c*.)

The net effect of applying a magnetic field is to create within the specimen an electric field (the effect of densely crowded charge) across the specimen. Across the sides of the specimen there will be a potential difference which a voltmeter should be able to detect. That this happens can be shown with a specimen of p-type germanium.

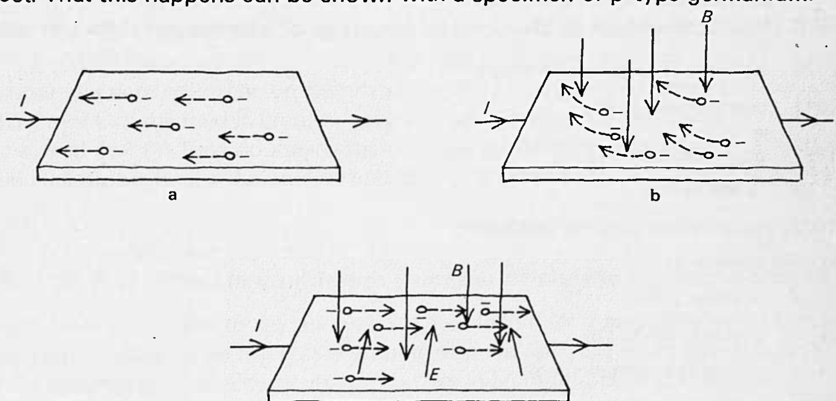


Figure 13
Hall effect with negative charge carriers.

Substitute another piece of germanium, which happens to be n-type. The effect is still there, but is reversed in sign. How could that come about? Figure 13 suggests a way of arguing that the carriers might now have the opposite sign. In figure 13 *a*, the current is the same as in figure 12 *a*, but the negative charge carriers go the opposite way. In figure 13 *b*, since the force on a current does not depend on what carries the current (the lefthand rule makes no mention of carriers), the same *B*-field must push

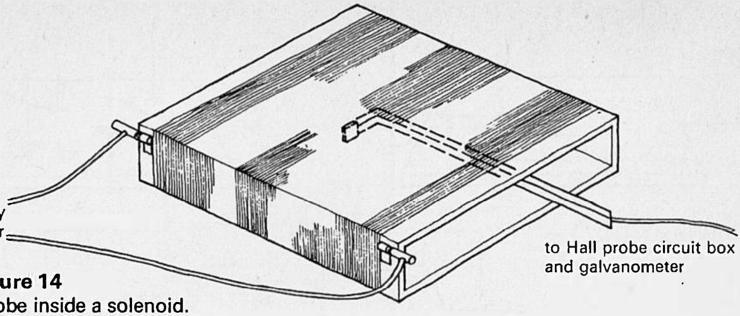


Figure 14
Use of Hall probe inside a solenoid.

7.4b **Using the Hall effect to measure magnetic fields**

Supply the solenoid with smoothed d.c. in the range 0–2 A. The probe is used with the slice fixed to its bent end perpendicular to the field. The circuit box for the probe supplies the probe with current, and carries connections for a galvanometer (the internal light beam type) to indicate the Hall voltage produced. With no field, and with the galvanometer on its x 0.1 range, adjust the potentiometer on the circuit box to zero the galvanometer. It is well to check the zero at intervals.

Show that as the probe is moved sideways, the field stays nearly steady, and that if the current is changed, the field changes in proportion. Because this has already been shown with a current balance, it can be regarded as a test of the linearity of the Hall probe. For really accurate work, small departures from linearity would have to be allowed for.

Long experiment (optional)

7.5 The Hall effect in aluminium (number of charge carriers per atom)

1029	Hall voltage apparatus for metals
1041	potentiometer holder *with*
1051	potentiometer 1.5 Ω
176	12 volt battery
1001	galvanometer (internal light beam)
1003/4	ammeter (1 A)
1003/5	ammeter (10 A)
541/1	rheostat (10–15 Ω)
1017	resistance substitution box
1055	micrometer screw gauge
1000	leads

Full instructions for doing the experiment are given in the *Students' laboratory book*. If this experiment is used at all, it can be fitted in either here as an independent task for an interested student, or at some other time in a group of longer experiments, more of which appear later in this Unit. See the *Teachers' handbook*, pages 42–3, for suggestions about long experiments.

these carriers towards the back edge of the slice, as before. But now negative charge accumulates along the back edge, and the p.d. across the specimen is reversed in sign.

The lefthand rule is needed to decide which is which. Using the rule can then suggest that the first piece of germanium behaves as if it has positive charge carriers (p-type) while the second behaves as if it has negative charge carriers (n-type).

If the carriers, charge q, go at velocity v on average, and $F = Bqv$, an electric field E will build up until the electrical force Eq on a carrier is equal to the magnetic force.

$$Eq = Bqv$$

so $$E = Bv$$

and $$V = Bvd$$ where V is the Hall voltage and d the width of the slice.

The potential difference across the specimen will be proportional to E (equal to E multiplied by the width). What sort of material will give a big Hall voltage? (One in which the carrier speed v is big.) Work in Unit 2 showed that big carrier velocities go with small numbers of carriers; that is why semiconductors have bigger Hall voltages than do metals, for the same current and field.

7.4b Using the Hall effect to measure magnetic fields

The Hall effect is a useful tool for measuring magnetic fields. Students will use a Hall probe a good deal later on: this is a good moment to show it working. As later arguments will depend on the uniformity of the field in a solenoid, the probe can be used to show that the field is uniform (more or less) across the middle of the wide flat solenoid, and that the field doubles when the current doubles. It is worth pointing out that the Hall probe, unlike the current balance, only gives relative indications of field.

Long experiment (optional)

7.5 The Hall effect in aluminium (number of charge carriers per atom)

Although there is no need to say more about the Hall effect than is suggested above, the way is now open for an interested student to develop ideas first mooted in Unit 2 about the number and velocity of charge carriers in a conductor, and to use a measurement of the Hall effect in aluminium to estimate the number of charge carriers per atom in that metal.

The exercise is worth doing as a problem in making and organizing a complex sequence of measurements, some of which are technically quite difficult. However it is not to be regarded as an essential piece of physics to be learned.

Motion in a circle. See Nuffield O-level Physics, *Teachers' guide V*, pages 32 to 58, particularly pages 45 to 48.

These arguments use no calculus, but if the sixth form class would find an argument using calculus cleaner and more powerful, clearly they should try it that way.

Fine beam tube measurement of charge to mass ratio. See Nuffield O-level Physics, *Teachers' guide V*, pages 60 to 71, especially pages 69 to 71, and *Guide to experiments V*, experiments 20, 23, and 24.

Students' book

Questions 2–7 are about circular motion. Question 16 is about the measurement of q/m. See also questions 18, 21, 22, and 24. The last involves a bubble chamber photograph.

Long experiment

7.6 Measurement of the charge to mass ratio for electrons

61	fine beam tube
	and
62	fine beam tube base
	or
138	deflection tube
	and
139	set of coils and supports
	and
140	stand for tubes
15	h.t. power supply (for item 61)
	or
14	e.h.t. power supply (for item 138)
1003/4	ammeter (1 A)
1003/5	ammeter (10 A)
176	12 volt battery
541/1	rheostat (10–15 Ω)
173	Malvern current balance kit
30	slotted base 2
501	metre rule
108/3	roll of tickertape (plain)
529	scissors
1000	leads

Full details are given in the *Students' laboratory book*. With students who have seen the experiment in the Nuffield O-level course, we think the right thing is to remind them of the principle, showing them as much by way of qualitative demonstration as they want, and then to leave the patient collecting of careful data to one pair of students, as a long experiment of their own.

This will probably not do for a class that has never met the idea before. Students can either be taken through the experiment and the argument in full, or, perhaps better, the jobs of preparing a demonstration, presenting the theory (two parts – circular motion and arguments for q/m) and working out results can be assigned to different groups of students, along with the other reading tasks suggested in the last pages of this Part of the Unit.

Making electrons go round in circles

A satellite orbits the Earth in a circle if the gravitational force of the Earth on it acts at right angles to its motion. The magnetic force on a moving electron is at right angles to its velocity, so electrons fired at right angles to a uniform magnetic field may be expected to go round in circles.

Some revision of circular motion may be needed, or the ideas may have to be taught from scratch. The essential point is to regard the force as accelerating the moving object by changing the *direction* of its velocity, but not the *magnitude*. One of the approaches to $F = mv^2/r$ suggested in the Nuffield O-level Physics course should be suitable.

Students who have never seen the Nuffield O-level experiment in which the electron beam in a fine beam tube is bent into a circle, should see it now or, as previously suggested, in experiment 7.1.

For electrons with charge q in a field B, going at velocity v at right angles to the field, the force F is

$$F = Bqv = mv^2/r$$

where m is the mass of an electron, and r the radius of its circular path.

The momentum mv of an electron is therefore

$$mv = Bqr$$

and this result is much used by nuclear physicists for measuring the momentum of a particle in a cloud or bubble chamber.

Long experiment

7.6 Measurement of the charge to mass ratio for electrons

In the fine beam tube, the energy of the electrons is controlled by the potential difference V across the electron gun, and

$$\tfrac{1}{2}mv^2 = qV.$$

Comparing this with the previous result

$$mv = Bqr$$

the velocity can be obtained by dividing them to give

$$v = 2V/Br.$$

But the result for the momentum says that

$$q/m = v/Br$$

and substituting for v gives

$$q/m = 2V/B^2r^2.$$

Purpose of the suggested reading tasks

As at other points in the course, we think it right that the teaching should be done in such a way as to encourage students to read, to help them acquire the skill needed to learn from books, and to find out, by telling others about what they have read, how successful they have been in understanding what they read.

The particular subject matter covered is not very important, and any of the topics suggested could be omitted. Others could be added, such as the working of a magnetron, as further instances of important technological applications of the same basic principles.

Suitable sources for reading tasks

Full details of the books and reprints referred to here appear on page 148. The topic numbers below refer to the list 'Topics for reading tasks' on page 35.

Reprints

Gell-Mann and Rosenbaum, *Elementary particles,* topics 14, 15.

Glaser, *The bubble chamber,* topic 15.

Nier, *The mass spectrometer,* topics 4, 5, 6.

Panofsky, *The linear accelerator,* topic 10.

Reynolds, *The age of the elements in the Solar System* topics 2, 4, 5.

Segrè and Wiegand, *The anti-proton,* topic 14.

Van Allen, *Radiation belts around the Earth,* topic 8.

Wilson, *Particle accelerators,* topics 12, 13.

Books

Arons, *Development of concepts of physics,* Chapter 33, topics 1, 2, 4.

Baez, *The new college physics,* Chapter 56, topics 10, 12.

Bennet, *Electricity and modern physics,* Chapter 16, topics 10, 11, 12, 13.

Born, *The restless universe,* topics 1, 2.

Caro, McDonell, and Spicer, *Modern physics,* Chapter 10, topics 1, 2, 3, 4, 6, Chapter 13, topics 10, 11, 12.

Classical scientific papers – physics, topics 1, 2, 7, 14.

PSSC, *College physics,* Chapter 28, topic 2.

PSSC, *Physics* (second edition), Chapter 30, topic 2.

Rogers, *Physics for the inquiring mind,* Chapter 38, topics 1, 2, 4, Chapter 42, topic 12.

Romer, *The restless atom,* topics 1, 2.

Wilson and Littauer, *Accelerators,* topics 10, 11, 12, 13.

These references vary in depth. style, and difficulty. Only the teacher can match the reading to the abilities and tastes of individual students.

The experiment yields not the charge q or the mass m of the particles in the beam, but their ratio. The mass is involved because a more massive particle would be accelerated less by the force on it, and would travel in a wider circle. The charge is involved because the bigger the charge, the bigger the force on a moving charge in a given magnetic field.

This and similar experiments with electrons agree on the value

$$q/m = 1.76 \times 10^{11}\ \mathrm{C\ kg^{-1}}.$$

A kilogramme of electrons carries enough charge, if it 'falls' through a p.d. of 240 V, to deliver some 4×10^{13} J. This is about the energy needed to cook Christmas dinner for the entire population of Great Britain (Unit 2, *Students' book*, question 59). It is enough energy to carry a mass of more than half a million kilogrammes out into space away from the Earth's gravitational pull (Unit 3, *Students' book*, question 31).

The charge on an electron is $q = 1.6 \times 10^{-19}$ C
so its mass is $m = 9.1 \times 10^{-31}$ kg, or 10^{-30} kg, very nearly.

The smallness of the mass of an electron has very important consequences; in Unit 10 it will be seen how it helps to decide what size an atom can have.

Mass spectrometers and accelerators: more reasons for making charges go in circles

If the only use for charges going round in circles in a magnetic field were the measurement of the charge to mass ratio for electrons, it might not be worth learning about. But the idea has many other uses.

One use concerns measuring q/m, and so m, for ions and fragments of molecules, by adaptations of the method used for electrons. Devices to do it are called mass spectrometers, and they are widely used in research and in industry for analysing new substances, monitoring processes such as steel-making, and many other purposes.

Another use is different. It is not easy to accelerate particles artificially, so as not to be limited to the bombarding particles provided free by nature (as Rutherford was in the alpha particle scattering experiments discussed in Unit 5). The particles travel so fast that they may go up to three hundred metres in only a microsecond, and it is not easy to deliver the necessary energy to them in so short a time. Rather than build long accelerating tubes across the landscape, another solution is to bend the particles' motion into circles or spirals, using magnetic fields, so that the accelerator can be fairly compact. (One of the largest circular accelerators, the CERN accelerator at Geneva, is 200 m across, but the linear accelerator at Stanford in the U.S.A. is 3000 m long.)

The precise details of the working of mass spectrometers and accelerators of various kinds are not too important; what matters is the principles they have in common. Many books and articles give plenty of interesting information, so finding out about

If the range of subject matter is not large enough for a big class, it could be extended to take in reading about electromagnetic machines, such as linear motors and induction motors generally and about such matters as the production of very big magnetic fields. The list of books and reprints (page 148) gives some suitable references. Alternatively, some students could be engaged on the long experiments, experiments 7.5 (Hall effect), 7.6 (charge to mass ratio for electrons), and 7.7 (d.c. motor dynamo), adding perhaps 7.15 (absolute measurement of current).

Long experiment

7.7 Behaviour and energy balance of a direct current motor dynamo

150	fractional horse power motor *ideally, 2*
176	12 volt battery *2*
1003/4	ammeter (1 A)
1003/5	ammeter (10 A)
1004/2	voltmeter (10 V) *2*
541/1	rheostat (10–15 ohms) *2*
10 A	ball of cord
81	newton spring balance (10 N) *2*
134/2	xenon flasher *or*
130/2	photodiode assembly with light source *and*
64	oscilloscope
507	stop watch or stop clock
1055	geared hand drill
1054	rubber pressure tubing to join 5 mm shafts
1054	steel rod, 5 mm diameter, 50 mm long

Note The electronics kit, item 1075, might be used in arrangements for measuring the speed of rotation of the motor.

Full instructions for this experiment are given in the *Students' laboratory book.* The experiment appears at this point in this *Guide* so as to be close to other long experiments, but it could be done at a later stage if that were desirable.

some of it is a suitable task to give to a student at this stage. Each student or pair of students could have one particular task, and be asked to tell the rest about it.

Topics for reading tasks

1 Thomson's analysis of positive rays, and the presence of neon of mass 22
2 The evidence for isotopes
3 Aston's mass spectrometer
4 Modern mass spectrometers
5 Uses of mass spectrometers
6 Ion guns and velocity selectors in mass spectrometers
7 The measurement of q/m for alpha particles
8 The motion of charged particles in magnetic fields in space
9 Magnetic deflection of the electron beam in a television set
10 Linear accelerators
11 Electrostatic accelerators
12 The cyclotron
13 The synchrotron
14 Making new sub-atomic particles
15 Curved particle tracks in cloud and bubble chambers

Long experiment
7.7 Behaviour and energy balance of a direct current motor dynamo

Experiment 7.7 involves several possible series of observations, not all of which need be attempted. The main ones are observations of the energy input and output of the machine used either as a motor or as a dynamo, but observations of the variation of torque with speed, current, and other factors can be made or, using the machine as a dynamo, the variation of output voltage with speed, field current, etc., can be investigated.

The experiment which follows this one, 7.8, uses demonstrations with a motor dynamo as a bridge between discussion of forces on currents and of induced voltages, which are the subject matter of Part Two.

The long experiment, 7.7, takes the simpler demonstrations suggested for experiment 7.8 rather further. It could be done before the demonstration, with students who had done it helping in that demonstration, or it could follow at a later stage.

Part Two

Electromagnetic induction

Time: up to two weeks.

The treatment suggested for this Part contains a series of demonstrations by students, followed by a number of individual investigations which they can do.

Letting the class make some of the running is bound to use up more time than a series of polished demonstrations by the teacher. Up to a point this is time well worth giving. But there will have to be a judgment of how long to allow. Much time could evaporate while students tinker with demonstrations that 'don't quite work yet', and then busy themselves with more investigations than they can cope with. Too long a time spent trying to cover every point exhaustively is unlikely to be repaid in extra understanding, and may induce a feeling of confusion and lack of direction.

Teaching strategy for developing ideas about electromagnetic induction

Electromagnetic induction is a rather involved affair. It embraces the idea that what decides the *induced voltage* is the *rate of change* of the *flux* which is *linking* a circuit making a number of *turns* about the flux, and that the *direction* of the voltage can be determined using the fact that energy is conserved. The flux is related to the *field* and to the *area* over which the field is spread. All these italicized items have in the end to be brought together in one rule.

The situation is too complex for it to be an easy matter to split the problems up and give each pair of students one aspect to investigate, especially as it is far from obvious, to begin with, what factors one would investigate. To announce what they are, and then to pretend that there is much real investigating left to do would be to falsify the situation far too much.

So we suggest that the teaching can begin with a statement, from the teacher or from books, of the law of electromagnetic induction. Then we suggest a series of demonstrations by students, prepared in advance, each making one or two definite points to illustrate some aspects of the law. A student who gives such a demonstration, and others who see it done, might be expected to come gradually to see how the remote, complex abstraction of this difficult law works out in concrete practical terms. In effect one is saying, 'This is the rule – now make it happen on the bench. See if you can persuade yourself and the others that there is sense in it.'

Given that real experimental tests are never as simple as theory makes them sound, preparing the demonstrations will usually involve some genuine thinking and experimenting; perhaps more in practice than if one asked a student to undertake the much tougher task of investigating induction, knowing (or pretending to know) nothing.

After this initial development, we suggest that a piece of much more open and free investigation can be offered, asking students to use what they now know, to study what happens in a transformer.

They will also, in Part Three, be asked to do some further genuine investigating, this time of the quantitative patterns into which the fields around currents and coils can be fitted.

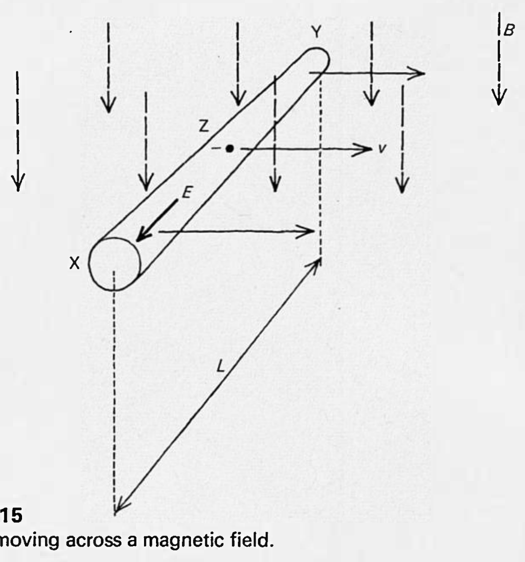


Figure 15
A conducting bar moving across a magnetic field.

Dynamos

Nearly every house in Britain has mains electricity sockets in it, 'out of which come electricity'. Of course that is not true: all the electricity that comes out along one wire goes back to the power station along the other. Then what are the Electricity Boards charging people for? (Energy: the work that each coulomb they supply and take back again can do, which is usually about 240 joules' worth.) What machine creates the necessary potential difference? (A dynamo.)

This may be the place to produce a fractional horse power motor, pointing out that when running as a motor it does work, delivering energy to loads and drawing energy from a battery or power supply, and then to turn it into a dynamo by spinning the rotor. The extra force needed to turn the rotor when a current flows can be felt, and the changes of voltage and current with speed of rotation can be noted and argued about.

To advance the discussion beyond mere observation, some theoretical ideas are helpful. These arguments are set out below before the experiment is described in this *Guide*, so that teachers can more easily weld the experiment and arguments into a whole.

Forces on charges and voltages induced in conductors

In a dynamo, wires wound on the rotor are moved through a magnetic field. Figure 15 shows something simpler, which is easier to think about: a single bar, XY, of conductor moving across a magnetic field.

Suppose the bar travels sideways at velocity v, in a field of strength B. An electron, charge e, in the bar at a place like Z, will be carried along at velocity v. What will happen to it, recalling the Hall effect arguments? (There will be a force on it, lengthways along the bar if that is at right angles to the B-field.) The magnitude of the force is

$$\text{force} = Bev$$

The directions are such (lefthand rule, 'current' opposite in direction to v since electrons carry negative charge) that the electrons in the bar are all pushed towards the end X. If they cannot get out, the extra electrons collecting near X will push back with an electrical repulsion on others trying to get nearer X. The two effects balance when the electric force eE counterbalances the magnetic force Bev.

$$eE = Bev$$

that is $$E = Bv$$

or $$V = BvL$$

introducing the measurable thing, the p.d. V across the wire, and using the fact that the electric field will be uniform and equal to V/L if B is uniform across the whole length.

Students' book

See questions 26 to 28, which are about using a motor as a dynamo, and the arguments leading to $V = BvL$ and $V = B\mathrm{d}A/\mathrm{d}t$.

Terms and units

At some stage, probably later on, it will be necessary to mention that the unit of flux (N A^{-1} m) has a short name, Weber, symbol Wb. B can be called the flux density, unit Wb m^{-2}, abbreviated to tesla, symbol T.

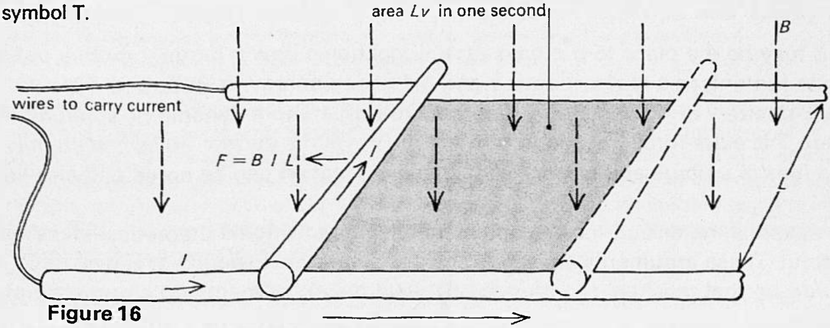


Figure 16
Force on a current and induced voltage.

Demonstration
7.8 Making a motor into a dynamo

150	fractional horse power motor
59	l.t. variable voltage supply *and*
176	12 volt battery (or another of item 59)
70	demonstration meter *2*
71/1	dial for demonstration meter, d.c. dial 1 A
71/2	dial for demonstration meter, d.c. dial 5 A
71/3	dial for demonstration meter, d.c. dial 5 V
541/1	rheostat (10–15 Ω) *2*
1055	geared hand drill
1054	rubber pressure tubing to fit 5 mm shaft
1054	steel rod, 5 mm diameter, 50 mm long
177	lamp (12 V, 6 W)
74	lampholder (s.b.c.) on base
1000	leads

The motor dynamo has separate field and rotor connections, both 12 V d.c. The field coils take about 1 A, the current being controlled with a rheostat.

To show that the voltage is proportional to the rate of rotation, connect the voltmeter across the rotor, and turn the rotor with a hand drill linked to the shaft of the machine by a rubber tube sleeved over a steel rod held in the chuck of the drill. It is easiest to turn the drill steadily so as to generate a small steady p.d.; count the number of revolutions of the drill handle in, say, ten seconds; and then repeat this process, turning the drill fast enough to double the p.d.

Forces on currents and induced voltage

Suppose power is drawn from the 'bar dynamo', perhaps by giving it conducting rails to run on, so that a current I flows (opposite to the electron motion, because of their negative charge) as in figure 16.

If there is a current, there will be a force

$$F = BIL$$

on the bar, pulling it to the left if the bar moves to the right. In time t, whatever pushes the bar a distance vt to the right against this force transforms energy equal to $BILvt$. This is the energy needed to deliver charge It at p.d. V, that is, ItV.

$$ItV = BILvt$$

so that $V = BvL$ as before.

Flux-sweeping

No practical dynamo is just a simple straight bar, so this result is not very useful as it stands. The beginnings of a more general way of thinking about induced voltages may be made by noticing another way of expressing the result.

Every second, the bar travels forward a distance v, and an extra area vL containing field B is included within the circuit-carrying current, which was previously outside it. Thus,

$$V = B\ (\textit{area swept out per second}).$$

The product of B and the area it passes through (at right angles to B) has a new name: the flux of field through the circuit, or, more briefly, the flux. The faster the circuit includes extra flux, the bigger the induced voltage.

Demonstration

7.8 Making a motor into a dynamo

This demonstration can be done alongside the theoretical arguments about induced voltages that have just been given. Other demonstrations by students follow, making various points more strongly and more economically than can be done with a motor dynamo alone. But the dynamo makes a good starting point.

When electrons are set moving in the rotor windings by passing a current, there is a force on the rotor if it is in a magnetic field, and it turns. If it is turned from outside, electrons in the rotor windings are carried round with the windings. If the argument leading to

$$V = BvL$$

by way of thinking about the magnetic force on the swept-along electrons in a rod is sensible, there will be a p.d. across the spinning rotor.

To feel the extra force needed when the dynamo delivers a load, turn the drill as fast as possible, and then suddenly connect a 12 V, 6 W lamp across the rotor terminals. The effect is easier to feel if the rotor is simply short circuited with a wire, but this gives no visual indication of the extra energy output. The ammeter can be used to indicate output currents.

The output voltage turns out to be quite accurately proportional to the field current over a fair range, though the effect of the saturation of the iron in the dynamo is very obvious at large field currents. It is best not to make much of this point, as B inside the machine cannot be measured directly with any ease, and to confine oneself to showing that a bigger field current produces a bigger induced voltage.

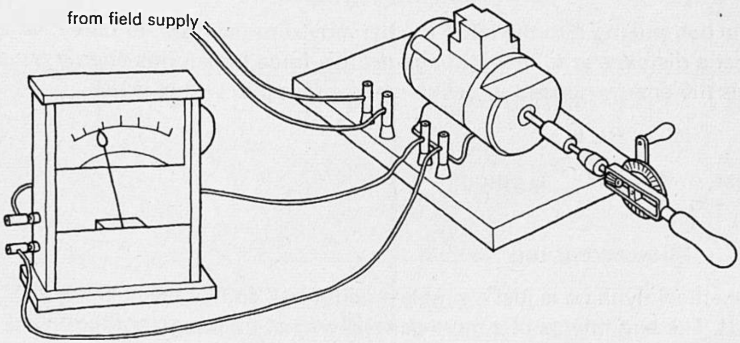


Figure 17
Fractional horse power motor as a dynamo.

Demonstration by students of aspects of the law of induction

Demonstrations 7.9 and 7.10 contain eleven demonstrations of relevant points. Those in 7.10 are intended to lead to the algebraic formulation of the induction law; those in 7.9 are more qualitative.

The demonstrations in 7.9 are:

a Moving a wire near a magnet, compared with moving the magnet, to see that the effect is the same.

b Extending **a** to induced currents in a disc rotating in a field.

c A variation on **a**, but changing the field without moving the wire.

d The effect of a continually changing, alternating field, as preparation for work with transformers and search coils.

The demonstrations in 7.10 are:

a Flux linking and turns.

b Flux linking and area.

c The importance of rate of change, with particular reference to an alternating field (frequency dependence of induced voltage).

d Flux linking and orientation, noting that the area is perpendicular to B.

e Equivalence of moving a wire in the field and of changing the field, so far as the induced voltage is concerned (expanding 7.9c).

f The difference made if iron is present.

g Flux as an imaginary 'flow', such that all of it that enters a space leaves that space.

The induced voltage should be in proportion to the speed of motion of the wires in the rotor; that is, to the rate of rotation. This can be tested. The induced voltage should rise as the field rises, and this can be checked too, by raising the current to the field coils. (The dynamo contains iron, and there is reason to think that the field will not always double if the field current doubles, since there comes a stage where the iron is magnetized as much as possible.)

If the argument about the induced voltage and the force on a current is right, when electrons are let out of the dynamo, to light a lamp, say, the dynamo should be harder to turn. This can be felt by someone turning the dynamo.

The law of induction

The energy available at an electric power point comes from a dynamo, inside which wires turn in a B-field. But it comes to us via transformers, inside which nothing moves, yet which also involve induction.

As experiments will shortly show, the arrangement of figure 16, a conducting framework, will also give an induced voltage if, as in figure 18, the wires are kept still, but the field within the complete part of the circuit is increased (or decreased) in magnitude.

Clearly this is not quite the same effect as before: no electrons are swept through the field so as to produce a force on them because they move. Yet, remarkably, the rules for the two distinct effects can be cast into exactly the same form. This is

induced voltage = rate of change of flux passing through the circuit.

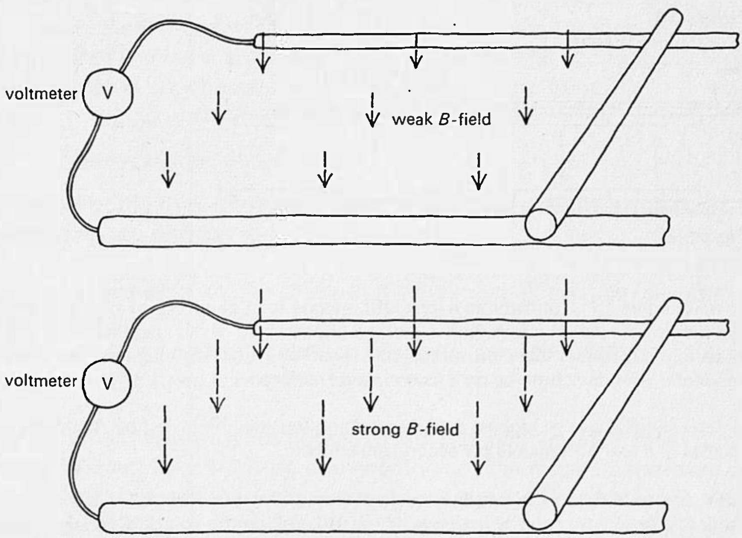


Figure 18
Inducing a voltage without moving any conductor. There is a voltage whenever B changes.

As suggested previously, we think there is much to be gained from asking students to show some of these demonstrations. They need not show all of them; some may be better kept in reserve for the teacher to show, particularly those like 7.10f where the explanation needs to be kept simple, or like 7.10g where the point made is subtle, and smooth demonstration technique counts for much.

It will probably be convenient for students to prepare the demonstrations using class oscilloscopes (item 158), while showing them using the double beam or single beam demonstration oscilloscopes (items 1007 and 64).

Students' demonstrations

7.9 Moving wires and changing fields

7.9a Moving a wire near a magnet, and moving a magnet near a wire

1001 galvanometer (internal light beam)

106/1 dynamics trolley *2*

92B Magnadur magnet *20*

92I mild steel yoke *5*

1054 copper wire, 14 s.w.g., bare

1040 clip component holder

1053 Plasticine

1000 leads

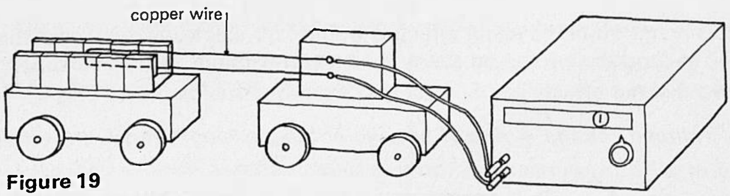


Figure 19
Moving wire or moving magnet.

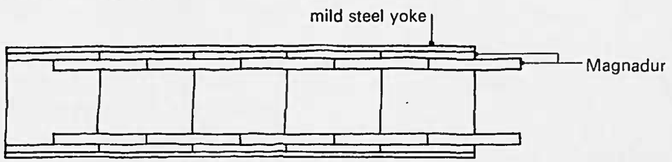


Figure 20
Detail of magnet arrangement.

The copper wire in figure 19 is formed into a long stiff, narrow loop about 0.3 m long and about 20 mm across, so that the vertical part of it falls well within the uniform part of the magnetic field. It is fixed to a block carried on a trolley so that the short vertical part is central within the magnets. The trolleys carrying magnet and wire must both be on a smooth level surface.

The galvanometer should have its highest available voltage sensitivity selected by switching to 'direct'. Velocities of a few centimetres per second are suitable.

The magnet is made, as in figure 20, from five steel yokes in a row, each carrying a pair of flat Magnadur magnets. Five more pairs of magnets are added, linking the yokes together and improving the strength and uniformity of the field.

The flux is calculated by multiplying the field B by the area, perpendicular to B, through which it passes. If the flux passes through N turns, in series, the voltage is N times larger than if it goes through one turn.

Any human, intelligent class will wonder what the rule means, and what use it could have. Why invent this strange thing, flux, and why calculate it like this? How does one decide how much flux 'passes through' a circuit? What if the circuit has several turns? Why should *rate of change* be involved? The following demonstrations may help to clear up some of these points.

Students' demonstrations

7.9 Moving wires and changing fields

Demonstrations 7.9a to d make mostly qualitative points and are particularly concerned to note the differences and similarities between cases where wires move, where magnets move, and where the B-field changes.

7.9a Moving a wire near a magnet, and moving a magnet near a wire

The short vertical piece of wire within the field in figure 19 can be moved slowly through the field. If the galvanometer reading is kept steady, the trolley is seen to be being moved at a steady speed. Reversing the motion reverses the p.d. across the galvanometer. Moving the wire faster increases the p.d., and the galvanometer deflection, more or less in proportion to the speed.

Moving the magnet on its trolley to the right (in figure 19) cannot be distinguished from moving the wire on its trolley to the left. Both give the same p.d. for the same rate of approach. Both increase the amount of field passing through the copper loop, at the same rate. The induced voltage depends on the rate of change of flux, but it doesn't matter in which way the change of flux comes about.

Theory: B-field and E-field

The teacher could then draw out some consequences of the experiment, though to do so may prove too difficult to be worth while.

When the wire moves, the electrons in it are carried along. The reason for thinking that there is a magnetic field B present is that there is a force on such moving charges, equal to Bqv, in a vertical direction in this instance. If the wire and the electrons do not move, $v = 0$, and there is no such force.

However, when the wire does not move, but the magnet does, there *is* an identical force on the electrons. Suppose one couldn't see the magnet, and were sitting beside the wire watching stationary electrons, which then began to be pushed up or down. What would one say was happening if there arose a force on stationary charges? This is what has always been called an electric field, though previously electric fields have not been made by magnets. What distinguishes the two fields is not their origin, but

In practice, the field is not uniform and the galvanometer reading is susceptible to the rising or falling of the wire loop relative to the magnets. A zero indication when both trolleys are moved together is, for this reason, the hardest thing to achieve. Success is improved by keeping the trolleys well apart, and impact is increased by asking the class what they expect, before trying it.

Relativity of electric and magnetic fields

It may be worth noting that Einstein said, in a letter written in 1952, 'What led me more or less directly to the special theory of relativity was the conviction that the electromotive force acting on a body in motion in a magnetic field was nothing else but an electric field.'

Students' book

Questions 30 and 31 are about the importance of relative motion in induction.

7.9b	**Induced currents in a rotating disc**
154/1	turntable
1061	aluminium disc
150	fractional horse power motor
59	l.t. variable voltage supply
50/3	magnet Eclipse Major
1001	galvanometer (internal light beam)
503–5	retort stand base, rod, and boss
1000	leads

Figure 21 *a* shows the arrangement; an aluminium disc fixed to the turntable, which is supported so as to turn in a vertical plane with its rim passing through the magnet's gap. The turntable is rotated, at a few revolutions a second, by means of a belt and the fractional horse power motor.

4 mm plugs make connection to the disc's surface, so that leads from the galvanometer, on its $\times 0.01$ range, can be put across various parts of the disc. If one plug is held near the disc's centre, and the other is held near the rim, and is moved round until it is within the magnet, the p.d. rises steadily as the radius between the tappings passes through stronger fields.

Flux linking a circuit

The reason why there is an induced voltage is clear: as in the moving bar (figure 15), electrons are carried through a field. But the disc is not easily assimilated to a rule about flux linking a circuit. This is just a fact of life. For every single form of words describing when there will be an induced voltage, one can think of some new topological form for a device for which that form of words is unhelpful.

Further reading

See the reprint, Newstead, 'The homopolar generator', for an impressive account of the use of the Faraday disc to deliver massive currents.

Students' book

See question 32, for a use of Faraday's disc.

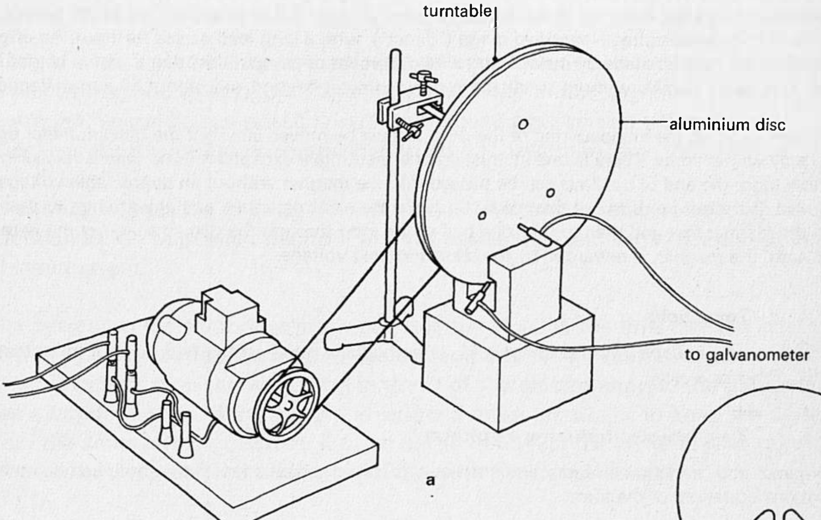
their effect, one giving a force on a charge at rest, and the other giving a force on a charge in motion. The field E is given by *force* $= Eq$.

The experiment says that the forces are the same.

$$Eq = Bqv$$
$$E = Bv.$$

Something which is a magnetic force from one point of view (sitting beside the magnet and watching the wire go by) is an electric force from another point of view (sitting beside the wire and letting the magnet go by). The lack of an absolute distinction between B-fields and E-fields arises from the fact that the apparatus does not seem to care which moves: relative motion is all that matters.

7.9b **Induced currents in a rotating disc**



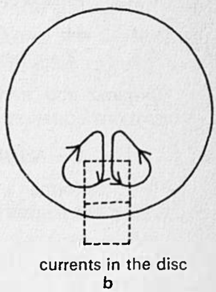


Figure 21
a A Faraday disc experiment and **b** Currents in the disc.

If a conducting disc is rotated, as in figure 21 *a*, so that it passes through the gap of a magnet, potential differences can be detected across some pairs of places on the disc. There is a big p.d. between points on the same radius if these points span the magnet. There is little if any p.d. between pairs of points equidistant from the centre of the disc. The p.d. between two places is proportional to the speed of rotation of the disc.
If the disc is spun freely, it stops much more quickly when the magnet is in place than when it is not; indeed the drag is large enough to feel. Currents can flow rather as suggested in figure 21 *b*. The important point is that the direction of flow is such as to take energy *from* the rotating disc.

7.9c Moving a wire near a magnet, and changing the field of the magnet

147 demountable transformer kit (use 300-turn coil, item 147D)

59 l.t. variable voltage supply

1064 low voltage smoothing unit

1001 *galvanometer (internal light beam)*

70 demonstration meter

71/2 dial for demonstration meter

507 stop watch or stop clock (clock preferred)

1000 leads (one long lead)

Figure 22 shows the electromagnet, with a lead joined to a galvanometer so that the lead can be passed through the gap of the electromagnet.

The electromagnet is supplied with smoothed d.c., having a rheostat and ammeter in series with its 300-turn coil. For the first part of the experiment, a current of 3 A is suitable. The galvanometer is switched to its most voltage-sensitive range ('direct'), with a long lead across its input. An effective demonstration can be made by introducing a mild element of competition: can the wire be got into the U of the magnet quickly without sending the galvanometer beyond, say, about 50 mm deflection?

However cunning the manoeuvring of the wire, it must be moved slowly if the galvanometer deflection is to stay within limits. There is one interesting and instructive exception: if the wire is folded into a long narrow loop, the end of the loop can be passed into the magnet without an appreciable voltage being induced. But the wire does not then pass 'through' the electromagnet, and any attempt to pass a loop into the magnet first and then to take one half of the loop through the gap so as to get the wire 'through' the magnet, is rewarded by the usual induced voltage.

Textbooks

Baez, *The new college physics,* chapter 41, is particularly good on the two sorts of induction. See PSSC, *Physics* as well.

Two ways of inducing a voltage

'Dynamo' and 'transformer' induction are distinct. The remarkable fact is that both can be computed from one equation, of the form

$$V = N\mathrm{d}(BA)/\mathrm{d}t = N(A\mathrm{d}B/\mathrm{d}t + B\mathrm{d}A/\mathrm{d}t).$$

The 'transformer' effect is the term $A\mathrm{d}B/\mathrm{d}t$; the 'dynamo' effect is the term $B\mathrm{d}A/\mathrm{d}t$ (provided one is willing to interpret $\mathrm{d}A/\mathrm{d}t$ pretty liberally in such cases as the Faraday disc).

But this can also be a rather muddling way of thinking about the distinction. Another way notes that the force on a charge – and an induced voltage requires a force on a charge in a wire – has two parts:

$$F = Eq \quad \text{and} \quad F = Bqv.$$

The second, Bqv term, is the one which is involved when charges in conductors are carried past fields. The first, Eq term, may be thought of as a force due to an electric field which comes into being when a magnetic field changes.

If, however, one now changes to a frame of reference which is moving relative to one's previous frame, although there are still two terms Bqv and Eq in the expression for the force, the fields B and E have not the same magnitude as before. Appendix A to this *Guide*, and Appendix B to the Teachers' guide, Unit 8, *Electromagnetic waves,* discuss relativity and electromagnetism in greater detail.

The rotating disc is a variation on the moving rod, figure 15. They would be more alike if the disc were a wheel with spokes. As it is, it is not so easy to persuade oneself that the disc is sweeping through flux, though the cause of the induced voltage is still the force on electrons carried round in the disc.

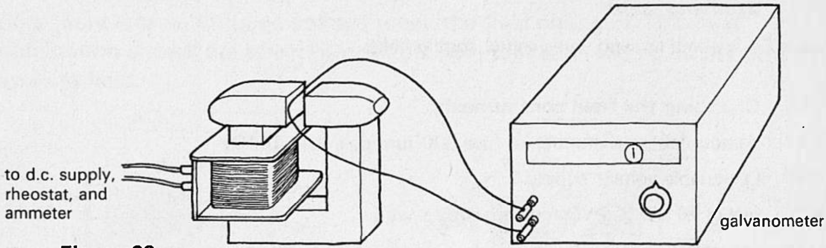


Figure 22
Moving a wire and changing a field.

7.9c **Moving a wire near a magnet, and changing the field of the magnet**

To begin with, a wire connected across a galvanometer can be moved into the gap of the electromagnet, as in figure 22, an attempt being made to get the wire into the U of the magnet as quickly as possible without exceeding a certain galvanometer indication. It turns out to be impossible to do it in less than, say, ten seconds.

It is equally impossible to bring the wire out in less time without exceeding an equal deflection in the opposite direction. In both cases, the electromagnet is supplied with a steady current.

If the current to the electromagnet's coil is made smaller, the time needed is reduced. Could one 'cheat' by first cutting off the current, and *then* pulling the wire out? If the current is cut off with the wire lying in the U of the electromagnet, the galvanometer gives a big deflection. If the current is reduced more gradually, to keep the deflection within the same limits as before, it turns out to need just the same time to get the current to zero, as it did to pull the wire out with the current steady.

Theory: a new sort of induction

The first part of the demonstration, with a moving wire, is no different from the earlier experiments. But in the second part, the wire does not move at all, yet there is an induced voltage when the field passing through the wire loop is altered.

This is a new effect, mentioned briefly before (page 43). Two things about it are remarkable. It is different from those induced voltages which are explicable in terms of electrons being carried through a field, and cannot be given so easy an 'explanation'. Yet it is also rather similar to such moving wire effects, in that both can often be described in the same way, as the result of changing the field (or flux, more properly) passing through a circuit, and the same rate of change gives the same induced voltage.

None of this is material fit for students. All we suggest is that the actual practical difference between the two sorts of induction (the wires move, or do not move) be noted, leading one to marvel that they can be given a similar 'flux-changing' description, rather than to treat it as obvious that this could be done.

Students' book

Question 34 is about moving wires and changing fields.

7.9d	**Changing the field continuously**
147	demountable transformer kit (use 300-turn coil, item 147 D)
59	l.t. variable voltage supply
92X	reel of 26 s.w.g., PVC covered, copper wire
541/1	rheostat (10–15 Ω)
1007	double beam oscilloscope
1057	a.c. ammeter
84	wire strippers
1000	leads

Figure 23 shows the apparatus. An a.c. ammeter can be inserted in series with the a.c. supply, rheostat, and 300-turn coil, to check the current. 1 A is suitable. Leads across the rheostat go to one beam of the oscilloscope, an appropriate sensitivity being 5 V cm^{-1}.

The coil can be made of half a dozen turns of PVC covered wire, formed round the edge of a matchbox, with perhaps a little adhesive tape to hold the turns together. Leads from the coil go to the first beam, whose sensitivity should be set at 0.1 V cm^{-1}. It is best to trigger the oscilloscope traces from the first beam, whose signal is larger.

Show, by setting the traces one on top of the other, that the maximum induced voltage comes at times when the field is zero, but is changing rapidly. As the coil is slid into the gap, the induced voltage rises, but if the coil surrounds the gap, small movements of it make no difference, as the whole of the field is in, or close to, the gap region.

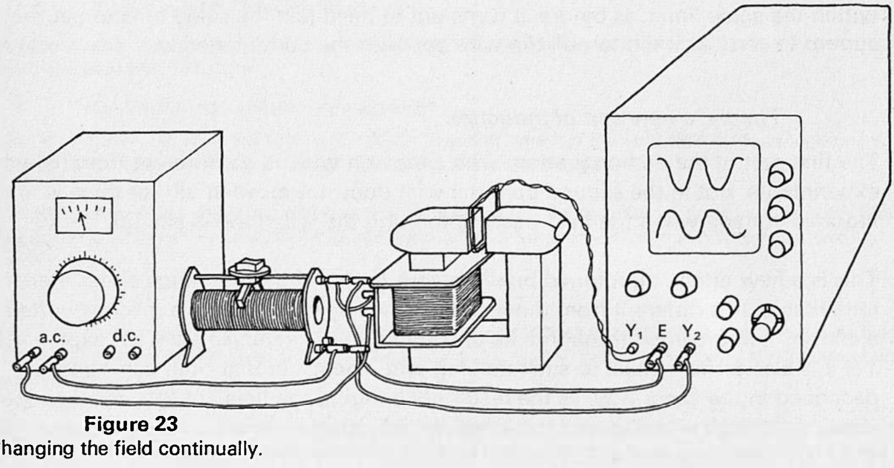


Figure 23
Changing the field continually.

If the induced voltage is proportional to a rate of change of something (flux), then in both these distinct effects the constant of proportionality is the same.

7.9d Changing the field continuously

In 7.9c, there was an induced voltage when the field changed. This next demonstration shows the effect of having a field that is changing all the time: an alternating field.

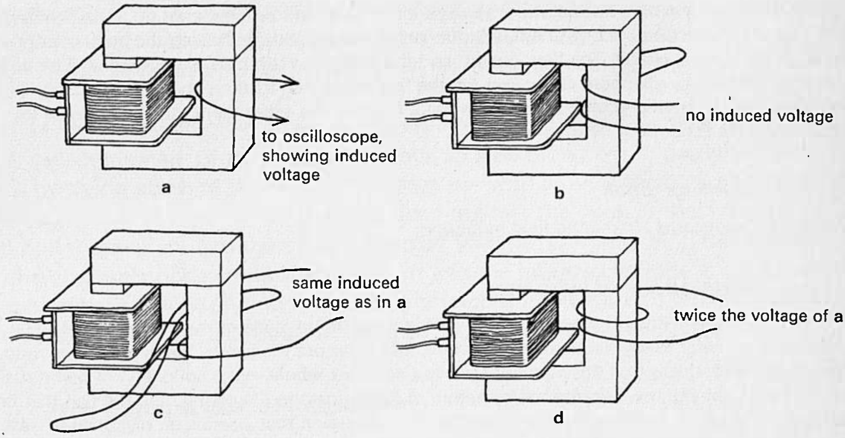


Figure 24
Changing flux through an electric circuit.

The electromagnet is fed with alternating current, and the p.d. across a resistor in series with the magnet is used on one beam of the oscilloscope display to indicate how the field changes.

A small coil placed across the gap has a voltage induced in it. This voltage alternates, but is big when the field is changing fast, and goes through zero when the field is at its greatest magnitude, when for a moment the field is not changing.

As the coil is slid into the gap, the induced voltage rises, and this would seem to be connected with the fact that more and more of the field passes through the coil's cross-section.

The product of the strength of the field and the area it goes through is called the *flux*. B may be regarded as a *flux density*, flux divided by area. This idea will be made more precise in later experiments.

Flux

The word flux suggests flow. The sense of such an association of ideas may be seen, perhaps, if one tries what happens when an iron yoke is clamped over the U-shaped iron core, so making something like a complete ring of iron, as in figure 24. Outside

Finally, replace the pole pieces of the demountable transformer with its iron yoke firmly clamped over the U-shaped core, as in figure 24 *a*. Move the detecting coil about near the iron. Except perhaps near corners, there is little alternating voltage induced in it.

If the coil is disconnected from the oscilloscope, and replaced by a single lead taken from one oscilloscope terminal to the other, through the closed iron circuit, an alternating voltage appears across this wire. The size of the induced voltage depends very little on where the wire lies, whether close to one part of the iron or another, just so long as the wire links the iron. If the wire is made to link the iron several times, the induced voltage rises in proportion to the number of linkages.

Students can try a similar but quantitative experiment with an iron core later on, in experiment 7.11, so it is best now to emphasize only that the induction effect depends on having the magnetic 'flux' passing *through* the electric circuit. The flux 'circuit' and the electric circuit must be entwined. Strictly speaking, this experiment tells one more about iron (all the flux lies within it) than about flux-linking. Given that the ideas will be examined more carefully in what follows, the experiment may be forgiven its imprecision on account of its effectiveness.

Students' book

Question 35 concerns alternating field induction.

Stating a law of induction

It will not be easy to know how much or how little to say in advance of the actual experiments. Some teachers may prefer to say the minimum amount, and draw out the law as the experiments proceed. The trouble with this is that this particular law is a complex whole, not a collection of parts, such that for example, 'linking' involves the vector nature of *B*, the turns in the circuit, and the fact that flux is continuous in space. Another trouble would be the impression that a series of 'discoveries' was being made, when what is being offered is a series of highly selective demonstrations of particular aspects of a difficult principle.

A difficulty with announcing the law in advance is that it may be largely unintelligible. That may be counted an advantage, in a way, since it *is* unintelligible without a good range of concrete experience of its use.

Students' book

Questions 35 to 37 concern the law of induction.

Students' demonstrations

7.10 The law of electromagnetic induction

7.10a Turns

1037 set of solenoids

1009 signal generator

1007 double beam oscilloscope (or oscilloscope – item 64)

92X reel of 26 s.w.g., PVC covered, copper wire

1000 leads

Figure 25 shows the arrangement of the apparatus. The best solenoid to use is the fattest and most closely wound one of the set, fed with sinusoidal oscillations at about 2 kHz from the low impedance output of the signal generator. Using 0.1 V cm^{-1} oscilloscope sensitivity, the experiment can begin with only one or two turns of PVC covered wire round the middle of the solenoid. For good quantitative results, twist the leads to the oscilloscope. For convenience, make these leads very long at first so that the iron ring, the coil detects little. Have all induced voltage effects ceased, or been much reduced? That they have not, may be shown by passing a wire through the iron ring so that it encircles the ring. The oscilloscope shows that there is a substantial voltage induced in the wire now, which can be increased by making the wire encircle the iron several times rather than just once.

The experiment gives a strong impression of something magnetic being confined to a closed loop of iron, almost as if something magnetic were going round in the iron, as charge flows round in an electric circuit. But we don't know what the 'something magnetic' is, and indeed there is no reason to think that anything actually flows round the iron. (Nor, so far as anyone knows, does anything go round.)

To get an induced voltage in a circuit, the changing magnetic flux must pass through that circuit. A moment or two might be spent on illustrating what 'pass through' means, by trying some of the ways of passing the wire around the core shown in figures 24 *b* to *d*. In figure 24 *b*, the wire does not link the core, in that neither need be cut to pull them apart, and there is no induced voltage. In figure 24 *c*, the wire still links the core only once (unlike figure 24 *d*) and the induced voltage is not increased. Electromagnetic induction and topology, a branch of mathematics which studies the interlinking of surfaces and boundaries of surfaces, have something in common.

One general law of induction

The law of induction was sketched in previously (page 43). If ϕ is written for the mysterious quantity, the 'flux' of B across the area of the circuit with N turns, the law can be written quite simply:

$$V = N\mathrm{d}\phi/\mathrm{d}t$$

The problem is not remembering this equation but understanding what it means, and how to use it. ϕ conceals a lot: the magnitude of B, the area it passes through, and the way the circuit is aligned. The flux is calculated from an equation like:

$$\textit{flux} = (\textit{field}) \times (\textit{area}) \times (\textit{angle factor})$$

The law is a complicated one, as well as being abstract. But it is of immense practical importance, for dynamos, transformers, motors, radio sets, and many other things depend upon it, and are designed using it. So it is worth learning to understand how to use it.

Students' demonstrations

The law of electromagnetic induction

The following series of demonstrations is intended to check the quantitative features of the law, and, more important, to give some concrete meaning to this abstract talk of 'flux' which 'links' things.

there is plenty of spare wire for wrapping extra turns round the solenoid. The number of turns can be varied from two to ten.

Accurate measurement of the trace height is easier if the time base is switched off, but it would be wise to make sure that all students see the sinusoidal trace as well, so that they know what is going on.

If preferred, the supply can be 3 A at 50 Hz. Numbers of turns from 10 to 20 are then advisable.

7.10b Area

Apparatus as for 7.10a, adding:

27 transformer

1039/1 search coil (axial)

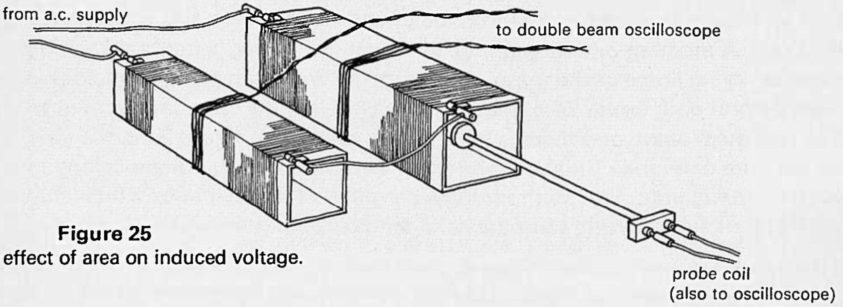


Figure 25
The effect of area on induced voltage.

The experiment can be done at 50 Hz, and it is an advantage to do this if signal generators are in use for other experiments. A pair of the more closely wound solenoids from the set are used, one 'fat' and one 'thin'.

The two solenoids are connected in series, as in figure 25, to an a.c. supply of about 12 V. Ten turns of PVC covered, copper wire are wrapped tightly round the middle of each solenoid. The two beams of the double beam oscilloscope are then used to compare the maximum voltage induced in each of these ten-turn coils. Use 0.1 V cm^{-1} sensitivity.

To show that the fields within the solenoids are equal, and are both pretty uniform across the cross-section of the solenoids, put the probe coil into each solenoid in turn, having connected it to the oscilloscope. It is best to confine observations at this stage to the middle of the solenoid (where the ten-turn coils are) and leave more detailed exploration of the whole solenoid field until later.

The solenoids are designed to have area in the ratio of two to one, very nearly, and it makes for a quick demonstration to check only that the induced voltages are in this ratio too.

The solenoids are best kept well apart, and parallel to one another, so that little field from one enters the other.

7.10a Turns

Having now introduced induction by an alternating field, it is convenient to use such fields in some demonstrations.

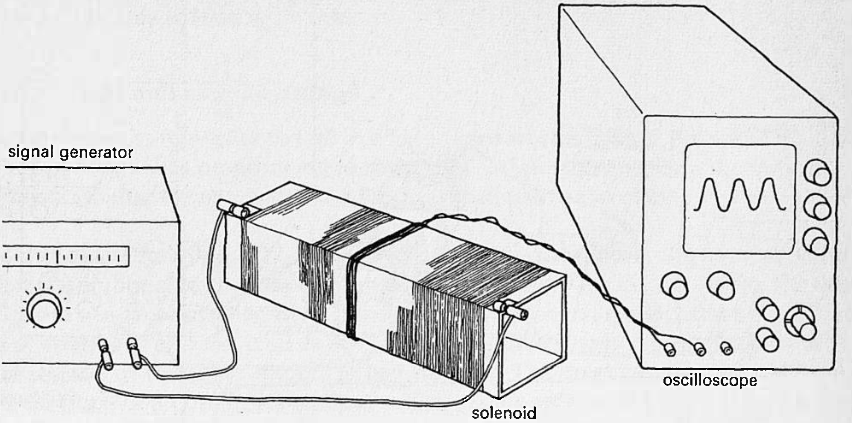


Figure 26
Effects of turns on induced voltage.

The vertical height of the oscilloscope trace is in proportion to the maximum induced voltage. As more turns are wrapped round the solenoid, the height increases in proportion to the number of turns. This is perhaps not surprising, as each turn is in series with the others .

7.10b Area

More of the same strength field going through a bigger coil produces a bigger effect, in proportion to the area over which the field extends. This was hinted at in experiment 7.9d, where more of a coil was pushed into the gap of an electromagnet so that more field went through it.

Figure 25 shows another means of looking at area effects. The two solenoids differ only in their area of cross-section, and if the current in them is the same, the B-field in them has the same strength. This can be shown by pushing a probe coil into the middle of each in turn. (It would be possible to go back to d.c. and try a Hall probe in each, but that would be tedious, and can be tried later in experiment 7.13 by anyone who wants.) The fatter solenoid has the B-field in it extending over the greater area.

Coils wound round the middle of each solenoid have induced in them voltages in the ratio of their areas, even though they have identical numbers of turns. The induced voltage is proportional to the area over which the B-field is spread as it passes through the coil.

7.10c Field and rate of change

Apparatus as for 7.10a, adding:

1017 resistance substitution box

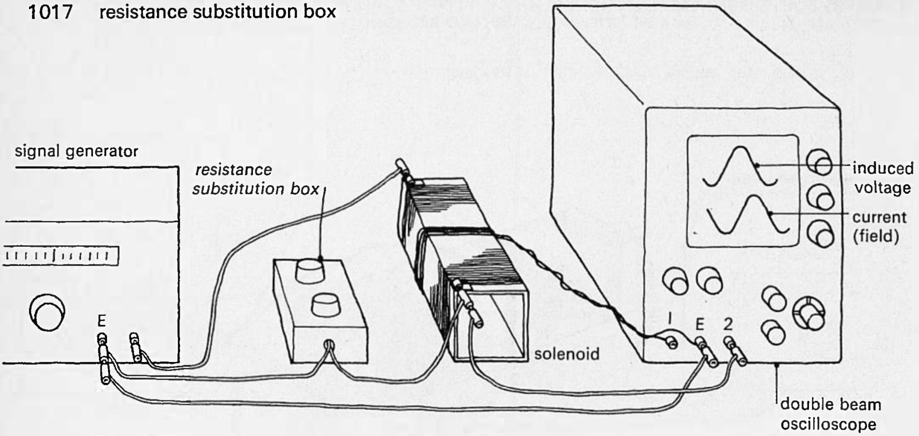


Figure 27
Induced voltage proportional to rate of change of flux.

Figure 27 shows the arrangement of the apparatus. A ten-turn coil of PVC covered wire is wrapped round the middle of a solenoid; choose the fattest and most closely wound solenoid if possible. The solenoid is connected via a resistance substitution box set at about 15 Ω to the low impedance output of the signal generator. The ten-turn coil is connected to one beam of the oscilloscope, sensitivity 0.1 V cm^{-1}; the other beam is connected across the resistance box.

It is convenient to trigger the oscilloscope from the latter (current) input, triggering as the current goes negative, so that with one complete cycle displayed, as in figure 28, there is a rising portion of the current trace in the centre of the screen.

Set the frequency at, say, 1 kHz, and record the peak-to-peak induced voltage. Increase the frequency to double the previous value, adjust the signal generator if necessary so that the maximum current is unchanged, and note that the peak-to-peak induced voltage has now doubled.

Note also that the slope of the most steeply rising portion of the current trace is now twice as great as it was previously.

Return the frequency to 1 kHz and halve or double the current by changing the output of the signal generator until the lower trace has half, or twice, its previous value. The induced voltage changes in proportion.

7.10d Orientation

27 transformer
1042 magnetic field board
92X reel of 26 s.w.g., PVC covered, copper wire
64 oscilloscope
1039/1 search coil (axial)
1057 a.c. ammeter
1000 leads

It may be worth showing that if the coil which fits the fatter solenoid is placed around the middle of the thinner solenoid, the voltage induced in it is no larger than that in the coil wound tightly round the thinner solenoid. The area of the coil only matters in so far as that area is filled with field.

7.10c Field and rate of change

When a wire was moved or turned in a field (experiments 7.9a, 7.9b, and 7.8), the induced voltage was proportional to the rate of movement, and, by a theoretical argument, to the rate at which extra flux was included in the circuit.

This demonstration, figure 27, shows that when no wires move, the induced voltage is also proportional to the rate of change of flux through the circuit. Again, the easiest thing is to use an alternating field. If the alternating frequency is doubled, the maximum rate of change is also doubled as long as the amplitude stays the same, since the field must change by the same amount in half the time. The point can be checked from the greatest slope of an oscilloscope trace which is proportional to the current in a solenoid, as in figure 28.

The voltage induced in a coil wrapped round the middle of the solenoid can be displayed at the same time on a double beam oscilloscope. When the frequency is doubled, the maximum induced voltage also doubles. The induced voltage can be doubled without change of frequency, by doubling the current. An earlier experiment showed that this doubles B. Thus the induced voltage is proportional to dB/dt. It is worth noting again that the induced voltage goes through zero when the current, and so the field in the solenoid, goes through its greatest magnitude and is, for an instant, unchanging.

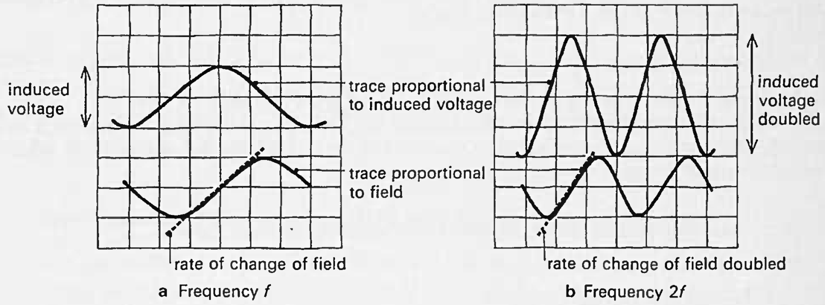


Figure 28
Induced voltage and rate of change of field.

7.10d Orientation

In most experiments so far, the magnetic field has been kept at right angles to any coil through which it passes, and in which a voltage is induced. Does the angle between coil and field matter? This demonstration shows that it does, and that the rate of change of flux rule will still serve if the flux passing through a coil is reckoned by

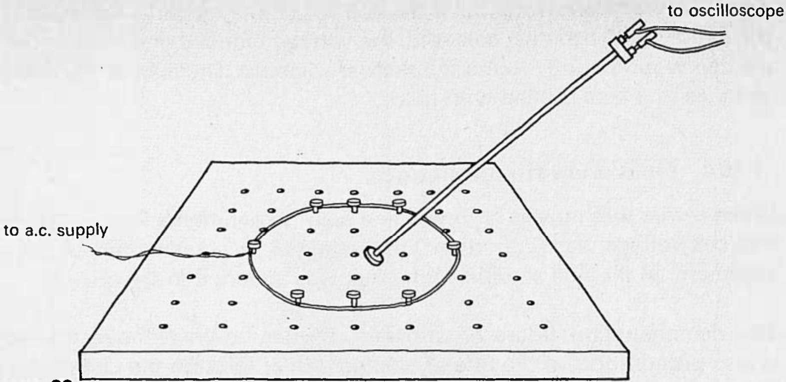


Figure 29
Magnetic field board and search coil.

Wind a coil of about ten turns of PVC covered wire round pegs on the magnetic field board. The coil can be roughly circular, or square. It is supplied with about 5 A at 50 Hz from the transformer.

The search coil is connected to the oscilloscope, sensitivity 0.1 V cm^{-1}. It is used only at the centre of the flat coil in this experiment; investigation of the rest of the field comes later (experiment 7.13).

Start by standing the search coil over the centre of the flat coil, with its handle (and so the axis of the search coil) vertical, at right angles to the plane of the board. Tilting the search coil in any direction, while keeping it in the centre, reduces the peak-to-peak value of the alternating induced voltage across the search coil, as displayed on the oscilloscope. Tilt the coil until the induced voltage is halved, when it will lie with its axis at 60° to the vertical (30° to the plane of the board).

It may be helpful to show that the effect is not due to any slight shift in position of the search coil, by moving it about a little near the centre of the flat coil. The field is uniform for small displacements either sideways or up and down. The demonstration is a helpful way of letting the class see the magnetic field board before they use it themselves later on.

B resolves like a vector

Another way of looking at this experiment is to say that it shows that B resolves like a vector. The experiment, and others that show that B also adds like a vector, are the basis for treating B as a vector quantity and employing the mathematics of vectors in dealing with it. See Appendix D, which discusses the mathematical concept of a vector.

7.10e	**Equivalence of changing field and moving through field**
1037	set of solenoids
59	l.t. variable voltage supply
1064	low voltage smoothing unit
70	demonstration meter
71/2	dial for demonstration meter, d.c. dial, 5 A
1001	galvanometer (internal light beam)
541/1	rheostat (10–15 Ω)
507	stop watch or stop clock
1000	leads

taking the area concerned as the area of the coil projected at right angles to the flux.

It is convenient to use one of the search coils, choosing the one with a handle which lies along the axis of the coil, so that the handle indicates the direction of that axis. So as to have plenty of space available to swing the coil about in, it is easier to use the field at the centre of a flat coil than to use the field of a solenoid.

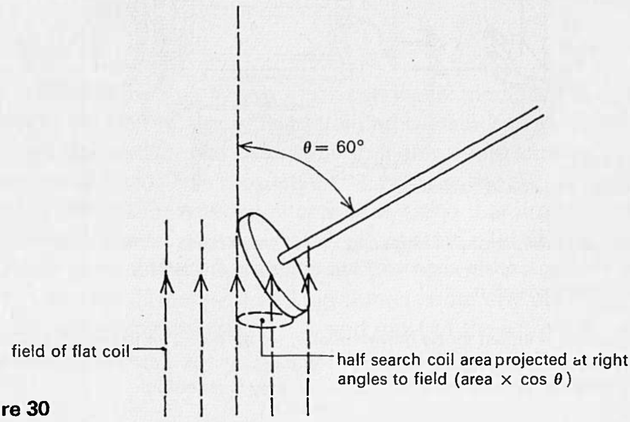


Figure 30
The cos θ rule.

For a simple test, show that the peak value of the alternating induced voltage is greatest when the search coil's axis is at right angles to the plane of the flat coil, putting the search coil at the centre of the flat coil. This agrees with the impression of the field direction seen earlier, using iron filings. Then tilt the search coil until the peak voltage is halved. The coil is found to have been tilted through about 60°, so that its axis is now at 60° to the direction of the flux, as in figure 30.

If a search coil of area A has its axis at angle θ to a magnetic field, the area of the search coil projected at right angles to the field is $A \cos \theta$. The cosine of 60° is 0.5, and this is just the angle at which the induced voltage, and so the flux linking the search coil (if the flux rule is to be useful), has halved.

7.10e Equivalence of changing field and moving through field

This experiment makes a point similar to one made in 7.9c. One solenoid is placed inside another which carries direct current. If the inner solenoid is slowly pulled out at a (varying) rate such that the deflection of a galvanometer connected to it is steady, the removal of this solenoid from the flux of the other takes a substantial time which can be measured.

Then, with the solenoids together again, the same effect, so far as the flux going through the inner solenoid is concerned, is achieved by reducing the flux through reducing the current to the outer solenoid. It is found that to keep the galvanometer reading steady at the same value as before, it is necessary to reduce the current, and so the flux, over just the same time as before.

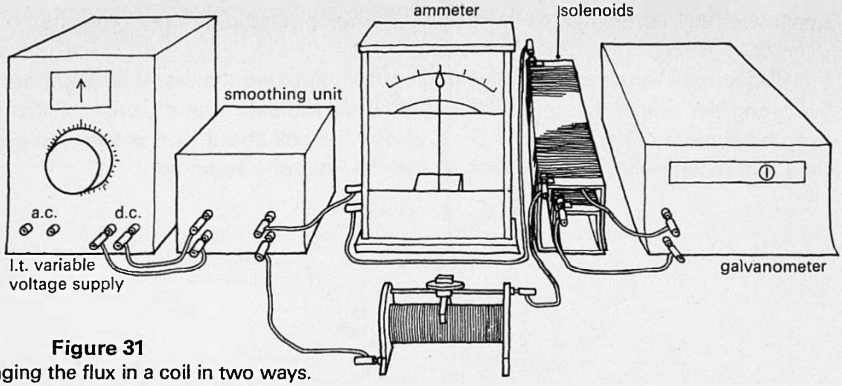


Figure 31
Changing the flux in a coil in two ways.

Two solenoids are required, one of large and one of small cross-section. Solenoids with closely wound turns are best. The larger one is connected to a smoothed d.c. supply via a rheostat and ammeter, and about 3 A is passed through it.

The smaller solenoid is joined to the galvanometer, set at 'direct', and placed inside the larger coil. It is then pulled slowly out, keeping the galvanometer indication as steady as possible at about 20 mm or so. The time needed to remove the solenoid completely is recorded.

Then, with the inner solenoid replaced, the current in the outer one is reduced to zero, using the control of the variable voltage supply, at such a rate as to keep the galvanometer indication steady at the value used previously. The time needed to do this is recorded, and is close to the time required in the first part.

The same apparatus is used for the first part of experiment 7.10f.

Moving lines of force

The experiment could be interpreted as 'showing' that the magnetic 'lines of force' move when the flux is reduced, so that moving the coil and changing the flux are both to be regarded as examples of wires cutting through flux. Such an interpretation is not wrong; it exploits the result of the experiment to give the flux a property (motion) that fits in with the result. The trouble is that the 'motion' of a field is not to be understood as exactly like the motion of some more concrete, graspable object, such as one of the solenoids. If a field moves, some pattern of intensities previously found in one region of space ought to be found in another place, as when a magnet is moved across the room. Nothing like that happens in this instance. So in this experiment, one is not discovering that the flux moves, but is giving 'move' a special meaning, not identical with its usual one, if one says that the changing flux is equivalent to moving flux lines. Nevertheless, the idea of moving flux is a very useful one for many purposes. Some electrical engineers use it a good deal; the good ones remember that all such analogies are fallible.

7.10f **The effect of iron**

Apparatus as for 7.10e, also using:

504	retort stand rod (steel)	*4*
27	transformer	
1007	double beam oscilloscope	
1037	set of solenoids	
92X	reel of 26 s.w.g., PVC covered, copper wire	
1000	leads	

The two effects are quite different. In the first, electrons in the moving coil are pulled past a magnetic field; the resulting force on them gives rise to the induced voltage. In the second part, no wires move, and there are no 'magnetic' forces on electrons in the wires. But, nevertheless, the remarkable thing is that the two effects can produce the same result: the induced voltage can in each case be accounted for by the rate of change of flux in the coil, even though the change is brought about differently.

7.10f The effect of iron

These demonstrations show that iron in a coil can vastly increase the flux, and that therefore the flux in the iron of any iron-containing system is likely to be large compared with the flux outside the iron (though it may be no smaller than it would be without the iron's presence). This property of iron makes the transformer a practical proposition, and is the reason why any motor or dynamo that has to produce substantial amounts of power without waste will contain a lot of iron. Indeed, the magnetic virtues of iron are such that engineers put up with the great weight it necessarily involves. One of the most striking things about any but a toy electromagnetic machine is how *heavy* it is, and most of the weight is iron.

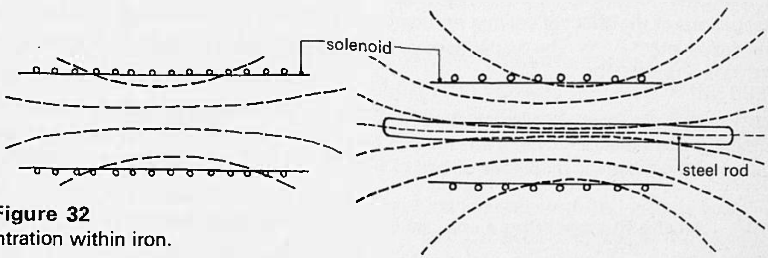


Figure 32
Flux concentration within iron.

First, one can simply put a steel rod down the middle of the two solenoids used in experiment 7.10e, figure 31, and again try timing how long it takes to reduce the current to zero without exceeding a certain galvanometer deflection. The time is considerably increased, and is increased still further by adding more steel rods. The greater the cross-section of iron or steel available to the flux, the greater is the flux. If one thought of flux as like a flow, one would want to say that steel 'conducts' it well, and that fat 'pipes' of solid steel 'conduct' it better than thin ones.

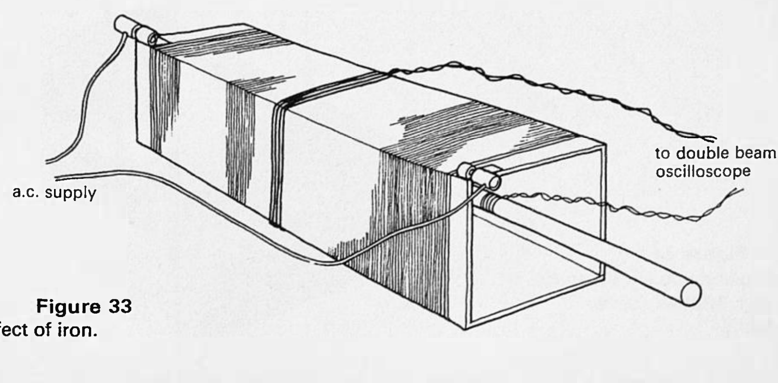


Figure 33
The effect of iron.

The first part of the demonstration uses the apparatus for experiment 7.10e. The time needed for the current in the outer solenoid, figure 31, to be reduced to zero without exceeding a fixed galvanometer deflection produced by the voltage induced across the inner solenoid, is recorded with one, two, and four steel rods placed inside the solenoids. Adding more steel increases the time. If the retort stand rods available are made of aluminium alloy or of stainless steel, mild steel rods will need to be bought for this purpose.

Figure 33 shows apparatus for the second part of the demonstration. Ten-turn coils of PVC covered, copper wire are wound on the middle of a solenoid and onto the middle of a 0.5 m steel retort stand rod. The rod is placed so that its coil lies in the centre of the solenoid.

The two ten-turn coils are each connected to an input of the double beam oscilloscope, both at a sensitivity of 0.5 V cm^{-1}. The solenoid is supplied with an alternating current of about 3 A from the transformer. The trace indicating the voltage across the outer ten-turn coil is only a shade bigger in amplitude than that indicating the voltage across the much smaller ten-turn coil round the steel rod.

It should be remembered, and can be shown with a search coil, that there is still flux in the air in the solenoid; indeed there is just as much as when the same current flows without the iron rod being inserted.

Magnetic circuits

This demonstration is likely to be followed up by other experiments about the importance of iron, and investigations of the effect of varying its length and cross-section, in investigations of transformer action (experiment 7.11). The matter need not now be pursued very far; this experiment need only serve to start a line of thought.

We do not propose much detailed study of magnetic circuits in the course, but no discussion of electromagnetism that pretends to any interest in practical machinery can ignore the enormous influence of the magnetic properties of iron or steel on the design and behaviour of machines.

7.10g **All the flux entering a volume of space leaves that space**

1082	coils surrounding a space
1058	coil with 120+120 turns
504	retort stand rod (steel, 0.2 m)
1009	signal generator
181	general purpose amplifier
183	loudspeaker (if not part of item 181)
1000	leads

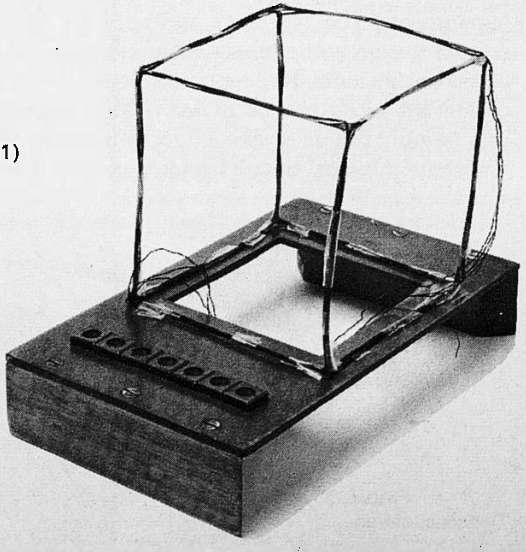


Figure 34
a Box of coils surrounding a space.
Photograph, Michael Plomer.
(*Continued.*)

A second experiment, with alternating current, compares the voltage induced in a ten-turn coil wrapped round a steel rod lying inside a solenoid with the voltage induced in a coil wrapped round the outside of the solenoid, as in figure 32. The two voltages are almost the same, suggesting that almost all the flux inside the solenoid is concentrated within the steel rod, since as much of it, very nearly, goes through the small coil round the rod as goes through the large coil round the whole cross-section of the solenoid.

7.10g All the flux entering a volume of space leaves that space

This demonstration makes a subtle but fundamental point. All the talk about flux, and any later talk about magnetic circuits, depend for their sense on magnetic flux having, in common with the flow of water down a river, the property of being like the flow of a substance that is conserved.

Because it has this property, authors of books are at liberty to draw continuous lines on diagrams or maps of the field or flux in parts of a machine. Because it has this property, the name 'flux' itself has point, even though there is no reason to suppose that anything flows. The analogy between flow and flux at least extends to the property that as much flux leaves any volume of space as enters that volume.

In the demonstration, one coil faces a magnet, which may conveniently be an electromagnet carrying alternating current, so that the voltage induced in the coil by the flux passing through it can be 'listened to' on an audio amplifier and loudspeaker.

The sound produced by the alternating voltage across a second coil a little way behind the first, as in figure 35 *a*, is fainter. This may be expected since the field spreads out (iron filing patterns) and the second coil has less flux through it. The question is, does the flux through the second coil together with that escaping between their sides add up to be equal and opposite to the flux going through the first coil?

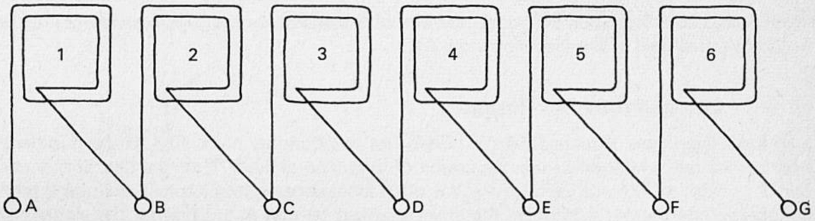
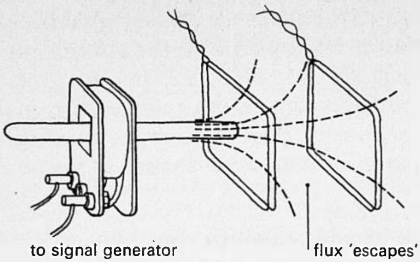


Figure 34 (*continued*)
b Connections to the six coils.



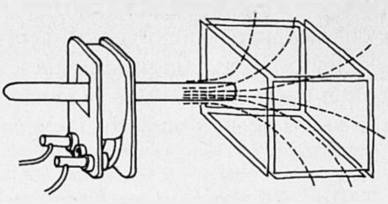


Figure 35
Coils arranged to catch all the flux passing through one coil.

The 'box of coils' shown in figure 34 *a* consists of six ten-turn coils of thin enamelled wire connected in series. Figure 34 *b* shows the series connection of the six coils to seven terminals. The sense of the winding of every coil must be the same when viewed from outside the box. This can be checked by connecting each in turn to a galvanometer, and thrusting the same end of a magnet into each from outside. There must be as little space as possible between the edges and corners of the coils.
The electromagnet can be a 240-turn coil round a steel retort stand rod, supplied at, say, 1 kHz from the low impedance output of the signal generator. Let it face coil 1 of figure 34 *b*, as shown in figure 35 *a*. The audio amplifier is connected across terminals A and B in figure 34 *b* and the gain adjusted so that the sound is comfortable.

Let coil 6 be the coil parallel to coil 1, some way behind it, as in figure 35 *a*. Connect the amplifier across terminals F and G, when the sound heard is fainter. Now move the amplifier lead connected to F in turn to E, D, C, and B, so including all the coils round the edges of the box. The sound is now as loud as that with the amplifier across AB.

Finally, connect the amplifier across AG. The total output should now be very small, resulting only from whatever flux leaks out at the edges or corners of the box.

B has zero divergence

The experiment bears directly on one of Maxwell's fundamental equations, and it may be worth mentioning this to some students. The equation is the one that says div $B = 0$. The divergence of a vector field is a measure of how much flux originates in a volume of space, per unit volume. (Actually, it is the limit of this ratio as the volume tends to zero.)

The equation says that none ever does: the flux of B has no sources. The experiment illustrates what a divergence-free field is like (see Appendix A).

Flux and total flux linkage

In all discussion here, ϕ means BA (or $\int B\mathrm{d}A$) not this quantity multiplied by the number of turns. This is for convenience later on in the discussion of magnetic circuits. Thus the law of induction takes the form $V = N\mathrm{d}\phi/\mathrm{d}t$. The number of turns N is often amalgamated into a total flux linkage term, which may be done by interpreting A to mean the areas spanned by turn after turn, not the single cross-sectional area of a closely wound, multi-turn coil. But we think that to keep the term N explicit for a while will do no harm; later it can be interpreted as a number of areas crossed by flux.

Direction of the induced voltage

The question whether or when the equation $V = N\mathrm{d}\phi\,\mathrm{d}t$ requires a minus sign arises here as it did in Unit 6 in connection with $V = L\mathrm{d}I/\mathrm{d}t$. We suggest that the emphasis should be on the physical situation, and on the direction of transfer of energy, rather than on its expression with a minus sign. The minus sign is needed if one is regarding the electromagnetic part of a system as a *source* of energy.

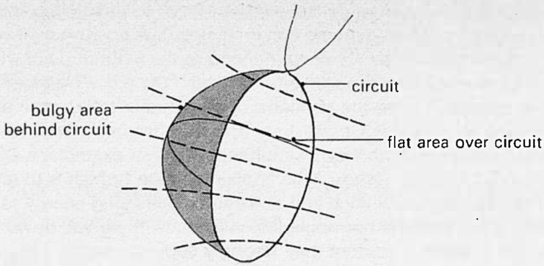


Figure 36
The same flux goes through any area bounded by the same circuit.

The point is made by arranging four other coils to catch the flux that 'escapes round the edges', so making a little box of coils, as in figure 35 *b*. The sound from the five coils behind the first is as loud as that from the first alone. If all coils are put in series, the total effect is zero, as it will be if as much flux leaves the coils as enters them.

Summary of the law of induction

The induced voltage in a circuit is equal to the rate of change of flux through it.

One result of the last demonstration (7.10g) is that 'the flux through a circuit' has one definite value in each situation. It does not matter what area is taken to calculate the flux, as long as its edges lie on the circuit, as do the edges of the two areas in figure 36. If they have the same edges, the flux through them is the same, because no flux gets lost or created in between. These are deep matters, worth having been seen in passing, but not easy to grasp.

If there is a uniform B-field over the area A of a coil which has N turns, and which is tilted with its axis at an angle θ to B, as in figure 37 *a*, the flux through the coil is

$$\phi = BA \cos \theta.$$

(If the B-field varies over the area of the coil, as in figure 37 *b*, one has to add up bits of flux $B \, dA \cos \theta$ one by one, over areas dA small enough for B to be constant within them.)

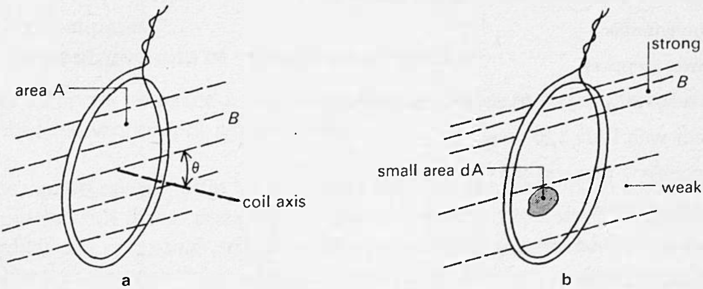


Figure 37
Flux linking a circuit.

That is, the flux change in a coil cannot deliver a current back to that coil, so as to assist the flux change in that coil (any more than a dynamo can drive itself). A positive sign is natural if one regards the system as a *sink*. Energy has to be *supplied* to increase the magnitude of the flux in a coil, just as it has to be supplied to an electric fire element, for which the p.d. IR is usually counted positive. On this view, the p.d. required across the terminals of an inductor to increase the flux is positive.

Difficulties only arise if one takes both views simultaneously. For example, it is tempting to say that the induced voltage across an inductor *opposes* the applied voltage (which is to regard the inductor both as a sink supplied from the applied voltage and as a source delivering energy to the external supply) and to deduce falsely that, if the inductor has negligible resistance, there will be *no* voltage across its terminals. Similarly, for a motor, a student may wrongly suppose that an 'opposing' induced voltage (or 'back e.m.f.') across the rotor 'cancels' the applied voltage.

Another way of presenting the matter is to distinguish carefully between p.d. and e.m.f. The e.m.f. is the energy (exchanged between the circuit and elsewhere) per coulomb passing round the *complete* circuit. A cell transfers energy from its constituents *to* the surroundings via the circuit. A motor driven by the cell transfers energy *from* the cell via the circuit to the load. If, as is usual, the cell e.m.f. is counted positive, the motor e.m.f. must be negative. A similar argument gives a minus sign to the e.m.f. of an inductor, when the magnitude of the flux in it is rising. Note that the assignment of the minus sign arises from the decision to give a positive sign to the energy delivered by the *source.* Chemists normally use the convention we suggest, in other contexts. They count ΔH *positive* for a chemical system which gains energy, and *negative* for a system which delivers energy. On this convention, $V = N\,\mathrm{d}\phi/\mathrm{d}t$ has a plus sign.

Students' book

The article, 'The generation and transmission of power', attempts to expand both on the social benefits and on the less desirable consequences of having electrical power distributed all over the country. It considers the need for high voltage transmission, the limitations on underground cables, and other matters, such as the trend towards larger and larger generators.

Questions 38 to 46 are about transformers. Some should wait until work on Part Three is under way.

Source of data

The annually published *CEGB statistical yearbook*, from which the data opposite were taken, is worth having as a source of information, for interest or for use in setting problems.

Investigation

7.11 Investigation of transformer action

The investigations suggested below require access to:

27	transformer	
84	wire strippers	
92X	reel of 26 s.w.g., PVC covered, copper wire	
1058	coil with 120+120 turns	*2*
92G	double C-core and clip	
1057	a.c. ammeter	
158	class oscilloscope	
177	lamp (12 V, 6 W)	*2*
74	lampholder (s.b.c.) on base	*2*
1039/1	search coil (axial)	

To increase the magnitude of the flux in a coil requires energy to be delivered to the circuit from outside, perhaps by a battery of voltage V, where

$$V = N\mathrm{d}\phi/\mathrm{d}t.$$

N is the number of turns in series in the coil, through each of which the flux passes.

If a coil carrying flux through it is to deliver energy to the outside world, the magnitude of the flux must decrease. Thinking of the coil as if it were a battery of voltage V,

$$V = -N\mathrm{d}\phi/\mathrm{d}t,$$

the minus sign indicating that the flux must decrease if the device is to deliver energy. Because energy is conserved, there must be a change of sign when one changes from looking at the device as something to be driven to looking at it as something to do the driving. If the flux in a coil increases in magnitude, the outside world is giving the coil energy; the coil, regarded as a *source* of energy, is then a *'negative' source*, since it is taking in energy rather than giving it out. This must be so, or a small rise in the flux in a coil could drive current through the coil, raising the flux still more, and so on until the coil spontaneously exploded.

The transformer

A transformer – two coils linked by a ring of iron – seems a simple thing, and is a very useful one. It is transformers which make it possible to transmit electrical power over long distances without having to use absurdly thick cables. This is because they transmit it at a high voltage, and so at a low current.

Britain alone is cobwebbed by about 16 000 km of high voltage cables, carried on over 50 000 pylons. These cables are interconnected, both to supplies to houses and factories and to power stations, by nearly 1000 transformer substations.

The efficient design of transformers is a necessary part of the phenomenon everyone usually takes for granted: that light is available in nearly every home at the touch of a switch.

Investigation
7.11 Investigations of transformer action

Students can now be asked to use what they know to devise experiments to find out more about the working of a transformer.

It may be necessary to begin by showing, say, the demonstration transformer (item 147), pointing out that it consists of a primary coil connected to an alternating supply; a secondary coil in no way connected to the primary, across which there may be an alternating voltage, and from which current might be drawn, and an iron core linking the coils.

504 retort stand rod (steel) *2*

541/1 rheostat (10–15 Ω)

1053 cards

1000 leads

and possibly

1075 electronics kit (with double beam switch)

1033 cell holder with four U 2 cells (for electronics kit)

Choice of investigations

A number of investigations are suggested below. Not every student should try all of them, and some may well find others. The job of deciding what to do is important enough to be left, at least in part, to students themselves, giving them what advice they want, rather than directing their ideas too strongly. Almost anything one can do with a pair of coils, ammeters, oscilloscopes, and an iron core is of interest. One useful way to guide investigation is to restrict the supply of apparatus, giving one group, say, a core, a coil, and a lamp to begin with, while another might have some wire and a couple of steel rods. More investigations are suggested than most classes will cover. The vital ones are g, h, and i, concerning voltages and currents in the transformer; a and e are good support for these, and are simple; b, c, d, and f are of interest; j and k are suitable only for a minority. The results of b, c, d, and f are needed later, but those omitted now can be demonstrated when wanted.
The *Students' laboratory book* gives outline suggestions for the investigations below.

a *Apparatus*

120+120-turn coil

double C-core and clip

steel rod

lamp and lamp holder

a.c. ammeter

transformer

leads

It may be better to start off with a 20-turn coil of PVC-covered copper wire round a steel rod, in which the currents will be bigger. With an iron core and a 120+120-turn coil the current with the core in place is almost too small to measure: a good point in itself, but one that may conceal the fact that the current is bigger if fewer turns are used. An oscilloscope across a resistor will reveal the difference.

b *Apparatus*

steel rod *2*

PVC covered wire and wire strippers

double C-core

a.c. ammeter

rheostat

oscilloscope

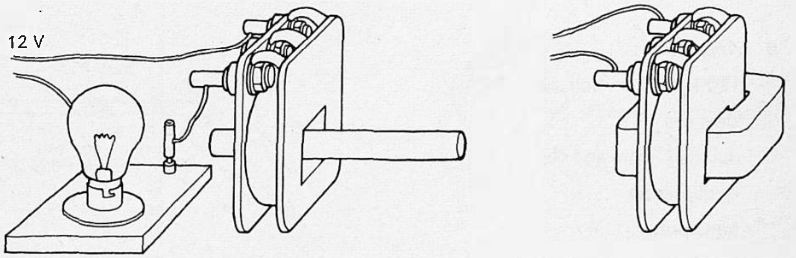
transformer

leads

A number of questions arise. How does the presence of the iron affect the currents in, or the voltages across, the two coils? Does it matter if the iron is long and thin or short and fat? What is the influence of the numbers of turns in the two coils? How does the voltage across the secondary depend on the current in or the voltage across the primary? If current is taken from the secondary, to light a lamp perhaps, what happens to the current in the primary? Can more current be taken from the secondary than is supplied to the primary?

It will be best to treat questions about currents and voltages in the coils as the central ones, with questions about the iron as profitable sidelines. Some suggested lines of investigation follow. All involve a.c. ammeters for measuring currents, and an oscilloscope for measuring voltages. Some look back towards earlier work on induction; others look forward to later work on self-induction and on magnetic circuits in electromagnetic machines.

a A lamp in series with a 240- or 120-turn coil and an alternating supply will light. What happens if an iron core is put through the coil? Does the current then depend on the iron core being closed? Does it depend on the number of turns? Figure 38 shows some things that might be tried.

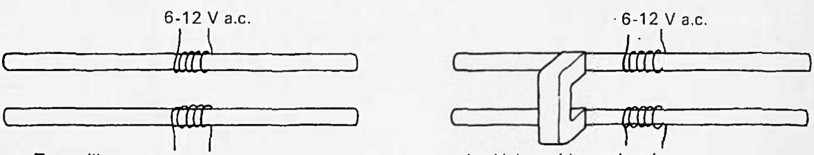


a Lamp goes dim as steel rod is inserted

b Lamp goes out as iron core is closed

Figure 38

b If twenty-turn coils are wound on steel rods, can a voltage be induced in one if an alternating current passes in the other? Does adding iron bridges across the rods help? Can a bridge be placed so as to *reduce* the induced voltage? Figure 39 shows some of the many things that can be tried.



a To oscilloscope

b Voltage bigger than in a

Figure 39
(Continued.)

It is best to warn that the current in the 'primary' may vary and that it might be better to keep it constant as the various arrangements with iron are tried. Twenty-turn coils on steel retort stand rods draw up to 5 A from 12 V, and get hot, but can be used at this current for short periods. In figure 39 *c*, the induced voltage falls as the iron bridges are moved apart, indicating that long lengths of steel do not encourage the greatest flux. Figures 39 *d* and *e* are of interest, indicating that the iron bridge can bypass flux round a coil.

This investigation suggests that flux passes through air, especially if the area offered is big (steel rods overlapped a lot), fairly easily through steel, and rather well through the iron C-cores.

c *Apparatus*

steel rod and 20-turn coil of PVC covered wire

double C-core and 120+120-turn coil

search coil

oscilloscope

transformer

leads

Flux emerges from the sides and end of the steel rod. Little flux emerges from a closed C-core. A 6 V supply is recommended if the 20-turn coil is not to become rather hot.

d *Apparatus*

120+120 turn-coil *2*

steel rod

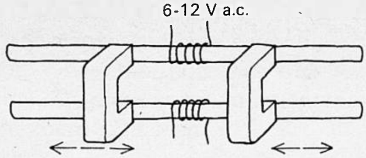
double C-core and clip

oscilloscope

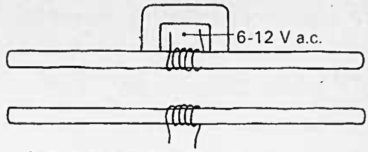
transformer

leads

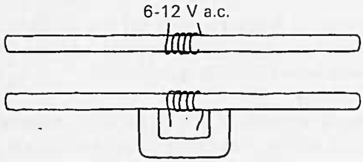
It is simplest to compare the voltages across the secondary, perhaps checking the current in the primary with an a.c. ammeter. The steel rod, it may be noticed, becomes hot (though the coils do not, or not so much), and this can be related to a suggestion that the solid steel is itself a secondary coil of a sort. The iron C-core is laminated to prevent or reduce such a flow of wasteful current in the core. A small gap in the core reduces the flux, reduces the output voltage, and lets the primary current rise a good deal.



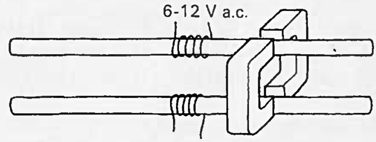
c Voltage large, but reduced if bridges are moved apart



d Voltage less than in **a**



e Voltage less than in **a**



f Voltage not much more than in **b**

Figure 39 (*continued*)

c Possibly arising from **b**, can flux be found emerging from the ends or sides of a steel rod with a coil round it carrying current? Does flux emerge from half a C-core inside a coil? From a complete C-core? See figure 40.

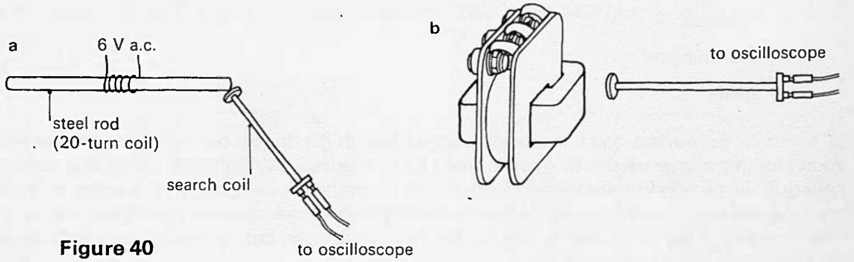


Figure 40

d How does a pair of coils with a steel rod passing through them compare, as a transformer, with the same coils joined by a C-core? Does it matter if the halves of the C-core have a small gap between them (try card spacers)? See figure 41.

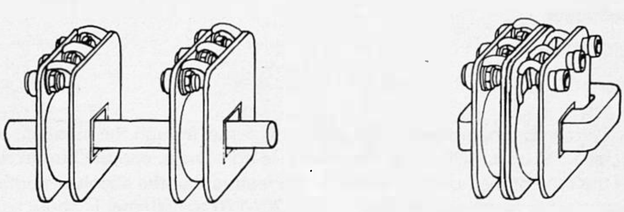


Figure 41

e *Apparatus*

120+120-turn coil

double C-core and clip

oscilloscope

transformer

leads

The voltage induced in the lead is proportional to the number of times it passes (in one direction) through the core. The voltage does not depend on whether the wire is tight round the core, or close to the coil, which is related to 7.11c, in which little flux will be found outside the C-core.

If there is doubt that figure 42 *a* is one full turn (half a turn?), a graph of induced voltage against number of passes through the core will, if extrapolated back to zero, confirm that *a* corresponds to one turn. The topology of turns linking a core is worth exploring, as in figure 42 *c* and other variants like it.

f *Apparatus*

double C-core and clip *2*

PVC covered wire and wire strippers

oscilloscope

transformer

rheostat

a.c. ammeter

leads

20-turn coils will suffice, and if the experiment starts with the double core arrangement, the coils wound for that can be used with a single core (7.11e suggests that tightness of winding does not matter). If the primary current is kept the same, the secondary voltage doubles. Another revealing way of getting the same result is to wind separate primary coils round each core, and have them in parallel. They then each draw the current drawn by one coil on one core, but the voltage across the secondary coil round both cores is doubled.

g *Apparatus*

120+120-turn coil *2*

double C-core and clip

transformer

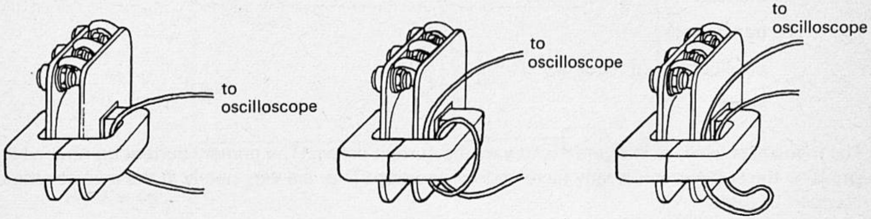
oscilloscope

leads

The secondary voltage is proportional to the primary voltage, though the numbers of turns have been chosen so that, at 12 V, using 120 turns, the core goes non-linear, and the output is distorted. The voltages are in the ratio of the numbers of turns. The feature that the absolute number of turns is relatively unimportant is worth noting (that is, the 120–120 transformer is about as good as the 240–240 transformer).

This investigation is one of the more important of the series, and several students should try it. All should see it done.

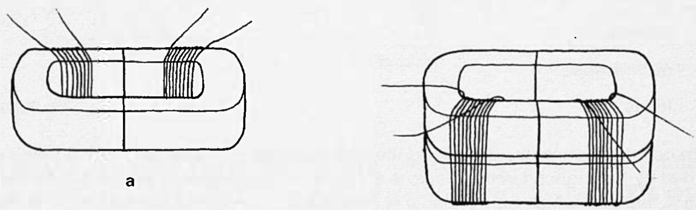
e Use a single lead as a secondary, together with a coil and a C-core. Does the voltage depend on how many turns go through the core? What is *one* turn? Does it matter where the secondary wire lies? Close to the core? Close to the coil? and so on. Figure 42 shows some arrangements of wire that may be tried (see figure 24 and experiment 7.9d, also).



a One turn b Two turns c No turns

Figure 42

f Does the fatness of a core affect the voltage induced in a coil? This can be tried with coils wound first round one core and then round two side by side, keeping the current in the primary the same on both occasions. When this is done, the influence of core cross-section is likely to seem rather obvious: twice as much flux links the secondary, if two cores are used, and twice the voltage is induced. See figure 43.



a b

Figure 43

g How does the secondary voltage depend on the voltage across the primary, and the numbers of turns in the coils? Do the voltages change much if the secondary is used to light a lamp? See figure 44.

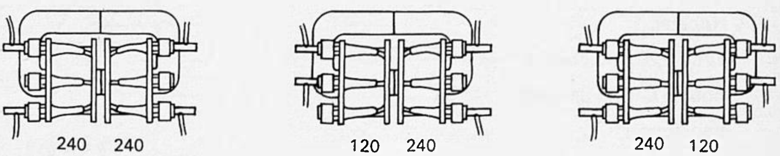


Figure 44

h *Apparatus*

120+120-turn coil *2*

double C-core and clip

a.c. ammeter *2*

rheostat

transformer

oscilloscope (if required)

leads

The rheostat is used, as in figure 45, to vary the current drawn. The primary current on no load is very small, so the two currents nearly increase in proportion. They are very nearly in the inverse ratio of the numbers of turns.

Lamps can be used in place of the rheostat, adding lamps in parallel to draw more current.

This, like 7.11g, is an important experiment, and all should see it done.

i *Apparatus*

double C-core and clip

PVC covered wire and wire stripper

a.c. ammeter

rheostat

transformer

oscilloscope

leads

A 20-turn coil is adequate for producing the flux, currents in the range 0 to 1 A being suitable. The flux, as indicated by the induced voltage across a 2-turn coil, increases in proportion to the current up to about 0.8 A, beyond which non-linearity is detectable. The current can be varied in the range 1 to 5 A if it is not left on too long, when the coil will overheat.

A very simple and important experiment is to find what current is needed to produce the same flux as, say, 0.5 A in twenty turns does, if there are ten or forty turns. The current needed to get the same induced voltage (same flux) is, respectively, twice as much and half as much. Flux varies as current-turns.

j *Apparatus*

120+120 turn coil *2*

double C-core and clip

transformer

double beam oscilloscope, or electronics kit with double beam switch

leads

The voltages across the two coils are taken to a double beam oscilloscope. If the electronics kit double beam switch is used, both voltages must be less than 1 V, which requires a rheostat as a potential divider in the primary circuit, since the lowest transformer tapping is 2 V. Alternatively, item 104, low voltage power unit, can be used to give 1 V a.c. directly.

h How does the current in one coil depend on the current in the other? Is it possible to get more power from the secondary than is delivered to the primary? Is it possible to get more current from the secondary than is delivered to the primary? See figure 45.

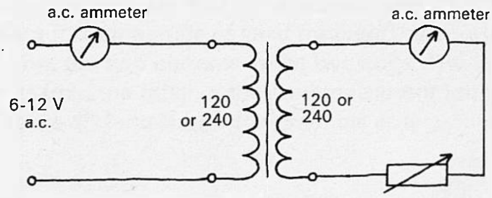


Figure 45

i How does the (maximum) flux depend on the current and the number of turns? If there are more turns, is less current needed to produce the same flux? Is the flux proportional to the current?

Figure 46 shows a suitable arrangement, which uses rather fewer turns so that the current is substantial.

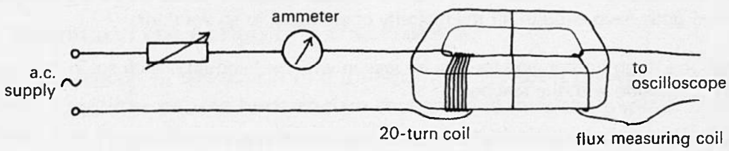


Figure 46

j Ambitious students could follow up **g** and **h** by looking at the relative phases of the voltages across the primary and secondary coils. The worst problem is the simple one of deciding which way round to make connections to the coils so that their windings traverse the core in the same sense. Figure 47 shows connections such that the voltages, correctly, are shown to be in antiphase. (A 'wrong' connection makes them seem to be in phase.)

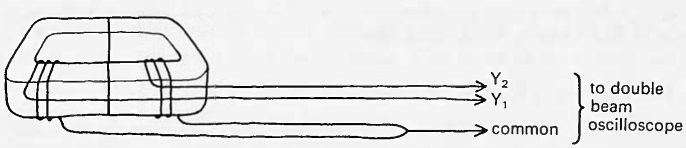


Figure 47

k *Apparatus*

120+120-turn coil *2*

double C-core and clip

PVC covered wire

oscilloscope

rheostat

a.c. ammeter *2*

transformer

leads

The transformer is made to deliver current as in the circuit for 7.11h (figure 45). As shown in figure 48, a 2-turn wire loop round the core, connected to an oscilloscope, is used to monitor the flux when the current drawn is varied.

Depth of discussion of transformer action

The transformer is one of those seemingly simple devices which offer almost inexhaustible depths of possible 'explanation'. We strongly suggest keeping the discussion simple with most students, while offering them practical experience which indicates that much remains unsaid.

The basic understanding outlined opposite, inadequate though it would be for the designer of a transformer, goes deep enough for the majority of students, or so we think.

A few may like to go further, and there is no reason why they should not do so, in their own reading or in private discussion with the teacher.

One line to pursue is the application of a phasor treatment (optional in Unit 6).

Another line is to ask what the effect of doubling the linear dimensions of a transformer would be. The coils would have twice the length, but four times the cross-section, and so would be halved in resistance. The core would also be twice as long, with four times the cross-section: it turns out, analogously to the electrical case, that the same current will now produce double the flux.

But if the primary voltage is the same as before, only half as many turns are wanted in it, as the flux for a fixed current has doubled. This reduces the resistance by another factor of two, a factor of four altogether. The net result is that the losses in the transformer are reduced: it is better just because it is bigger.

More about the effect of scaling electromagnetic machines can be found in Laithwaite, *Propulsion without wheels* and *The engineer in Wonderland.*

Eddy currents and laminations

Eddy currents are discussed in Part Three, but it may be well to mention the importance of laminating the core of a transformer at this stage.

Students' book

See questions 38 to 46, about transformers.

k A fast working student may like to investigate the effect of drawing current on the flux in the core. The surprising thing is that, to a first approximation, there is no effect. The secondary current increases, so does the primary current, and the flux in the core stays much the same. This can be related to the constant amplitude of the voltage applied across the primary. This voltage maintains a constant rate of change of flux, and so a constant flux amplitude at fixed frequency across the primary. Then there is 'extra' flux from the two currents in the two coils. The flux from each current is in antiphase with that from the other, if the currents are not too large, so that the two fluxes cancel. See figure 48 for a suggested practical arrangement.

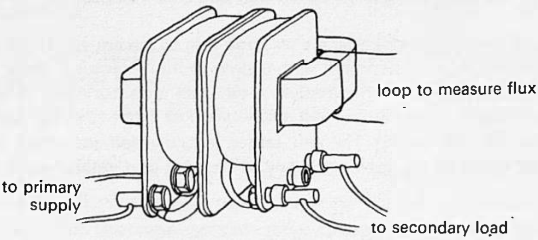


Figure 48

Summary: the action of a transformer

A detailed discussion of the action of a transformer will soon get very complicated, and the investigations should have shown that there is much to explain and understand. But all students should try to understand the simpler aspects of its behaviour.

Much of what follows can emerge out of discussion of the various experiments (7.11).

There is an alternating voltage across the secondary because there is an alternating flux through it. The voltage across one secondary turn is equal to $d\phi/dt$. If the secondary has N_S turns in series, the voltage V_S across it is given by

$$V_S = N_S \, d\phi/dt.$$

If the iron core is a complete ring, pretty well all the flux in the iron goes through both coils, and hardly any escapes round the outside. The voltage V_P across the primary maintains magnetic flux through the primary, and if it has many turns, and the iron core is fat and short, very little current need flow in the primary, so little voltage is needed to drive current through the primary resistance. Almost all the applied voltage V_P maintains a changing flux $d\phi/dt$ through N_P turns of the primary, and V_P is given by

$$V_P \approx N_P \; d\phi/dt.$$

In a transformer with a good iron core, requiring little current to generate the flux if the primary's resistance is small, and if little flux escapes from the core,

$$V_S / V_P \approx N_S / N_P.$$

Textbooks

See:
Baez, *The new college physics*, Chapter 41.

Bennet, *Electricity and modern physics* (MKS version), Chapter 12.

PSSC *College physics*, Chapter 29.

PSSC *Physics* (2nd edition), Chapter 31.

Work on inductors in Advanced Physics

Some teachers will have preferred to omit work on inductors from Unit 6. If so, that work should find a place here. If not, the work suggested below can be used, if necessary, for revision.

Self-induction, as a topic, does not play a very large role in the course. Inductors are needed in Unit 8, *Electromagnetic waves*, in an experiment with a slow motion electrical wave along a row of inductors and capacitors. For that purpose, what matters is what an inductor does. Nowhere is it necessary, for example, to go so far as to calculate the self-inductance of a coil (indeed such calculations are very difficult unless they are very crude). The aim, rather, is to use self-induction as a new kind of problem upon which students can try out their gradually deepening understanding of electromagnetic induction.

Students' book

Questions 50 and 51 are about self-induction. See also question 54.

Demonstration

7.12 Self-induction

1030	high inductance coil
92G	double C-core and clip
92R	m.e.s. bulb (2.5 V, 0.3 A) *2*
92S	neon lamp
92T	m.e.s. holder *3*
1007	double beam oscilloscope
1033	cell holder with two U2 cells
541/1	rheostat (10–15 Ω)
59	l.t. variable voltage supply
1064	low voltage smoothing unit
70	demonstration meter
71/1	dial for demonstration meter, d.c. dial 1 A
71/3	dial for demonstration meter, d.c. dial 5 V
71/8	dial for demonstration meter, a.c. dial 1 A
1017	resistance substitution box
1000	leads

The transformer itself contains no source of energy; indeed some energy transformed by it must go to warming it up, because the coils have resistance (and also because the iron becomes warm when its magnetization is switched to and fro). The electrical power out of the secondary cannot exceed that into the primary. If the currents are I_S and I_P, then

$$I_P V_P > I_S V_S$$

and $$I_S/I_P < N_P/N_S.$$

Many transformers have such modest losses that the inequality is almost an equality.

Self-induction

Many questions about self-induction will inevitably have arisen during the investigations of transformer behaviour, particularly when the changes of current in a primary when iron was inserted into it were noted.

Inductors may have been introduced in Unit 6, *Electronics and reactive circuits*, being treated there in a wholly empirical way. The reasons for the behaviour of coils which seem to induce voltages in themselves can now be cleared up a little.

If there is current I in a coil, there will be a B-field in the coil. Let the flux crossing the coil's area be ϕ. The bigger the current, the bigger the flux. If the current rises, the flux linking the coil rises. How does one write down the voltage across the coil for a certain rate of change of flux? As before,

$$V = N\mathrm{d}\phi/\mathrm{d}t.$$

Let $N\phi = LI$, where L may sometimes be constant.

Therefore $$V = L\mathrm{d}I/\mathrm{d}t$$

which is how the self-inductance L was introduced in Unit 6. A voltage V is required to achieve a rising current in a coil.

Demonstration

7.12 Self-induction

The argument above can be illustrated and amplified in discussion around some simple experiments, showing the effects of inductance, and making a measurement of the inductance of a coil.

7.12a The behaviour of an inductor

Experiment 7.12a repeats experiment 6.12 from Unit 6, and could be omitted.

Figure 49 shows circuits for two simple demonstrations. In figure 49 *a* a 2.5 V lamp is lit in series with the inductor. Adjust the rheostat connected to the second lamp so that it is lit as brightly as the first. When the switch connecting both lamps to two cells is closed, the lamp in series with the inductor comes on after the lamp in series with the resistor.

Figure 49 *b* shows an inductor in series with a resistance of about 5 Ω, across which leads go to an oscilloscope to indicate the changing current in the circuit. When the switch is closed, the current grows gradually, with a time constant of the order of one second. For simplicity, raise the gain of the oscilloscope, to about 0.1 V cm^{-1}, so that only the first, almost linear portion of the trace is seen, as in figure 51 *c*. The complete rise in current will ultimately flatten out at the maximum current, and may also show a sudden change in its rate of increase if the core goes non-linear as in figure 51 *d*. Using more than one cell will make this difficulty worse.

It is best to arrange for the oscilloscope spot to rise linearly and go off the screen before there is very much flattening out of the curve. The gain can be reduced afterwards, to show that there are complications.

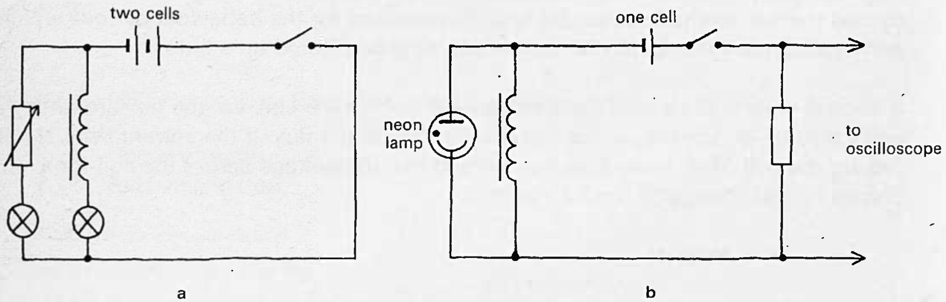


Figure 49
Simple inductor experiments.

7.12a The behaviour of an inductor

If a coil has self-inductance, it will take some time for a battery to increase the current in it enough to light a lamp, since the rate of rise of current can be no larger than that capable of being produced in that coil by the available voltage. And indeed, a lamp in series with an inductor comes on later than one in series with a resistor.

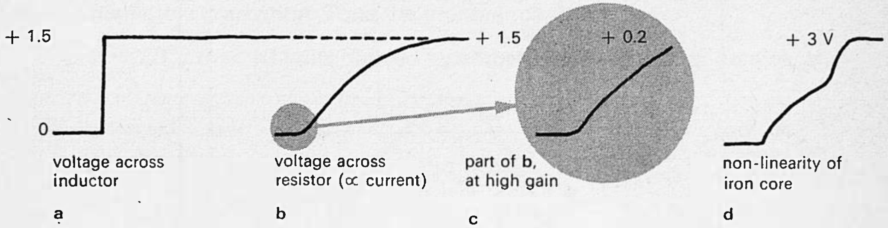


Figure 50

The slow rise of the current can be watched on an oscilloscope connected across a resistor in series with the inductor. While the current is small, so that little of the battery voltage is used in keeping this current going through the circuit resistance, the rate of rise of current is constant, there being a nearly constant voltage across the inductance.

The inductance can be estimated roughly from the rate of rise of current (see Unit 6, experiment 6.12) but the next experiment offers a rather better measurement of the inductance of the coil.

7.12b Measurement of self-inductance

When connected to a 5 V, smooth, d.c. supply, the inductor carries a little under 1 A, so its resistance is 5 or 6 ohms. Inserting the iron core makes no difference, except for a dip in current as it goes in.

Connected to an a.c. supply of similar voltage, the coil on its own conducts rather less than before. When the iron core is put in, it conducts much less; the current cannot now be detected on a meter of range 0–1 A.

The reasons for this behaviour, probably familiar from earlier experiments (7.11) can be argued out. The alternating current is continually changing. The largest voltage available sets the limit on the largest rate of rise or fall of current, and so on the largest current that flows, since if the frequency is fixed, the current has to change by the greatest magnitude every quarter cycle.

The current can be observed by using an oscilloscope connected across a resistor in series with the inductor. The resistor can be as large as 100 Ω, more than ten times the resistance of the coil, and yet have only a small part of the p.d. across the circuit across itself. With about 20 V across the circuit, the maximum p.d. across the resistor may be less than 1 V, so that the maximum current in the circuit is less than 10 mA.

7.12b Measurement of self-inductance

To show first that the resistance of the coil is low, connect it in series with a 1 A demonstration meter, with a 5 V voltmeter across it, to the *smoothed* output of the l.t. variable voltage supply. Insert the core, and remove it again. The effect on the current is transient.

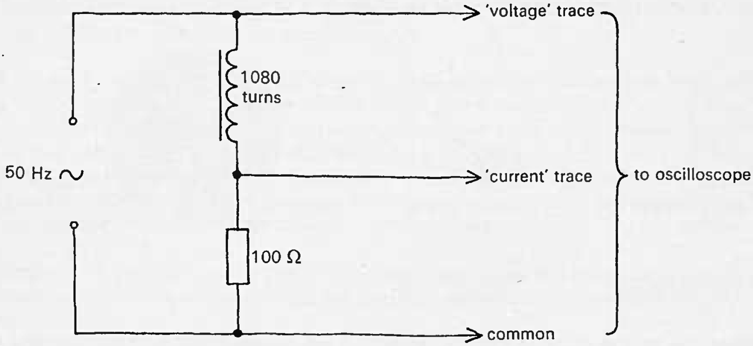


Figure 51
Measurement of inductance.

Now try the a.c. output of the supply, having removed the voltmeter and replaced the d.c. 1 A scale by an a.c. 1 A scale. The current is small, and becomes undetectable when the core is inserted.

Replace the ammeter by a resistance substitution box, set at 100 Ω, in the circuit of figure 51. If leads across the resistor are now taken to one oscilloscope beam, sensitivity 0.2 V cm^{-1}, with the oscilloscope triggering negatively from this beam, and the time base set at 2 ms cm^{-1}, one cycle of the 'current' trace taken across the resistor can be made to fill the screen. By adjusting the X and Y shift controls, and the voltage from the l.t. supply, it is not difficult to set the most steeply sloping part of the curve in the middle of the screen, as in figure 52, and to adjust its slope to a conveniently measurable value.

The voltage across the whole circuit can now be taken to the other beam, as in figure 51, using a sensitivity of about 5 V cm^{-1}. Measure the maximum value of this voltage, as in figure 52.

The inductance is the ratio of the maximum voltage to the maximum rate of change of current, the latter being deduced from the slope of the 'current' trace.

The voltage across the resistor is a negligible correction. The point can be avoided by measuring the voltage across the inductor itself (neglecting the even smaller voltage across its own resistance), but this has the disadvantage that the two traces are not seen together, unless the junction between resistor and inductor is made the common connection to the oscilloscope, when the phase relationship is changed through 180°.

The simplest way round the difficulty is probably to use the circuit of figure 51, measure the maximum p.d. across the resistor, and so show that it is much smaller than the p.d. across the whole circuit. Any attempt to allow for the voltage across the resistor would have to take account of the phase difference between the two voltages.

What matters is how fast the current changes. The maximum rate of change can be estimated from the oscilloscope trace, as in figure 52, and may be 0.4 V across 100 Ω, or 4 mA, in 2 ms. The fastest rate of change of current is then about 2.0 A per second.

The fastest rate of change of current should coincide with the largest voltage across the inductor, which may be 20 V. The p.d. across the resistor is, as has been shown above, a negligible correction. Thus the inductance L is

$$L = 20/2.0 = 10 \text{ volts divided by amperes per second, or henries, H.}$$

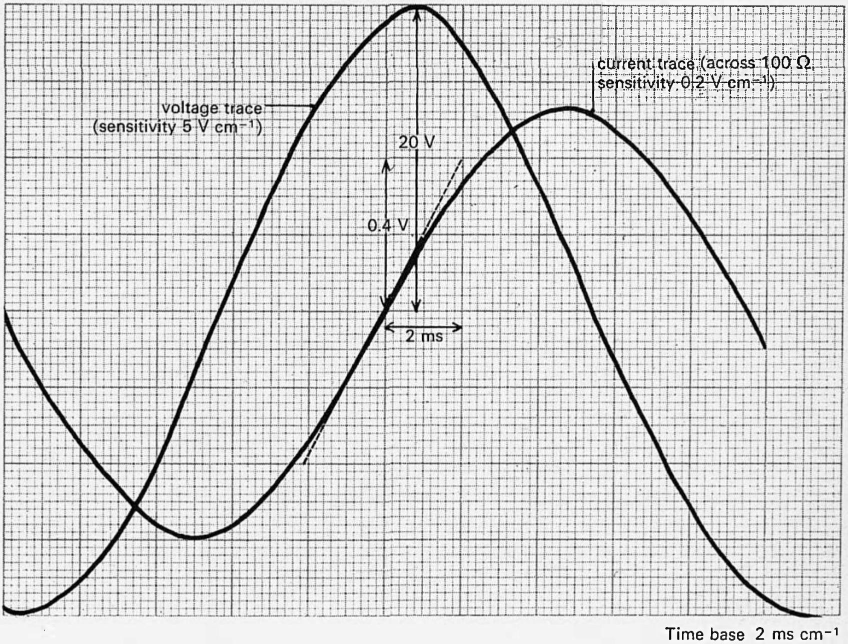


Figure 52
Oscilloscope traces used to measure an inductance.

Part Three

Flux near currents

Time: up to two weeks.

This Part could easily take longer than it deserves, not least because, since some of the material is unfamiliar, the *Guide* is necessarily rather long. Much of it will succeed better at a fair pace than if it is taken in a slow and detailed fashion.

The suggested pattern of Part Three

The suggested development for Part Three begins by looking at what has been neglected so far, the size and shape of fields produced by currents. This is not based on such rules as the formula for the field of a current element, followed by a series of integrations, but upon careful measurement and comparison of the measurements with various formulae. The course so far has tended to lack such quantitative investigations of functional relationships, and that aspect of what physicists do deserves some place. It should help to give careful measurement the emphasis it deserves, which is not much, but a little; that little being concentrated on cases where a careful measurement will reveal a difference that an inaccurate measurement will not. Formulae for the fields of wires and coils are ideal in this respect: they come in great variety, with simple ones and harder ones, and many are approximations valid in some limiting case.

Such a choice involves sacrifices. Students will emerge not able to pass from the current element formula to one for a long wire, for example. In our judgment, the sacrifice is worth making. Naturally, mathematically gifted students can be shown where to find the integrations, if it would give them pleasure to see how a whole variety of relationships can stem from just one rule. But this is not a part of the course.

The next step suggested is to link together what was found out about transformers, that flux depends on current turns, with a similar rule for the field in a solenoid, generalizing this to a simple form of Ampère's rule, that *field* × *length* is proportional to current turns. Applied to a path round a straight wire, this rule allows the ampere definition to be linked to the constant μ_0, which is the constant in the proportionality above.

Finally, the threads of the Unit as a whole are brought together in a discussion centred around the design of induction motors, where most of the ideas offered earlier are used again.

B and *H*

As explained in the Introduction, B is used in this Unit, but not H. This means that some of the relationships in Part Three are, as they stand, applicable only to a vacuum, and some cautious noises about extending them to all circumstances would be in order. H is present, in the guise of current turns per metre, which are the cause of a magnetic field, just as H, in similar circumstances, can be regarded as the cause of the B-field. (The purist will observe here that 'cause' needs some thinking about, as H does not precede B in time.) We think that densely packed current turns, which a student can see in front of him, are a better way of first getting to grips with the idea than is a second abstraction, H.

Students' laboratory book

Suggestions are made in the *Students' laboratory book* of coil and wire shapes to try in the quantitative investigations of fields from currents, in experiment 7.13. In particular, the notes suggest appropriate currents to use in various circumstances, with particular field detectors, so that time need not be spent on rough trials, but can be given over to the matter of making careful measurements.

Not much is said, however, about the form of relationships to test, as what each student needs to know beforehand will vary. Some students will work best if they are given the $1/r^3$ law for a small coil, and then try it. Others will enjoy trying to fit data to various forms of law. Some will be able to cope with more complicated functional relationships; others will need simpler problems, such as, 'Does the field of a flat coil always go through the plane of the coil at right angles to that plane?'

Suggestions of possible problems are made below, for the teacher to select from. Each group of students need only do one, or at most two, investigations.

How can strong fields be made?

This may be a good question with which to begin the work of Part Three, which is at first concerned with how much field can be got from currents in wires in various arrangements. The general answer should already be clear from previous experience in Part Two: to get a big field one needs lots of current, lots of turns, and maybe some iron would help.

But other questions arise. How are the wires best arranged to make a strong field? Must as many wires as possible be as close as possible to the place where the field is wanted? Just how much field could one expect to get from a given amount of copper? How does the field fall away as the distance from a wire or coil is increased?

The quantitative investigations that begin the work of this Part bear upon such questions.

It is, as it happens, possible to find rules, analogous to the inverse square law for the electric field, but more complicated than that rule, which allow one to calculate the field of a suggested coil shape by adding up the contributions of all the bits of the coil. Indeed, books on electromagnetism are full of such calculations. The trouble is that the calculations are only reasonably easy for simple arrangements of wires such as long straight wires and circular coils. Although such calculations play a part in designing, say, a new sort of motor, there is often no substitute for measuring the field, especially if iron is used. So for a first look at the field produced by currents, measuring the field will take precedence over calculating it.

There is a whole variety of rules for how fields vary with distance. The field of a long wire varies as $1/r$, while that of a small enough coil varies as $1/r^3$, r being the distance from the wire or coil to the place where the field is measured. Other rules give the field direction. These rules can be found in books, and they are not worth learning by heart. One thing that is worth doing is to find out by experiment which rules work in what circumstances. Testing a suggested rule against the results of careful measurements is something scientists do a great deal, and is of interest here because most of the rules are only partly true; they usually rely on some extra conditions, such as, '*only if the long wire is very long*'.

So the next experiment is about measuring the field of a wire or coil rather carefully, varying the distance, or the turns, and similar relevant things, and seeing whether the measurements agree with a rule, or if they set limits on the application of a rule.

A useful by-product of such experiments is a widened firsthand acquaintance with the fields of various things. This is a useful experience if one needs, say as an engineer, to make a guess at the shape or strength of the field from some new complicated coil shape for which calculations would be very long. For example, does it make any great difference if the wire in a round coil is squashed into a square shape? Trying it on the bench is easy; working it out on paper is a good deal harder.

7.13 Fields around electric currents

Field measuring devices:

either

1038 Hall probe and circuit box

1001 galvanometer (internal light beam)

or

1039/1 axial search coil

1039/2 lateral search coil

158 class oscilloscope

Conductors:

either

101 large Slinky

30 slotted bases *2*

1053 wooden strips (e.g. rulers, to support Slinky) *2*

52K crocodile clips *2*

or

1037 set of solenoids

or

1042 magnetic field board

92X reel of 26 s.w.g., PVC covered, copper wire

or

1058 coil with 120+120 turns

or

1030 high inductance coil

Sources of current:

either

176 12 volt battery

541/1 rheostat (10–15 Ω)

1003/5 ammeter (10 A)

or

27 transformer

541/1 rheostat (10–15 Ω)

1057 a.c. ammeter

or

1009 signal generator

1057 a.c. ammeter (or 1005 multi-range meter)

All require:

1000 leads

7.13 Fields around electric currents

As suggested previously, all the investigations in this series involve careful measurement of a magnetic field, and comparison of the measurements with some mathematical rule about how it should vary.

For later work in the course, investigations of the fields of a solenoid and of a long straight wire are essential. Others, such as the fields of large circular coils, small coils, and wires placed into other shapes, can be deployed according to the number of students, their tastes, and their abilities.

Two tools are available for measuring fields; the Hall probe and the search coil (the current balance is not accurate enough). The first will measure steady fields made by direct current, the second will measure alternating fields made by alternating currents. As was said in Part Two, the maximum voltage across a search coil is proportional to the maximum field at the coil, at a fixed frequency. If the voltage is too low for comfort, raising the frequency may help, by making the field change faster. At, say, 10 kHz, the search coil is a very sensitive detector.

Both tools will reveal the direction of the field, which is at right angles to the coil or Hall slice when the indication from either is largest.

Possible investigations

The field of a solenoid can be investigated in two ways, using a Slinky spring or the set of solenoids.

A long wire can simply be a piece of wire stretched out along the bench.

Other shapes of coil can be wound over pegs placed on the magnetic field board, and a wide variety of investigations are possible. For instance, of the effects of length of wire, size of coil, shape of coil, or distance from a coil. A small ready made coil can also be used (120+120 turns, or 1080 turns).

Slinky solenoid

See figure 53. A simple problem is, 'How does the field at the centre change, when more and more turns are used, if the current is held constant?' The Slinky is easy to stretch, so another question is, 'How does the field at the centre change if the current-carrying turns are spread out more?' Here it would be possible to say beforehand that the textbook rule is that *field* × *length* is constant, or that *field* is proportional to *turns* divided by *length*, as long as the length is big (find out how big).

The field at the end is reputed to be equal to half the field at the middle. Is this correct? This is of interest because the field at the end varies rapidly with distance, and care is needed to test the assertion (plot a graph).

Slinky solenoid

The Hall probe can be used, with a few amperes d.c. in the coil, but the laterally mounted search coil is more convenient. The field at 3 A a.c. is big enough to make it unnecessary to use a frequency higher than that of the mains, and the apparatus shown in figure 53 is the most convenient arrangement.

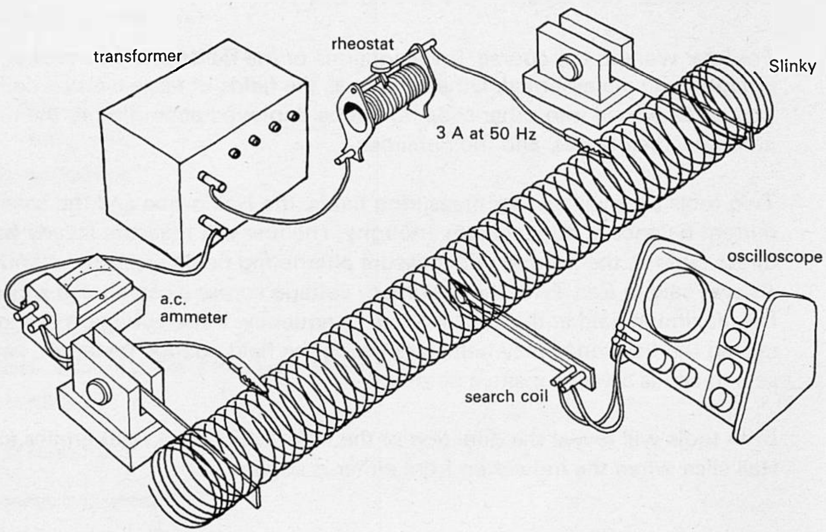


Figure 53

Set of solenoids

The solenoids may be used equally well with the search coil and a.c., or with the Hall probe and d.c. 1 A is a suitable current in either case.

Depending on the problems set, it may be better to split up the set of four solenoids (two winding densities, two areas) amongst different groups of students, to offer them in pairs, or to give them out as a set of four.

As a reminder, it is useful to give one group two or three steel rods, so that the fact that the presence of magnetic material in the field may alter the field is not forgotten.

The field in a long solenoid does not depend upon its shape of cross-section, even though most books discuss only the circular shape, perhaps because of ease of integration, or perhaps from habit. If a circular-section solenoid can be compared with a square one (or with the flat solenoid, item 1079) so much the better.

At high frequencies, the fields of solenoids surrounding one another may seem not to add. This is because of the effect of their mutual inductance.

The field outside is said to be zero, but the field inside is said to be uniform across the width of the solenoid. This too can be tested. The wide-awake student may notice that there is a field outside, circulating *round* the solenoid, which can also be regarded as a long wire.

Those who like difficult problems could have a general formula for the field along the axis of a finite solenoid, and test that, but this should be a rarity.

Set of solenoids

See figure 54. The set contains solenoids having two turn-densities and also two cross-sectional areas. Possible problems are similar to those suggested for the Slinky solenoid. Some additional ones follow.

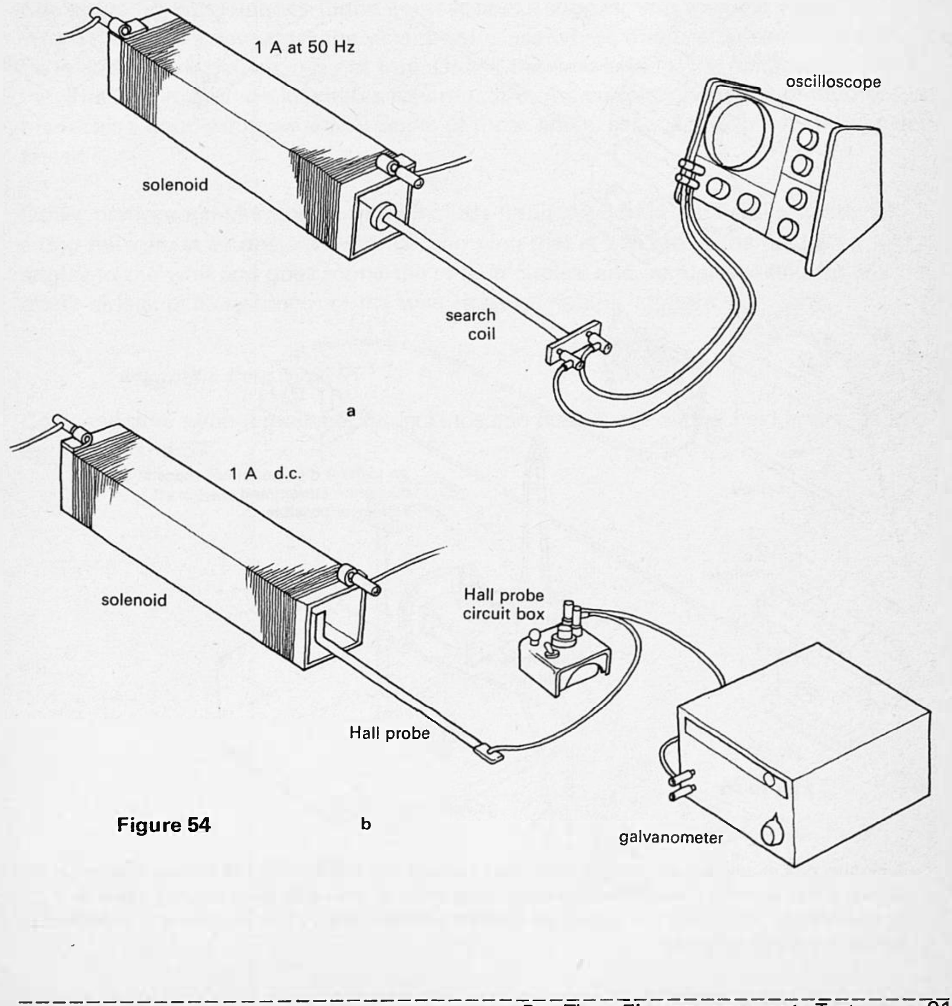
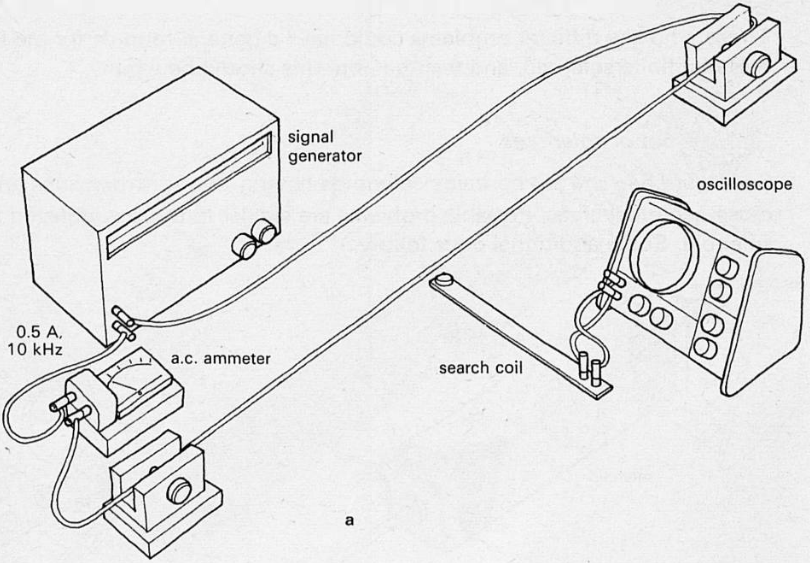


Figure 54

Long straight wire

The wire should be at least a metre long, stretched between bases as in figure 55. The field is small, so if the search coil is used, a high frequency current (10 kHz) from the low impedance output of the signal generator is advisable. Less conveniently, the Hall probe can be used, if a d.c. current of up to 10 A is available.



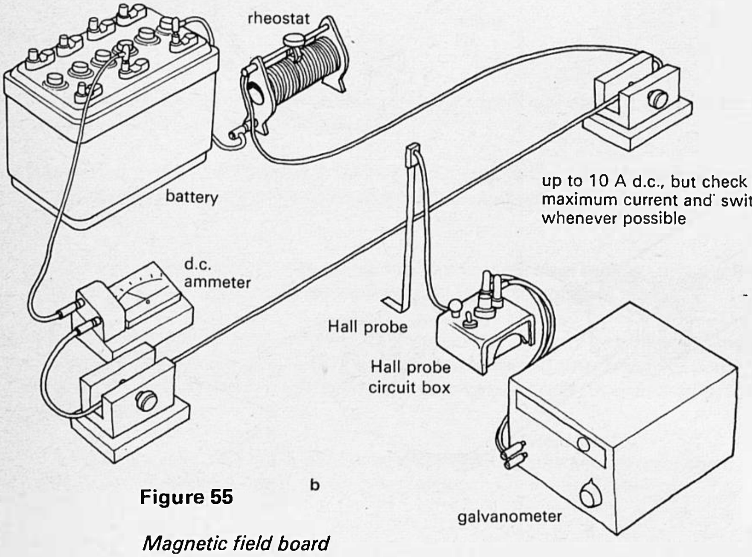


Figure 55

Magnetic field board

A circular coil of several turns can be used with a search coil and a current of several amperes at 50 Hz, or with a Hall probe and several amperes d.c. Large coils, or ones with few turns, are easier to investigate with the search coil and a high frequency current, say 10 kHz from the low impedance output of a signal generator.

Does the area of the solenoid matter? Is the field proportional to the density of turns? Do the fields of solenoids slid over one another add together? (This produces a problem, since, if two coils are first tried separately, and then together in parallel connection, the current divides between them, and the field inside both may be the same as the field inside either. In series, with the same current in both, the fields add together, or subtract.)

Along what fraction of the length is the field constant to within five per cent? Calculations suggest that it will be a fixed multiple of the width – test this. The field between two solenoids, end-on, ought to be equal to the field at the middle of either (if they are equally densely wound). Is it?

Long straight wire

See figure 55. Calculations found in most books suggest that the field varies as $1/r$, where r is the distance from the wire to the place where the field is measured. This can be tested and, of course, it is not true. Only if the wire is long, the distance r is small, the wire is thin, and the inevitable return path of the current is well out of the way, is the result a good approximation. Some of these limits, especially that of length, can be tested.

Other, perhaps simpler, things to try include finding whether the field is steady all along the wire at a constant distance; showing that at one place, the field is at right angles to the wire and goes round the wire in circles, and, harder, looking for any effect of lack of straightness of the wire (how straight is 'straight'?).

Magnetic field board

Coils and wire arrangements of many kinds can be laid out on the field board, as in figures 56 and 57.

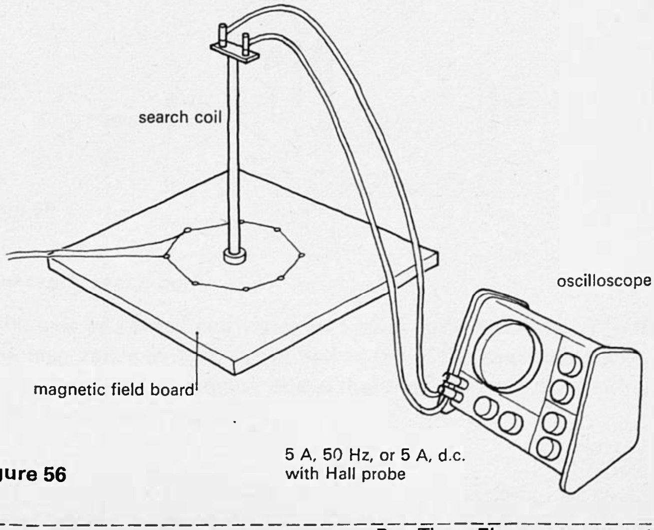


Figure 56

A difficulty appears at high frequencies, if the geometry of the circuit is being varied. The self-inductance changes if extra turns are wound on, or if the size of the coil is changed, and a high frequency current will not be constant, even though the generator output is left unaltered. An Avometer, or a resistor with an oscilloscope across it, to monitor the current, is advisable.

The field board consists of a perforated board, with non-magnetic pegs around which PVC covered wire can be wound to make various shapes of coils. The shape of coils is easily changed, and there is no reason to prevent students from trying square, rectangular, or even more eccentrically shaped coils.

Figure 57 shows some possibilities. As a rule, single conductors should be used with a search coil at 10 kHz; coils with several turns can be used at 50 Hz, or with d.c.

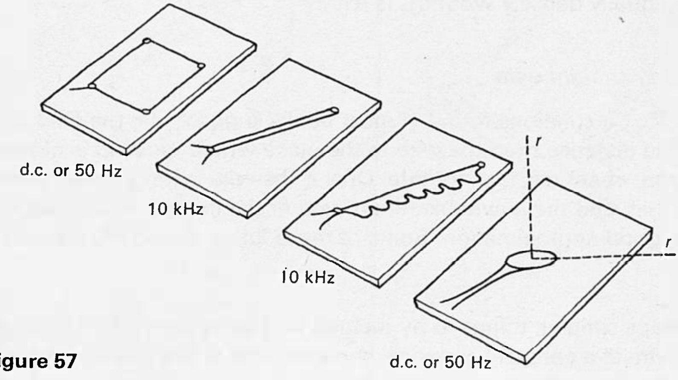


Figure 57

Small ready made coil

One of the coils made to fit the C-cores can be used as a compact coil having many turns. It is simplest to use 50 Hz a.c. and a search coil.

The circular coil offers several relationships to be tested. At constant current and radius, the field at the middle should be proportional to the number of turns. For fixed numbers of turns, the field at the centre should be inversely proportional to the radius.

Everywhere on the board, the field should go through the board at right angles to its surface – does it? The field near the centre should be a minimum for sideways displacements of the probe, but a maximum for displacements along the axis – a sort of three-dimensional saddle point. The formula for the variation of the field on the axis of the coil could be given, for trial. It is worth pointing out that this formula is about all that can be derived by simple integration. It is much harder to calculate the field anywhere off the axis, whilst measurements there are easy to make. Over what area, or volume, is the field constant to within ten per cent? This result may usefully be linked to the use of a pair of circular coils in experiment 7.6 to deflect an electron beam.

Do the leads to the coil have a field, if they are close together? Two wires can be laid side by side on the board, as in figure 57, and the absence of a field found. A fundamental experiment is also shown in figure 57: one of a pair of wires is made very kinked, but following the same path as the other. The net field is still zero. This relates to the fact that current elements can be resolved, and is similar to one of Ampère's famous series of experiments.

A small coil can also be tried, though a ready made one may be more convenient (see below).

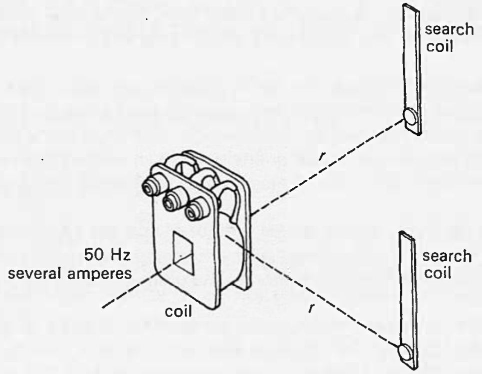


Figure 58

Small ready made coil

The field on the axis of a small coil varies as $1/r^3$ at large distances. The field to its side, figure 58, also varies as $1/r^3$, but is half as big at the same distance. Such relationships can be tested. A simpler one is that the field anywhere should be proportional to current and to turns.

Ampère's Law and the magnetic circuit

The argument developed from here to page 119 uses Ampère's circuital law (relating the field around a closed path to the current-turns enclosed) to move from the solenoid field to that of a long wire, and so to introduce the ampere definition and the value of μ_0.

The development is unusual, though not new. It arose out of worries about various approaches investigated during the trials but, as an attempt to deal with these worries, it has not – in the nature of a Project of fixed duration – itself had much trial. It may yet prove harder than we suppose, and Appendix B offers an altogether different treatment. (See also question 57 in the *Students' book*.) We hope, however, that it may prove easy and vivid. It has the virtue of linking the formal matters above with the practical engineer's problem of estimating how much flux will be present in a device. This is achieved by thinking of flux as like a flow driven around a circuit. If the approach is to work, the idea of flux as a flow will need to be presented with a sort of cheerful literalness (despite a word of two of caution).

Some of us like the approach because it offers scope for the future engineer to see in what sort of way engineers use ideas. But the adding up of flux around a closed path is also a practical expression of a deep idea – the circuital law – which in later years may be generalized to the Maxwell equation which links the curl of the magnetic field to the current density. So the approach has theoretical merits too, offering in some sense a concrete realization of the meaning of the curl of a vector field.

We wish to acknowledge our indebtedness to Professor E. R. Laithwaite for many of the ideas used in this approach, though he is not to be held responsible for the use or misuse we have made of them.

Time

The argument as far as Ampère's Law is concerned should not extend beyond a lesson or so.

Is flux really a flow?

In so far as physicists understand the electromagnetic field, they do not think of flux as the flow of anything corporeal, in the sense that a river is a flow of water which can be collected in tanks.

The equations which describe magnetic flux are identical in form with some of the equations which describe the flow of an ideal, non-viscous, incompressible fluid: a fluid graphically called 'dry water' by Feynman, following the mathematician von Neumann. A prediction made about the flow of such a fluid is therefore likely to have a counterpart or analogue in an electromagnetic problem. So one might say, 'If I want to say that flux is like a flow, I may do so', and no one could dispute the point.

The issue is not one of 'the truth', or of the 'real nature' of flux. No one simple criterion of truth can be applied to the use of models in science. Every scientific statement involves relating one thing to other things, and does not represent a final penetration to the ultimate heart of the matter.

The issue is one of tactics. For some problems, the comparison of flux with a flow of 'something' is very helpful, not least in aiding intuition. For others, it may not be to the point, or may even be positively unhelpful. Since it *is* helpful for the kinds of simple argument made at this stage in the course, we use it without inhibitions.

The flow of flux round currents

Magnetic flux is like the flow of something; like the flow of water, or of electric current, or of air past your face. It need not *be* the flow of anything, but it is *like* the flow of something magnetic.

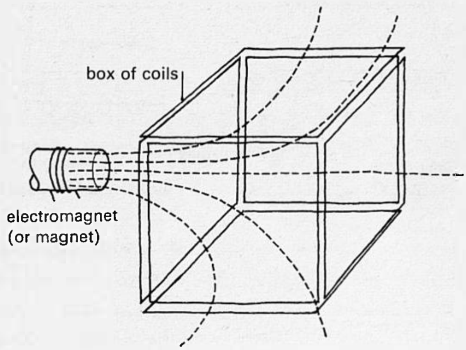


Figure 59
Flux passing into and out of a space.

The analogy is illustrated by an earlier experiment (7.10g) with a box of coils surrounding a space, shown again in figure 59. The voltage induced in each coil indicates the flux through it; together, the voltages add up as they should if as much flux leaves the volume the coils surround, as ever enters that volume. Flux does not 'get lost'. The total output from the coils indicates the rate at which flux is building up inside the box, and this rate is always exactly *zero*. It would be just the same for the flow of an (incompressible) fluid. A similar rule applies to the flow of currents in circuits.

Some of the consequences of this imaginative comparison are now explored.

Flux down a solenoid 'pipe'

A solenoid looks like a pipe. So far as flux is concerned, it *is* very much like a pipe, with flux 'streaming' uniformly along it. Suppose that the flow idea is worth taking seriously, for a solenoid. The results of earlier experiments with solenoids (7.13) can be used as a guide to thinking.

What causes there to be any flux in a solenoid? (Current in the wires round it.) To increase the flux in a solenoid of given size, without using more current, one could wind on more turns. So current-turns NI are, for flux, what pressure is for the flow of water in pipes, or what voltage is for the flow of electricity in wires; that is, the thing which drives the flow.

$$NI \propto \phi.$$

E

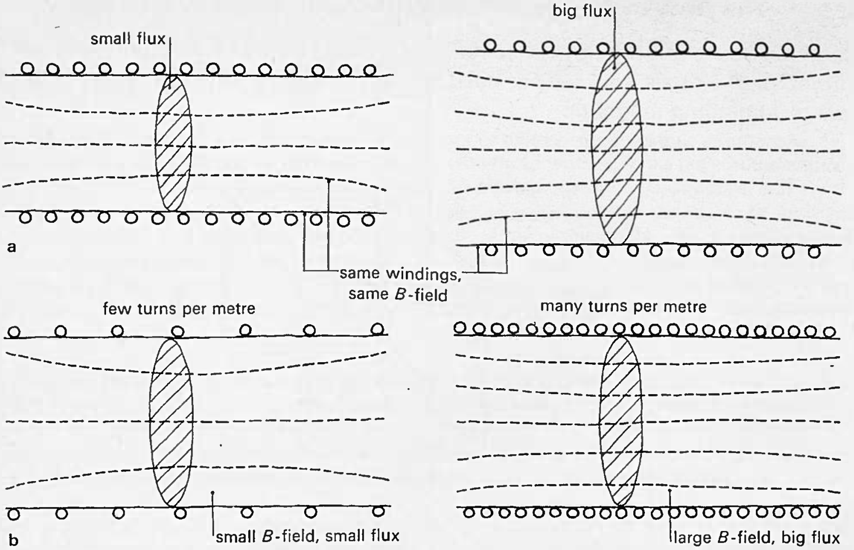


Figure 60
Field, flux, turns, and area in a solenoid.

Students' book

See questions 52–53.

The quantities μ_0 and μ_r

Three names for μ_0 may seem excessive. The trouble is that what μ_0 'is' depends upon what kind of problem one happens to be concerned with. Appendix A gives a further discussion of the place of μ_0 in the logic of electromagnetism.

Note that μ_0 has dimensions (unit N A^{-2} or H m^{-1}), and that in the SI, its value is settled by decision, not by measurement. For that reason, its value appears later on in the work of the Unit (see page 115). μ_r, introduced below, is a very different beast, though for the flow analogy it is convenient to ignore some of the differences. It is a numerical factor, without dimensions, relating the magnitude of the flux in a material substance to that in a vacuum. It can, at least in principle, have its magnitude *explained*, if a good enough model of the material can be invented. μ_0, by contrast, calls for no such explanation.

How does the current flowing in a wire with a certain voltage across it depend on how fat the wire is? (The current increases in proportion to the cross-sectional area.) Does the flux in solenoids of differing cross-section vary in this way too? (Yes.) Figure 60 *a* illustrates what was found in earlier experiments (page 55): that the flux is proportional to the area A (or that ϕ/A is constant, other things being equal).

$$NI \propto \phi/A.$$

What happens to the flux if the same number of turns is stretched out over a greater length L? (The flux decreases, in inverse proportion to L.) Figure 60 *b* illustrates the results of such experiments, which may need to be demonstrated again. (See page 89.)

$$NI \propto \phi L/A.$$

All this works so easily because the flux simply streams in straight lines along the solenoid 'pipe', as one might have guessed from symmetry alone, if one had not seen it in experiments showing that B is uniform within the solenoid. Other, more complex field patterns are harder to cope with.

One may want to ask, 'How do the current-turns reach round outside themselves to drive the flux?', but no answer can be given in terms of the ideas given here. The comparison is between how things behave, not a suggested mechanism.

'Magnetic conductivity'

The constant in the proportionality is usually written $1/\mu_0$, giving

$$NI = \phi L/\mu_0 A.$$

Compare this with an analogous equation for the electric current in a wire of length L, cross-sectional area A, under a potential difference V:

$$V = IL/\sigma A = IR.$$

The constant $1/\sigma$ is the *resistivity* ρ of the wire. σ is the *conductivity*.

Comparing the two equations, μ_0 and σ are seen to play similar roles in them. In that sense, one might playfully call μ_0 the 'magnetic conductivity'; a measure of how easy it is for current turns to make flux in the space inside a solenoid. But the comparison implies no greater similarity than a likeness in the places of two terms in distinct equations.

μ_0 has other names; the *permeability of free space* is the official one, for what it is worth. Because it relates also to the forces that currents exert on one another, via their magnetic fields, it might also be called the *magnetic force constant*. Its value, which is intimately connected with the ampere – the unit in which the currents that exert these forces are measured – will appear shortly. An engineer who makes use of flux in transformers, motors, and dynamos, might be more interested in how to increase magnetic conductivity, so as to get more flux for his money.

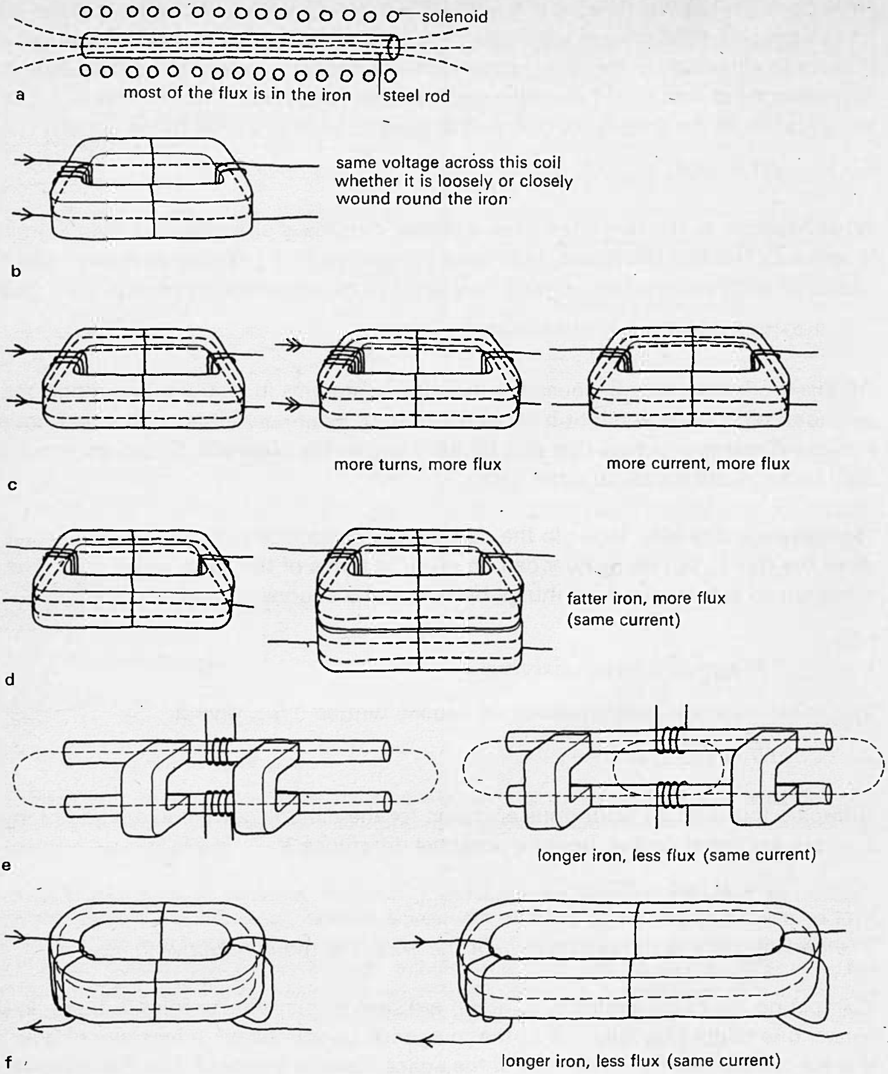


Figure 61
Flux in iron cores.

Flux and length of iron

Figure 61 *f* shows an experiment that will have to remain an imaginary one, unless suitable extra lengths of iron of the same material used for the C-cores (item 92G) become available; and assuming also that the problem of avoiding extra air gap effects can be overcome. For the present, the rather inadequate experiment shown in figure 61 *e* may have to serve.

Flux in iron

If an iron rod is put into a solenoid, the flux increases (for constant current). Iron seems to be less reluctant than air (or empty space) to let flux pass. Indeed, an iron rod or core is so much more willing for flux to pass than air is, that when iron is introduced into a coil, the total flux increases a great deal, and the flux in the air becomes unimportant compared with that which goes through the iron. Figures 61 *a* and *b* illustrate earlier experiments showing this property (7.10f and 7.11e). In a closed iron ring, the flux seems as if it circulates round in this solid iron 'pipe', staying more or less within the iron.

Other experiments, also illustrated in figure 61, have indicated that the flux is (within limits) proportional to current-turns (7.11i); that the flux is larger the greater the cross-sectional area (7.11f); and that the flux seems to be smaller the longer the length of iron. Those points which need demonstrating can be shown now.

A flow-rule, like that for the solenoid, sums up the results:

$$NI = \phi L/\mu_r\mu_0 A.$$

μ_r is a numerical factor, which expresses how much better iron is at 'conducting' flux than is the same shaped piece of empty space. It may be as big as 1000, though it should not always be expected to be constant even for one material. Looked at in another way, iron 'conducts' flux well because it becomes magnetized, and so makes a lot of extra flux of its own. From this point of view, μ_r is related to the extent to which iron is magnetized by a given number of current turns wrapped round it.

Reluctance

In the equation

$$NI = \phi L/\mu_r\mu_0 A$$

the part $L/\mu_r\mu_0 A$ is analogous to the resistance R in

$$V = IR \quad (R = L/\sigma A)$$

and has been given the name *reluctance*.

Electrical engineers work out the flux in iron-containing machines in much the same way as they work out the current in a circuit, or as heating engineers work out the flow of water in a system of pipes provided with a pump. Figure 62 *a* illustrates the analogy.

An air gap in a magnet (figure 62 *b*) is like a section of high resistance wire, or a long narrow pipe. A small gap makes a lot of difference since its conductivity is low ($\mu_r \approx 1$) as previous experiments with transformers (7.11d) may have shown. In the same way, the current in a copper circuit would be reduced a great deal by putting even a short piece of high resistivity material into the circuit. In series arrangements, reluctances are added up, as are resistances in a series electric circuit.

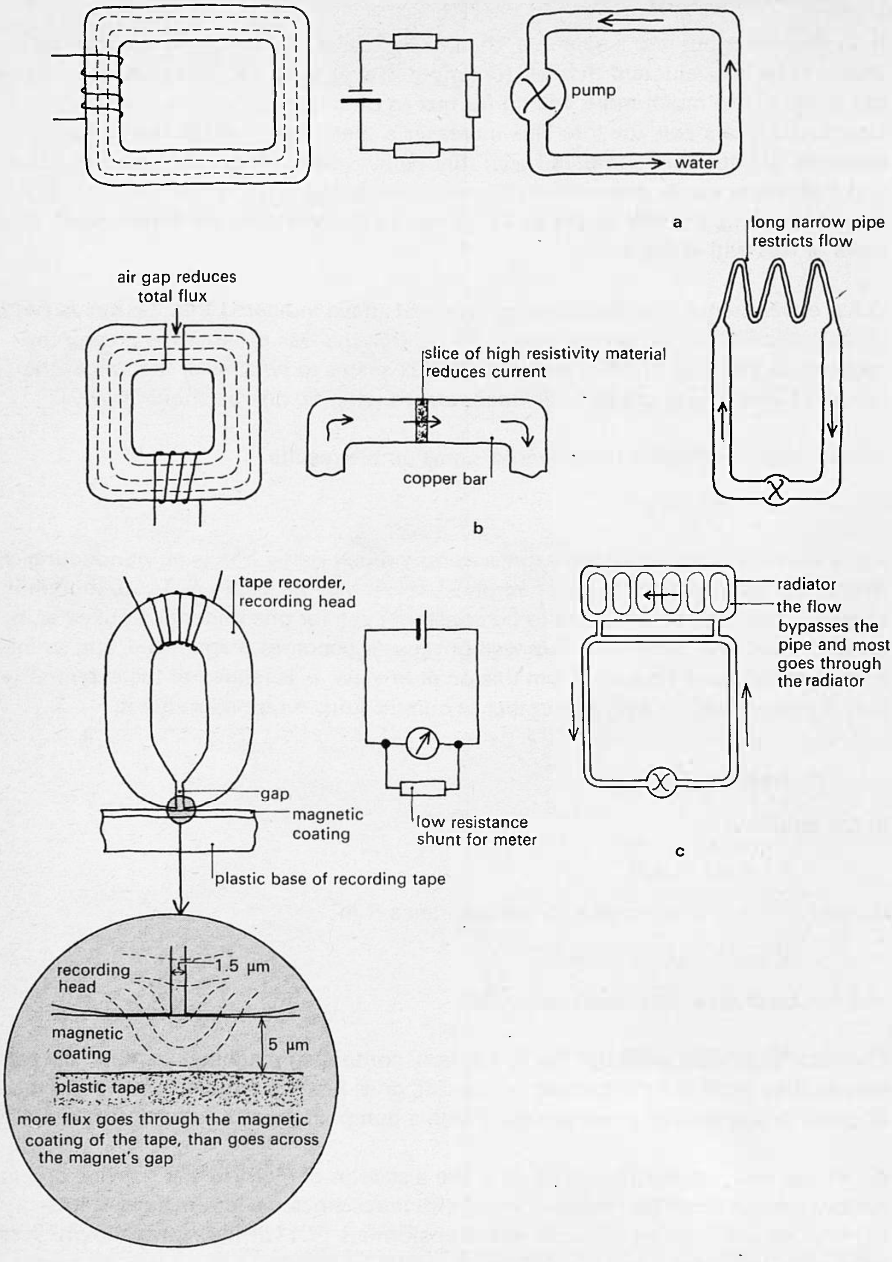


Figure 62
Magnetic circuits, electric circuits, and water circuits.

A piece of iron or ferromagnetic material can bypass flux, as was suggested in another experiment (7.11b). Figure 62 *c* illustrates the similar case of flux passing through magnetic tape, which lies across the gap in the recording electromagnet of a tape recorder. Many domestic heating radiators are connected as shown in this diagram, the water mostly choosing to flow through the many wide radiator channels rather than go through a narrow pipe.

In thinking like this, an engineer is treating the iron as a *magnetic circuit*. The idea is not confined to systems containing iron, though it is with them that it finds its greatest use. It is harder to apply when the flux 'flows', not along straight-sided iron 'pipes', but in such a way that it can spread out in more complex patterns. Nevertheless, the attempt to extend the idea a little will prove profitable.

The flow of flux in space around currents

When Oersted found that the magnetic field of a current went *round* the current, he is reported by Maxwell to have said, 'The electric conflict acts in a revolving manner.' The remark was prescient: magnetic flux is remarkably like water in a whirlpool, going endlessly round and round. The comparison can be given an exact mathematical form, and the following work is devoted to understanding the comparison better.

The field of a long, straight wire

Figure 63 *a* shows the whirlpool-field of a long straight wire. Oersted discovered its shape; it has also been seen in previous experiments (7.2, 7.13). That the field is exactly circular if the wire is immensely long, with no other part of the circuit nearby, might have been guessed from symmetry.

So far, the idea has been to write

$$NI = \phi L / \mu_0 A$$

for the flux ϕ driven along a channel of area A which follows the field direction for a distance L. What sort of channel would follow the field direction for the long wire's whirlpool-field? (A circular one.) Suppose the flow rule works for such a channel.

If the channel has radius r, its length L once around the channel is $2\pi r$. So the flow equation becomes, for one wire ($N = 1$),

$$I = \phi 2\pi r / \mu_0 A.$$

Now ϕ / A is the magnitude of B, the flux density within the channel. So:

$$B = \mu_0 I / 2\pi r.$$

The B-field of a long straight wire is predicted, if the flow rule can be extended in this way, to diminish as $1/r$ with distance r from the wire. That it is so has been shown in an earlier experiment (7.13), which could be demonstrated now if necessary.

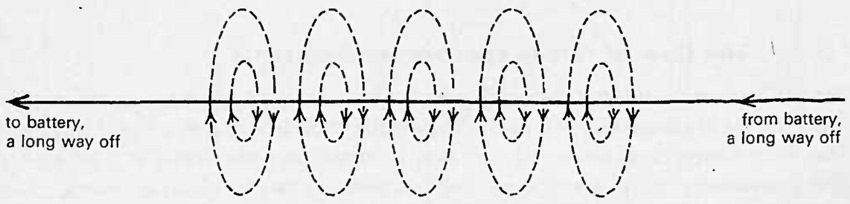
Flux within iron 'pipes'

Nearly all the flux is to be found within an iron core because μ_r is so much greater than unity. If the iron core has a simple shape, the flux goes uniformly around it, and the flow equation takes a simple form. This fact can be exploited in teaching in the way suggested in the text and in figure 62.

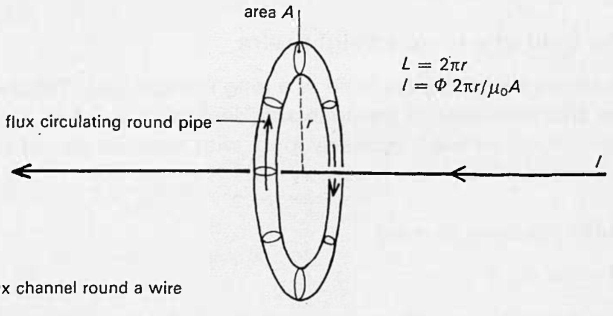
It is important to remember that, for the same current in the coil, the introduction of a closed iron core does *not* reduce the flux in the air, but reduces its importance relative to the much larger flux in the iron.

Students' book

Question 54 is about the design of an inductor. Question 55, about the 'goodness' of machines, may interest some students. Question 56 sets out the argument for $B = \mu_0 I/2\pi r$.



a The whirlpool-like field of a long straight wire



b A circular flux channel round a wire

Figure 63
Calculating the field of a long straight wire.

Ampère's circulation law in other than restricted cases

So far as the rest of the course is concerned, there will be no loss if teachers omit further discussion of flux circulating around currents, and pass on to using the $1/r$ field of a long wire to discuss the absolute measurement of current (page 115).

However, the experiment (7.14) which follows, is an easy and a striking one. If there is a difficulty, it is in understanding what it means. In the experiment, a real tube-like channel, wound with search coils to measure the flux circulating round the channel, is taken in a circle around a wire, as in figure 63. The output from the search coils is shown to be proportional to the number of current turns it encircles. Then, the tubular channel is allowed to lie in many different paths around currents in wires of any shape. It emerges that the path the channel takes makes no difference; the flux circulating within it depends only on the current turns encircled (see figure 69).

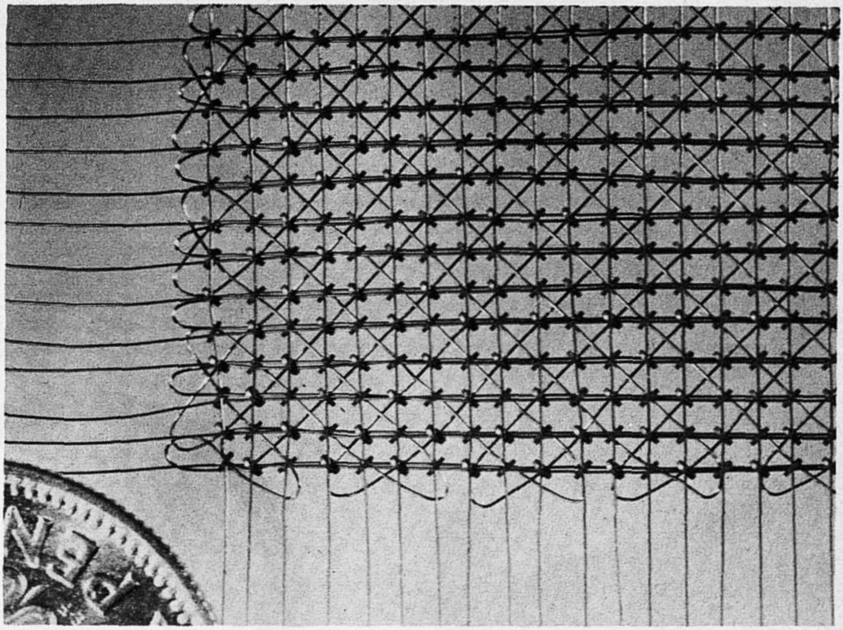


Figure 64
Ferrite rings threaded on wires in a computer memory.
Photograph, Michael Plomer.

The reason for the $1/r$ dependence is not hard to describe. A channel of large radius has a large reluctance $2\pi r/\mu_0 A$, so the 'driving force' I can send relatively little flux around it.

In computer memories, circular rings of ferromagnetic material are threaded on wires, as shown in figure 64. Such a ring offers a low reluctance path and the flux in it is much larger than the flux which is still there in the air nearby. The ring does not divert flux into itself; it allows the current to create extra flux within it.

Ampère's circulation law

The fact that the flow rule can, suitably adapted, give a result that agrees with experiment for the field of a long wire, might be taken as enough reason for having some further confidence in the rule. Knowledge of the field of the long straight wire can next be put to use in understanding how the ampere is defined, and in measuring currents absolutely. But it is tempting to turn aside for a moment, to illustrate the general validity of the flow rule applied to the space round currents and to support it with an independent experiment. Some may think the detour a profitable one even though it is not essential.

This might be enough; the experiment shows that the flow rule, used only for a special path in arguments so far, can be applied to *any* closed path. If it is thought desirable, however, some further arguments about what the channel wound with search coils is measuring can be used to produce Ampère's circulation rule in a form like that in which some students will meet it in later years; that is,

$$\oint \frac{B\cos\theta}{\mu_0}\mathrm{d}L = NI.$$

Much will depend on whether the idea of *circulation* can be made to seem easy. If it can, the rest follows without trouble, and the student will have gained a valuable first acquaintance with an idea of considerable future value: the essence of the idea of the curl of a vector field.

We are indebted to R. W. Pohl's great book, *Electricity and magnetism* (regrettably out of print in English) for the tubular channel wound with search coils – the Rogowski spiral – used in the experiment (see figure 65). It appears there as the 'magnetic potentiometer'; a device for measuring differences of magnetomotive force.

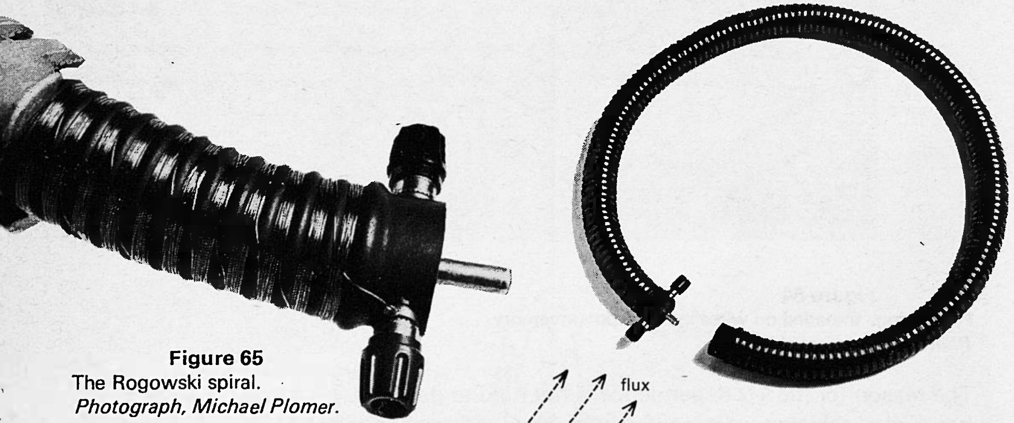


Figure 65
The Rogowski spiral.
Photograph, Michael Plomer.

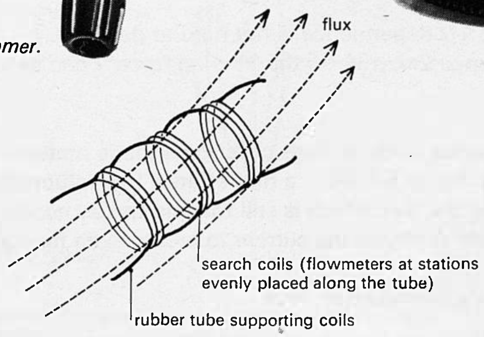


Figure 66
Row of search coils as flowmeters for flux.

Less obvious cases of circulation

The two cases chosen in figure 67 are obvious ones. It is not always obvious by inspection whether a flow has circulation. If the water at the top of figure 67 *a* is going faster than the water at the bottom, there *is* a net circulation round the channel, though no water goes back up one arm of it. But the non-uniform velocity flow could be regarded as a superposition of flows down river at the top and up river at the bottom, onto a uniform flow such as that shown. The uniform flow has no circulation, but the down and back flow clearly has.

Flow in rivers and in whirlpools

The water flowing down a river goes on and on, but the water in a whirlpool goes round and round. So much is obvious, because one can see the flow pattern of water by looking at air bubbles or pieces of driftwood carried along by it. Magnetic flux carries no such flotsam with it; indeed, the 'flow' here is just a vivid image. Some more abstract way of distinguishing magnetic whirlpools from magnetic rivers will be needed, and, if it is to be useful, it should be one that can be set out mathematically.

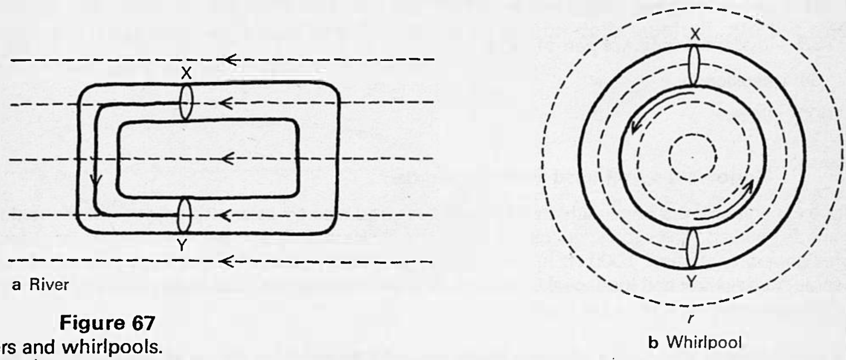


Figure 67
Rivers and whirlpools.

One could tell that the water in the uniformly flowing river, figure 67*a*, is not circulating round, if one could measure the water flow at places around an imaginary closed channel, and add up the flows all round the channel. A flowmeter at X in figure 67*a*, facing to the left, would record flow coming from behind it at a certain rate. When the flow meter is carried round the channel to Y, it has turned to face the flow. It records the same sized flow, but in the opposite direction through itself. The net flow of water *around the channel* is zero.

The same test made on the whirlpool in figure 67 *b* would give a different result. Whether the flow meter is at X or Y makes no difference. If the flow is from its back to its front at X, it is also from back to front at Y. Water *does* circulate in the channel.

A similar experiment can be done to see if the magnetic field of a wire, for example, is whirlpool-like. The 'flow meter' can simply be a search coil, because the voltage across a search coil is proportional to the maximum flux through the coil, if the flux alternates. A number of previous experiments have used a search coil in this way.

Rather than carry a search coil round from place to place on a closed path, solemnly taking flux readings at each place and adding them up for the whole path, it is easier to have a lot of flow-meter search coils strung out on a tube which can be bent into any path one may please. Produce such a tube – the Rogowski spiral – a sort of necklace of search coils on a flexible tube. (See figures 65 and 66.)

It consists of coils strung evenly along the tube, and all connected in series so that the voltages, across the coils, each proportional to the flux through that coil, add up to give an output proportional to the total flux circulating through the tube. Discussion of the working of the device will be easier if it is seen in use.

Demonstration

7.14 Ampère's Law

1027 Rogowski spiral
1037 set of solenoids
1053 length of thick insulated wire (see below)
1009 signal generator
181 general purpose amplifier
183 loudspeaker (if not part of 181)
64 oscilloscope
1000 leads

Rogowski spiral used with solenoids

All the experiments are done with alternating fields, produced by solenoids or wires connected to an alternating supply. The supply can be a low voltage 50 Hz supply, but the low impedance output of a signal generator at about 1000 Hz is much better, because the output of the Rogowski spiral can be fed to an audio amplifier and loudspeaker, as well as to an oscilloscope. The class can then hear the results of the experiment as well as see them.

It is convenient to start with a narrow, closely wound solenoid from the set of solenoids, fed, as above, from a signal generator. The Rogowski spiral (or flux-sampling tube) is connected to the oscilloscope and to the audio amplifier, and one end of it is pushed progressively into the solenoid. See figure 68 *a*.

As the end of the spiral enters the solenoid, the sound from the loudspeaker grows, and the indication on the oscilloscope becomes bigger. Note the change in the height of the oscilloscope trace for a 50 mm movement near the middle of the solenoid, and then the equal increase for a further 50 mm movement.

Next, one can put a wider, closely wound solenoid in series with the first, keeping it well away from the narrow solenoid, which should now have the spiral right through it. Then slide the wider solenoid over the narrower one as in figure 68 *b*. The output of the spiral will either double, or go to zero (depending on which way round the second solenoid is connected). Reverse the connection to one solenoid to demonstrate the two cases.

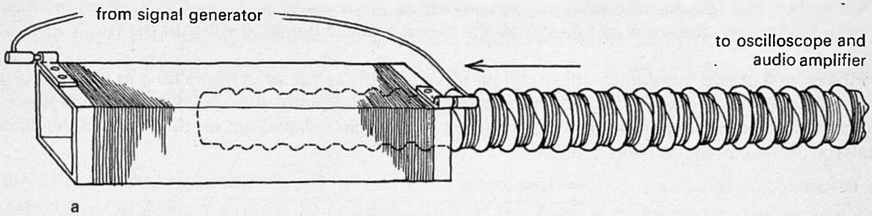
Note for teachers on enclosing turns of a solenoid

If the spiral is a long one, bringing its two ends together so that it follows a closed path round the solenoid (instead of lying straight with its two ends in the weak field region far from the solenoid) makes no appreciable difference to its output.

If this is done, it might be explained by pointing out that there is practically no flux along the return path beside the solenoid (the river is stagnant) while in the part of the path going at right angles to the solenoid's axis, the flux does not go *through* the flow-meter search coils, but slices across them.

Demonstration
7.14 **Ampère's Law**

As a first step, it is useful to push the tube progressively into more and more of the river of flux down the centre of a solenoid, as shown in figure 68. The part of the tube in the flux is like one arm of the channel in the river in figure 66 *a*. As more and more of the search coils have flux through them, because the tube is going further into the solenoid, their combined outputs add to produce a growing total output. It is clear that the tube will indicate the summed flux going along the various parts of it. As is proper in a uniform river, equal extra numbers of search coils pushed into the middle of the solenoid give equal increases in output.



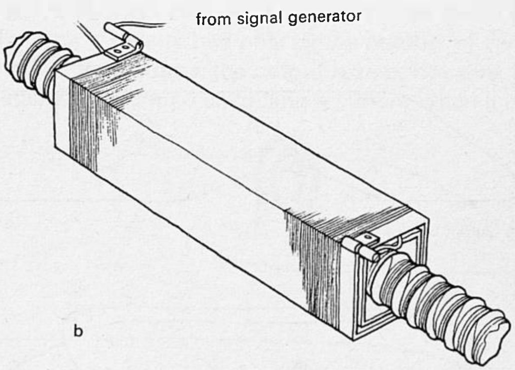


Figure 68
Rogowski spiral and solenoids.

Rogowski spiral encircling currents in circuits of arbitrary shape

Replace the solenoids by several metres of wire connected to the low impedance output of the signal generator, again at 1 kHz. The demonstration is easiest if stoutly insulated wire is used, so that it lies easily on the bench, falls into smooth curves if part of it is lifted up, and can be seen clearly from the back of the classroom. Start with a long loop laid out down the bench and back again, as in figure 69 *a*, and lift up one wire, passing the Rogowski spiral once around it, closing the spiral.

An output from the spiral should be audible. Show that a greater current in the wire gives a greater output, and adjust the amplifier, the current, and the oscilloscope so that the sound level is reasonable, and the oscilloscope trace covers a whole number of graticule divisions. Taken twice round the wire (figure 69 *b*), the output doubles.

Then the loop can be taken round two wires carrying current in the same direction (figure 69 *c*), when the output doubles, and also round wires carrying opposite currents (figure 69 *d*), when the output is zero. In this case, the spiral can be slid off the circuit without breaking either of them.

Finally, one or two topological tricks can be played on the spiral, as in figure 69 *e* to *h*, with the wire loosely coiled for *g* and *h*. Only when the spiral encircles current is there an output. If it does encircle current, the output depends only on the current turns encircled, and not on the shape of the path or the shape of the current carrying circuit.

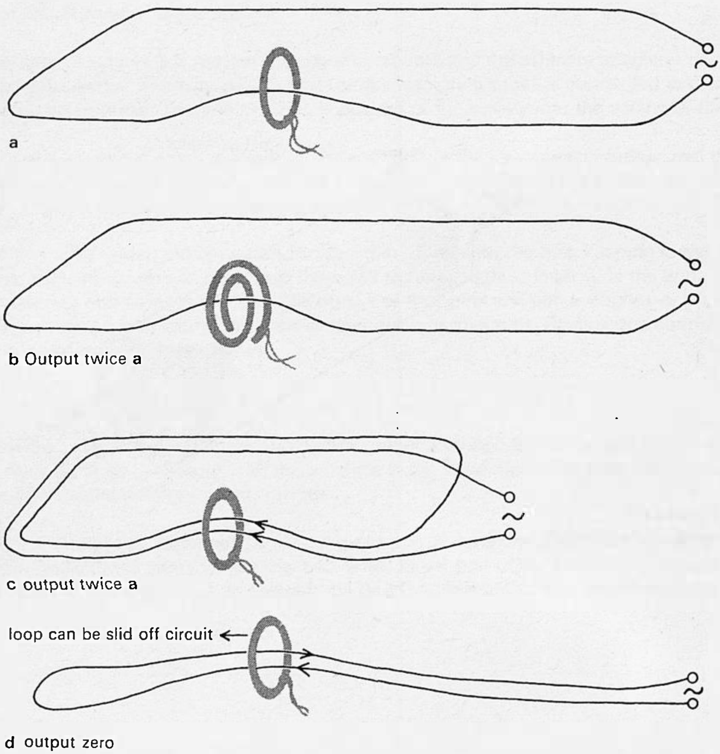


Figure 69
Experiments with a Rogowski spiral.
(Continued.)

The circulation of flux around currents of arbitrary shape

Now the tube of search coils can be used to investigate the circulation of flux in the whirlpool-like field of a single wire.

Figure 69 *a* shows the tube taken round such a wire, carrying alternating current. This is a concrete realization of the imaginary situation shown in figure 63, which was used in an argument about the flux density such a wire produces. The tube gives an output. If the tube is taken twice round the wire (figure 69 *b*), its output is doubled.

If the current is increased, the output increases. If the tube is taken once around two wires carrying current in the same direction, the output doubles (figure 69 *c*). Thus the net flux driven round a closed tube is proportional to current-turns, as the flow rule used previously has said. If the tube enclosed wires carrying opposite currents (figure 69 *d*), the output is zero. It behaves as if it now encircles no current turns, and it does not, for it can be pulled off the circuit without cutting the circuit or the tube.

Finally, it quickly becomes clear that the tube need not follow a circular path round a straight wire, to obtain exactly the same result. If the tube is held off centre, as in figure 69 *e*, the output is no different from that in figure 69 *a*. Indeed, the tube path can be bent into more extravagant paths (figure 69 *f*) without altering the output, presumably still proportional to the flux circulating in the tube. Nor need the wires be straight. The same result is got with wires coiled in any shape at all. If the tube path encircles current-turns, the output is determined only by the number of current-turns encircled. If it does not encircle current-turns, the output is zero, however hard one tries to fool the tube into thinking it might be encircling a current when it is not (figures 69 *g* and *h*).

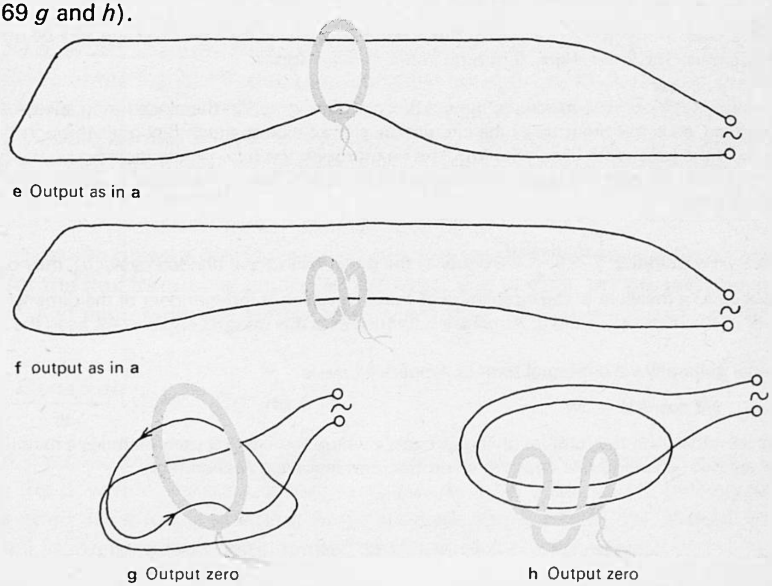


Figure 69 (*continued*)

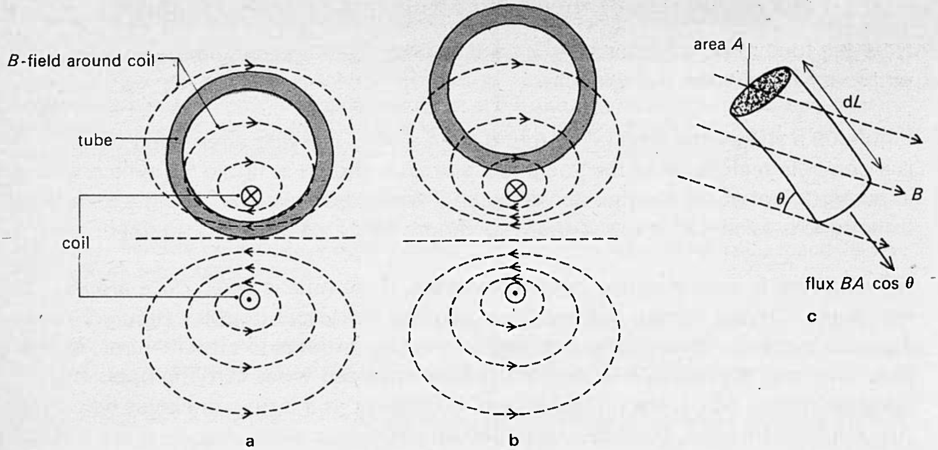


Figure 70
Flux all round a closed path.

Ampère's Law in loop integral form

There is no need, so far as the rest of the course is concerned, to express Ampère's Law in loop integral form. We include it for satisfaction and completeness, so that some students – having seen the experiment – can then see the compact and elegant mathematical expression of its result. It is not worth attempting with those students who would find it more puzzling than powerful. As suggested on page 106, the experiment may be enough by itself for many. Not every tale is improved by having its moral drawn too explicitly.

Various forms of Ampère's Law

Ampère's Law, in the guise of a sum of flux × *reluctance* terms for a tubular pipe, will be unfamiliar to many teachers. This note relates it to other, more familiar forms.

The quantity $\oint BA \cos\theta \, dL$ measures the net flux circulating within the closed tube, area A, length L. If A is doubled, so is this measure of the circulation, since twice as much flux goes through the tube. Similarly, if the tube were filled with iron, the flux through the tube would increase by the factor μ_r. (Note that only the material inside the tube matters; what is outside the tube does not alter the integral round the tube.)

Thus the new quantity $\oint \frac{B \cos\theta \, dL}{\mu_r \mu_0}$, equal to the previous integral divided by $A\mu_r\mu_0$, may be introduced as a measure of the circulation of the field which is independent of the dimensions of the tube, or of the material within it. Ampère's Law then sets this integral equal to NI, as in the text opposite.

The most generally valid integral form of Ampère's Law is

$$\oint H \cos\theta \, dL = NI$$

This is identical with the form involving B, except where the integral path includes a material in which B and H are not parallel to one another, when the form involving H is correct.

A rule for flux encircling currents

Figure 70 *a* shows a tube or channel in the B-field of a loop of current, placed so as to encircle the current. In figure 70 *b*, the same tube is in almost the same position, but it does not now encircle the current.

As shown in figure 70 *c*, where a length $\mathrm{d}L$ of the tube lies at an angle θ to the B-field, the flux *along* the tube, through its area A, is given by

$$\textit{flux along } \mathrm{d}L = BA\cos\theta$$

The reluctance of the short length $\mathrm{d}L$ of tube, area A, is given by

$$\textit{reluctance} = \mathrm{d}L/\mu_0 A$$

(μ_0 being replaced by $\mu_r\mu_0$ if the tube is filled with iron).

Previously, the flux has not varied from place to place, and the rule has been simply,

$$\textit{flux} \times \textit{reluctance} = \textit{current-turns enclosed.}$$

To extend the rule to cope with a flux which is not the same at each place round the closed channel, presumably the thing to do is to add up the contributions bit by bit, giving

$$\text{sum of } (BA\cos\theta)\,(\mathrm{d}L/\mu_0 A) = NI$$

The particular tube used has a fixed total length and area, so the above sum will depend only on the sum of the terms $BA\cos\theta$, in the experiments with the tube of coils. The net flux through the tube can be zero, as may be seen from figure 70. In figure 70 *a*, the tube does encircle current, and flux goes clockwise around the tube. In figure 70 *b*, where the tube does not encircle the current, flux goes clockwise round the tube at the top of the diagram, but goes counterclockwise round the tube nearer the wires. The sum of flux terms, and the sum of *flux* × *reluctance* for the whole tube, clearly could be zero in the second case. Experiments have just been done which show that it *is* zero, whenever the closed tube path does not encircle a current, whatever the shape of the path.

These ideas can be given a precise mathematical expression, by taking the two terms $BA\cos\theta$ for the flux through a section of the tube, and $\mathrm{d}L/\mu_0 A$ for the reluctance of the section, and expressing the sum of their products at all places round a closed path as

$$\oint \frac{B\cos\theta\,\mathrm{d}L}{\mu_0} = NI \quad \text{(for vacuum)}$$

The area A cancels, and the sign $\oint$ signifies adding up all around a closed path. Following the flow rule, the sum of *flux* × *reluctance* is set equal to NI. This equation is one of the more usual forms in which Ampère's Law appears in books, though it is not so usual to interpret it as being related to a sum of *flux* × *reluctance*.

The ampere definition

Students need to *recognize* the definition. We have no wish actually to prevent anyone from learning it by heart, but it is not essential to do so. Examination questions would not ask for the definition to be set down, but could well state all or part of it and ask for the definition to be used in the discussion of a problem.

Similar remarks apply to formulae like those for the field in a solenoid or near a long wire.

Choice of the force 2×10^{-7} N in the ampere definition It may be helpful to point out that the ampere has not always been defined in the way given here, and that the value of the force in the definition was chosen so that the newly defined ampere was as close as possible in size to its value on earlier definitions. Nevertheless, the value 2×10^{-7} is exact, not approximate.

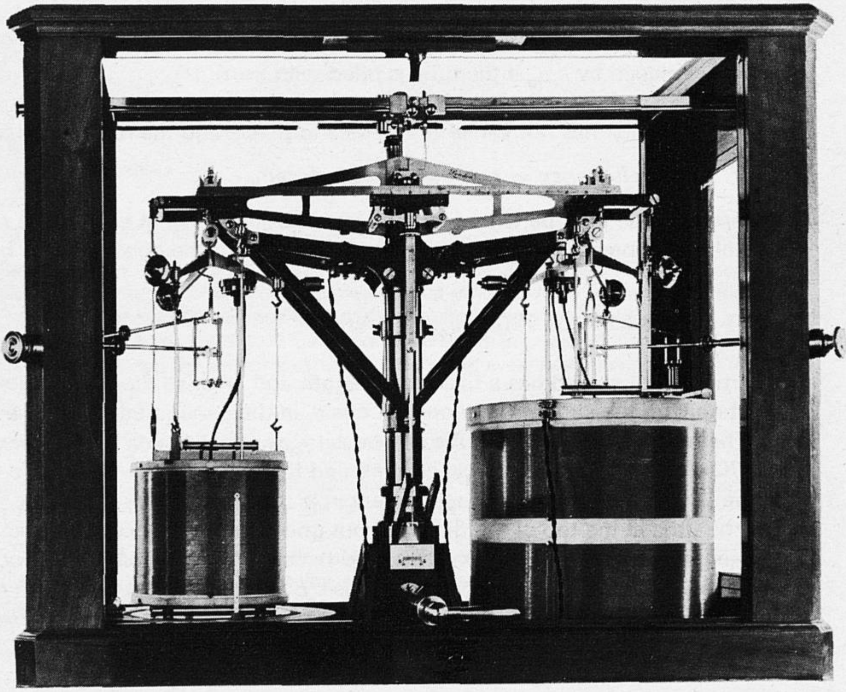


Figure 71
National Physical Laboratory current balance.
Photograph, National Physical Laboratory, Crown Copyright.

Measuring a current without an ammeter

Throughout the course so far, a student might be forgiven for supposing that ammeters occur naturally, already carrying reliable markings. Of course, it would be possible to decide that *this* ammeter *here* is the 'standard' one, and compare others with it, but ammeters include magnets which will vary in strength as time goes by, so the standard current could alter without anyone being any the wiser. A more reliable standard is needed.

The chosen standard is quite arbitrary, settled upon for the convenience of physicists who have to make accurate current measurements. In the S.I. one ampere is chosen to be *that constant current which if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between those conductors a force equal to* 2×10^{-7} *newton per metre length.*

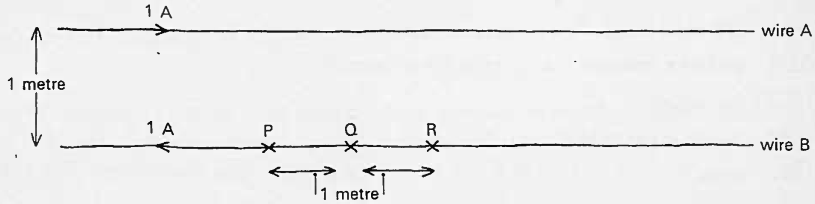


Figure 72
Ampere definition.

No sensible person would set up two extremely long wires one metre apart and measure the force between them, because 2×10^{-7} newton is much too small a force to measure accurately in this situation. But the two wires A and B in figure 72 can be thought of with wire B as a current balance carrying one ampere, measuring the magnetic field produced by one ampere in wire A. Any one-metre length of B, such as PQ or QR, carries one ampere through a field which is uniform along the length of wire B, and perpendicular to wire B. So the fact that PQ experiences a force of 2×10^{-7} newton, means that the field which wire A produces, one metre away from itself, is 2×10^{-7} N A^{-1} m^{-1}. Substituting in the equation,

$$B = \mu_0 I/2\pi r$$
$$\mu_0 = 4\pi \times 10^{-7}\ \mathrm{N\ A^{-2}}$$

Once the size of one ampere is settled, the value of μ_0 is settled, not by measurement, but by calculation. Given the value of μ_0, magnetic fields such as those in a solenoid can be calculated, in this instance from,

$$B = \mu_0 NI/L \quad \text{(long, air-filled solenoid)}$$

Employing other such formulae, it is possible to use practical current balances, like that shown in figure 71, between the coils of which the force can be measured. It can also be calculated from the dimensions of the coils, for a current of one ampere.

7.15 Absolute measurement of current (and other electrical quantities)

1003/5	ammeter (10 A)
1079	flat solenoid
1036	wide current balance
1054	copper wire, bare, about 22 s.w.g.
176	12 volt battery
541/1	rheostat (10–15 Ω)
1000	leads

For further demonstration or further long experiment:

1037	set of solenoids
27	transformer
92X	reel of 26 s.w.g., PVC covered, copper wire
1003/4	shunt for ammeter (1A) or other 0.1 Ω resistor
1057	a.c. ammeter
1007	double beam oscilloscope
1000	leads

Current measurement with a long wire

Connect a wide current balance and a long length of wire in series, as shown in figure 73, with the wire stretched out about 10 mm below the equilibrium position of the arm of the current balance. It is best to set the rheostat beforehand so that the current is about 5 A, and then to put the ammeter back in the cupboard, so that it is clear that the experiment requires no ammeter. If the current exceeds 5 A, the razor blade edges which support the current balance will overheat, and the current should in any case be kept on for the least possible time.

When the current is switched on, the balance arm lifts a little, and the magnetic force on the arm can be counterpoised by a small piece of paper tape hung on it. For a quick demonstration, it is simplest to adjust the height of the slot through which the pin on the balance passes, until the pin bears lightly against its upper edge. When the current is switched on, the pin comes down from the upper edge as the current-carrying arm of the balance lifts. A paper tape counterpoise can now be adjusted (cutting pieces off with scissors) until the pin only just comes off the upper edge when the current is turned on. This technique requires the current to be on for short times only, and saves the fuss of watching the balance swing and of waiting for it to settle down.

Weigh the tape, measure the distances r and L (or estimate these quantities roughly), and calculate the current from them.

7.15 Absolute measurement of current (and other electrical quantities)

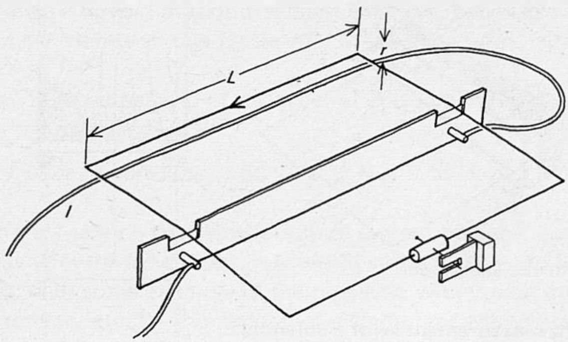


Figure 73
Crude absolute measurement of current.

Figure 73 shows a long straight wire running parallel to another, which forms one arm of a current balance. How big a field might the long wire produce at the balance wire? If they are 10 mm apart, since $\mu_0 = 4\pi \times 10^{-7}$ N A^{-2}, $B = \mu_0 I/2\pi r$,

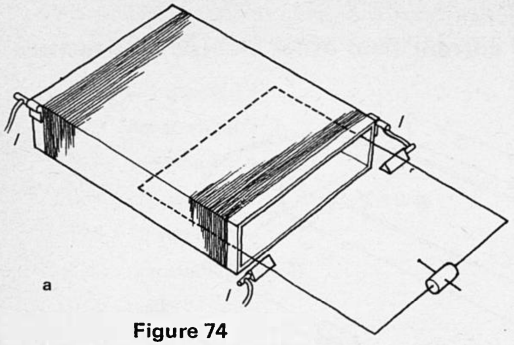
then for $I = 5$ A, $B = 10^{-4}$ N A^{-1} m^{-1}.

The balance arm may be 0.3 m long, and if it, too, carries 5 A, the force on it, given by BIL, is 1.5×10^{-4} N. This is equal to the weight of a mass of about 15 mg. If such a force could be measured with any accuracy, which it cannot in practice with this apparatus, the size of the current could be calculated from the force F.

$$F = BIL = (2\times10^{-7}\, I/r) IL$$
$$I^2 = Fr/(2\times10^{-7} L).$$

The quantities F, r, and L are none of them electrical, needing only metre rules, masses, and clocks for their measurement. (The clock is wanted in principle to measure a force from the acceleration it gives to a known mass. In practice we let someone else measure the acceleration of a mass under the gravitational tug of the Earth, and use that value to calculate the weight of a counterbalancing mass hung on the current balance.) The current I can then be found from these measurements, without the need for an ammeter. Such a measurement is said to be an *absolute* one.

The quality of a measurement with the apparatus in figure 73 would be very poor, though the principle is worth showing. The current balance is deflected, and can be roughly counterpoised again with a small weight, perhaps a small piece of paper tape. Its very crudeness points to a need to do better.



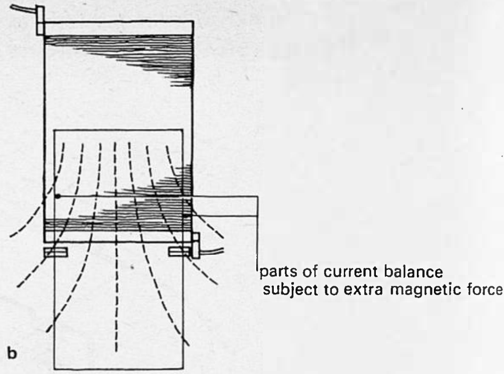


Figure 74
Use of a solenoid to measure current.

Current measurement with a solenoid

Figure 74 shows the use of the wide solenoid to increase the force on the current balance for a given current. The principle is worth showing, but careful measurement is best left to students.

The solenoid, current balance, rheostat, battery (or *smooth* low voltage supply) and an ammeter to check that the current is less than 5 A, are put in series. If necessary, the connections to the balance need to be reversed so that the arm of the balance inside the solenoid is pushed downwards when the current is switched on. A counterpoise can then be used on the arm outside the balance, which does not carry current.

The easiest thing for a demonstration is to choose a counterpoise which roughly balances the beam, and then to adjust the current for an accurate equilibrium.

Measurements of the length L of the balance arm, the number of turns per metre n wound on the solenoid (count the turns in 50 mm) and the force F give the current from

$$I^2 = F/L\mu_0 n.$$

Further absolute measurements

Details of other absolute measurements, leading to an absolute measurement of a resistance, via measurements of flux and voltage, are given in the *Students' laboratory book*. They are optional.

These further measurements employ a coil around alternating flux within a solenoid, and compare the maximum voltage induced across this coil with the maximum rate of change of p.d. across a resistor, through which the solenoid current flows. The apparatus is shown schematically in figure 75.

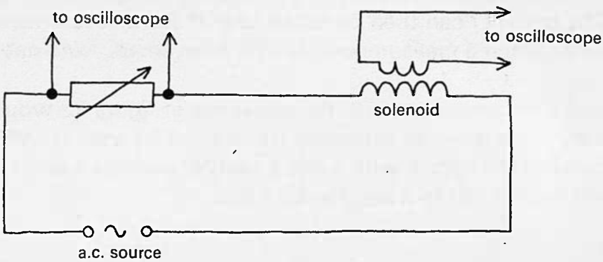


Figure 75
Further absolute measurements.

Better absolute measurements of current

The main need is for a bigger B-field, so a solenoid might serve. The flat solenoid would be better than a square or round-section solenoid, because a longer current balance wire can be put into it. See figure 74.

The solenoid may have something of the order of 300 turns wound onto a length of about 0.3 m. For a current of 5 A,

$$B = \mu_0 I \times \textit{density of turns} \approx 50 \times 10^{-4}\ \mathrm{N\ A^{-1}\ m^{-1}}.$$

The field, and so the force on the same length of current balance, is about fifty times bigger than it was with the long wires. It is worth showing that the force exists, and can be measured, with some estimate of the precision with which the force can be measured (still not very great). The making of a careful measurement can then be left to one group of students, as a long experiment. Difficulties remain, the force on parts of the wire leading into the solenoid as illustrated in figure 74 *b* being one of them.

Further absolute measurements

It is worth pointing briefly to further possibilities that now open up. If the current is known absolutely, so is the *field* in the solenoid, by calculation. If the field is known, so is the *flux*, if the area of cross-section is measured and taken into account. If the flux produced by a known current is known, so is its *rate of change*, if that current is the maximum value of an alternating current (pass the steady and maximum alternating currents through the same resistor, and adjust the alternating current until the maximum p.d., judged by an oscilloscope deflection, is the same as that for the steady current). If the rate of change of flux is known, so is the maximum *voltage* induced across a search coil wrapped round the middle of the solenoid. If the voltage is made the same as that across a resistor carrying the known current, the *resistance* is known.

Once one electrical quantity is known absolutely, others can also (with some ingenuity) be found absolutely. The addition of the ampere to the units of mass, length, and time is sufficient to fix all the other electrical quantities, the only other fundamental operations needed being the counting of turns and the judging of the equality of such things as a pair of potential differences.

Induction motors

The remainder of the Unit is concerned with practical engineering. In principle, just what devices are discussed does not matter too much, as long as the ones chosen can be used to illustrate something of engineering design, using principles developed in earlier work in the Unit. They should also demonstrate something of the practical, creative, and imaginative flair which the good engineer needs.

We think that a discussion of some types of induction motor could fulfil these aims. In this, we have been much influenced by Professor E. R. Laithwaite's two books, *Propulsion without wheels* and *The engineer in Wonderland*. Teachers are urged to read them, not to imitate their style in the classroom, but to catch something of the spirited, gay, but essentially serious way in which the subject can be approached.

We like induction motors because they involve most of the principles discussed so far: forces on currents, currents circulating around flux and flux 'circulating' round currents, and electromagnetic induction. We also like them because they are of immense practical importance: by far the greater part of all the energy transformed by electric motors is transformed by one or another sort of induction motor. We like them because they take so many forms, each of which illustrates the way a good engineer can take one principle and bend it to his will in many ways.

Of necessity, the experimental work has to be with laboratory apparatus rather than with large-scale machines, except where a school has access to substantial pieces of electrical machinery. This limitation has its advantages, for the experiments involve simple apparatus and easily obtained materials, and it is easy for a student who thinks of a new experiment – and there are many novel things that can be tried – to try it out, in a way that is less easy with a large 'given' piece of machinery. So the work offers students a chance to get their minds engaged and their hands dirty.

Time

The work on induction motors is more of a dramatic story than a piece of detailed teaching, and the pace needs to be smart. One double period will be about the right time; two at most.

Demonstration and experiments

7.16 Eddy currents

154/1	turntable
1061	aluminium disc
50/3	magnet Eclipse major
503–5	retort stand base, rod, and boss

Further experiments

1019	air track
1020	air blower
1053	aluminium plate about 40 mm by 0.2 m, 2 mm thick
1053	Plasticine
92B	Magnadur magnets *20*
921	mild steel yokes *5*

Making magnetic flux do something useful

Unit 7 began by looking at electromagnetic forces; forces that can be used to drive trains or power industrial machinery (not to mention sewing machines and electric toothbrushes). Motors, large and small, are very useful things, as are dynamos and transformers. The engineer needs to know how to design such machines so that they serve their purpose as well as possible. Even more important, he (or she) will want to invent new sorts of machines as well as designing better conventional ones.

For example, the motor in a toy car, train, or sewing machine creates electrical interference with radio and television signals when sparks jump from its brushes to the connections to its spinning rotor. The same sparks and the rubbing of the brushes make brush-trouble the most important single cause of the failure of such motors. Could a motor without brushes be made? How would the current get into the rotor? This problem was solved by the engineer Tesla, and will be discussed a little in what follows. There are many similar problems which are as yet unsolved, or which have yet to be shown to be incapable of solution.

How might one make a brushless motor?

A good start can be made by looking at forces which have been noticed previously: forces on eddy currents in conductors. Such currents need no brushes.

Demonstration and experiments

7.16 Eddy currents

Figure 76 shows something that was done before, in experiment 7.9b. An aluminium disc is spun so that its edge passes through the gap of a powerful magnet. Figure 77 shows the same experiment with a new geometry; an aluminium plate glides on an air track vehicle through the magnet's gap.

The disc and the plate behave as if the gap of the magnet were filled with glue; both are stopped or slowed down in it. The effect is large if the plate is thick and is a good conductor; it is absent if the plate is an insulator. In so far as materials are available, such trials with different plates can be made to test the suggestion that the effect is due to currents induced in the plate.

Where would such currents go to? Discussion can bring out the suggestion that they go nowhere, but circulate in closed rings, like whirlpools or eddies. Indeed, the name *eddy current* is the usual one given to them. Students may suggest cutting slots in the plate or using gauze, to see if the eddy currents can be discouraged in this way.

Optional class experiment

92 B	Magnadur magnets
92 I	mild steel yoke
92 P	aluminium ring
92 Q	aluminium ring (split)
92 C	reel of cotton

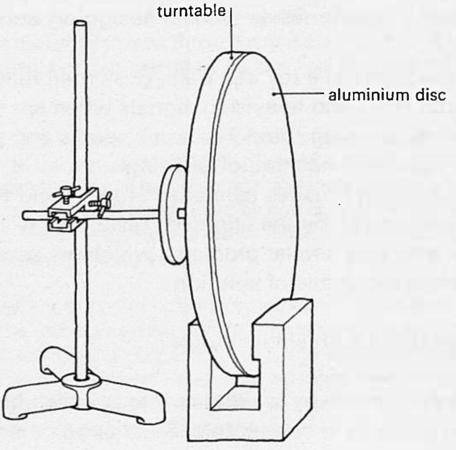


Figure 76
Eddy currents in a disc.

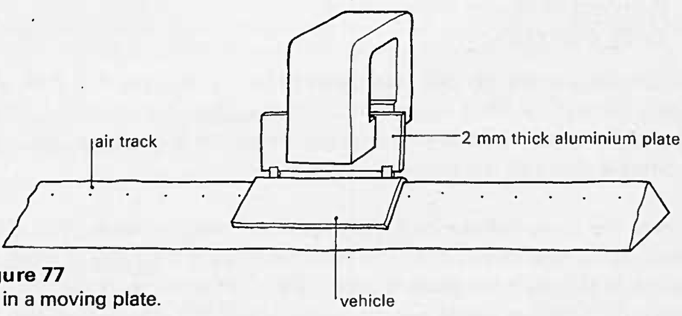
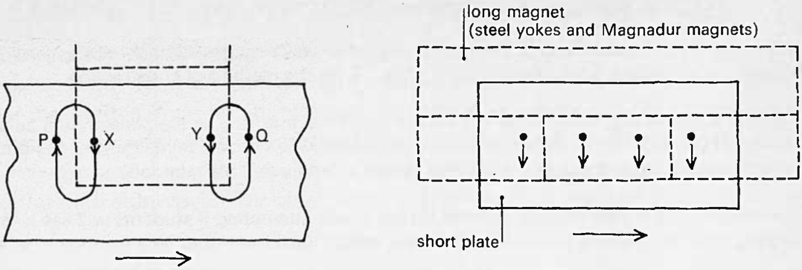


Figure 77
Eddy currents in a moving plate.

The disc is started moving and then the magnet is brought up so that the disc passes between its poles. The disc will slow down rapidly. It may be dragged round by moving the magnet sideways. It will also rotate if the magnet is held, poles downward, over it and moved in a circle. See figure 76.

See figure 77. The aluminium plate is mounted in a vertical plane on an air track vehicle, using Plasticine or other means. The vehicle should be balanced until it no longer drifts (it will move towards the more loaded end). A vehicle sent through the magnet will slow down. If the magnet is moved, the plate can be dragged along.

Note that the air track vehicle may have ferromagnetic material, such as spring clips, on it. The plate will then need to be taller. Steel vehicles are unsuitable. The class may suggest using thinner plates, or plates with holes or slots, or wire mesh, and so on. Such requests ought to be taken up if they are within the immediate resources of the laboratory.



a Eddy currents

b No eddy currents

Figure 78

It may be worth arguing a little about where the eddies of current would be found. Figure 78 *a* shows a long plate going through the gap of a magnet. Within the gap, at places like X and Y, electrons carried along by the plate will be pushed upwards or downwards, say downwards, by the magnetic force on them. At points like P and Q there is no such force (or the force is smaller), so an electron at X will tend to travel round in a loop via P, while one at Y will tend to travel round a loop via Q. Both loops enclose an *edge* of the magnet. What if there were no edges to the magnet?

Figure 78 *b* shows an arrangement that can be tried to test the point. The plate is shorter than the magnet. In so far as the magnet's field is uniform, charge will be pushed towards (say) the bottom of the plate, but cannot circulate. There are no eddy currents, and there is no drag when the plate is well inside the magnet.

A 'negative motor'

The experiments produce an electromagnetic force on a conductor, which is what is wanted for a motor. No brushes are needed, so the device is a brushless 'motor'. But it is the very opposite of a motor, because instead of an electromagnetic force making the conductor move, the movement of the conductor produces a force which stops it moving. It is a 'negative motor'. It must be, or the device would act as a source of energy needing no supply.

Moving the magnet

What will the plate do if the *magnet* is moved? Earlier experiments showing that induced voltages in such situations depend only on relative motion suggest an answer. When it is tried, the moving magnet is found, as may have been expected, to drag the plate along (or the disc round) with it. If the field moves, the conducting plate tries to keep up with it. This is also a motor, but another bad one, in which mechanical movement needs mechanical movement to produce it, and uses very wastefully the mechanical energy which is supplied.

Magnet longer than the plate

A long magnet can be made out of five steel yokes and twenty Magnadur magnets, as was done previously in experiment 7.9a. See figure 20, page 44, for the method of construction.

The B-field is less strong than that of the Eclipse Major magnet, and so the plate should be as thick as possible; not less than 2 mm. It suffers a retarding force as it enters or leaves the magnet, but while it is within the magnet's gap it will move in either direction with very little retardation.

This discussion of the path of eddy currents is only worth attempting if students will see it as an interesting problem, leading to a curious paradox, which turns out not to be a paradox after all.

Optional class experiment: a ring spinning in a field

If the teacher wants something for students to do themselves, they could suspend a ring on thread between the faces of a magnet. A complete ring spinning on a twisted thread will slow down when the magnet surrounds it, but a split ring will not.

Minus sign and Lenz's rule

This is a good moment to refer back to the requirement that an induced voltage must be in such a direction as to conserve energy. The induced currents can flow in many possible paths and directions in the plate in the eddy current experiments. They choose just those which *take* energy from the moving plate.

Student's book

Questions 60 to 64 concern eddy currents.

Demonstration
7.17 Induction motors

7.17a A sideways moving field

1058	coil with 120+120 turns *2*
92G	double C-cores
1051	electrolytic capacitor, 500 μF, 50 V *4* (see below)
1040	clip component holder *2*
59	l.t. variable voltage supply
154/1	turntable
1061	aluminium disc
503–5	retort stand base, rod, and boss
1057	a.c. ammeter *2*
1007	double beam oscilloscope
1039/1	search coil (axial) *2*
1000	leads

The two coils, each with half a C-core in it, are stood side by side facing the rim of the aluminium disc, as in figure 79. The edge of the disc should overlap the top part of each C-core, as in the elevation, figure 79 *b*. The gap between the faces of the C-cores and the disc should be as small as possible. It is important to balance the turntable, perhaps with a blob of Plasticine on its back, so that it rotates freely.

Making a moving field without moving a magnet

The plate moves with the magnet when the magnet moves, because the slab of magnetic field between the poles of the magnet was at one moment in one place, and at a later moment is in an adjacent place. Can the class think how to produce a similar effect, using two magnets side by side? They may think of using two electromagnets, raising the current in one as the current in the other is reduced, and so, in effect, shifting the field sideways. The idea seems at best speculative, but perhaps worth a try.

Demonstration

7.17 Induction motors

7.17a A sideways moving field

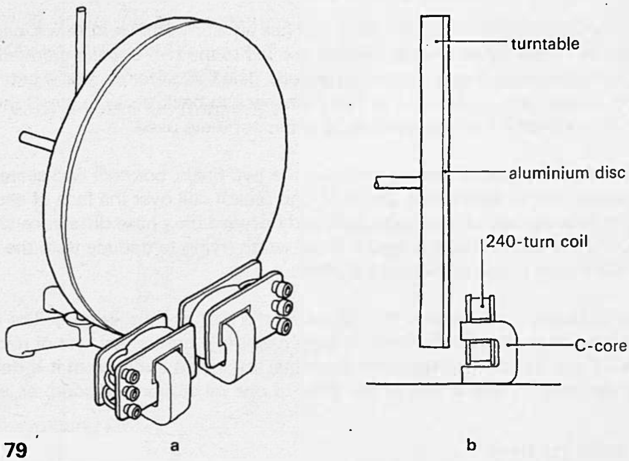


Figure 79
Spinning a disc with two electromagnets.

Figure 79 shows two coils, each with half a C-core, placed side by side near the edge of the aluminium disc used previously. The problem is how to raise and lower the currents in them so that the field of one grows to a maximum a little time after that of the other. One way is to exploit the phase changes in alternating current circuits, when capacitors or resistors are put in the circuit. A capacitor of suitable capacitance in series with one coil introduces a phase shift between the two fields, as may be shown by holding search coils over the face of each magnet, and displaying their outputs on a double beam oscilloscope.

The fields of both magnets pulsate, but that of one coil rises and falls behind the other in time. The question is, will the metal disc 'think' that this is like a continual shift of the field from one to the other? When it is tried, the disc rotates.

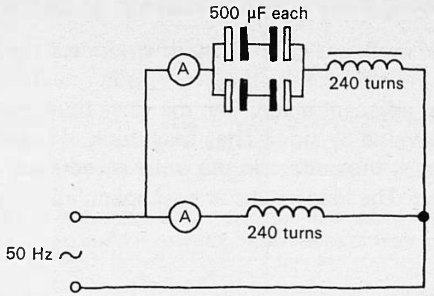


Figure 80

Figure 80 shows the circuit for the coils. Each coil has an a.c. ammeter in series, and one has a 500 μF capacitor in series. Raise the alternating voltage applied to the two circuits gradually, until the current is about 1 A in each arm (less than 6 V may be needed). The 500 μF capacitor is best made from four such electrolytic capacitors, connected as two pairs back to back, so as to avoid the risk of damage which would be involved if a single electrolytic capacitor were used.

To show that there is a phase difference between the two fields, connect two search coils to the double beam oscilloscope, one to each beam, and hold one search coil over the face of each C-core. Because the search coils indicate rate of change of flux, and because the phase difference shown depends on which way round the coils are connected, it is not worth trying to deduce from the display which of the two fields is retarded in phase relative to the other.

When the two coils and cores are side by side facing the disc, the disc rotates. The metal travels towards the magnet whose phase is retarded. If there were negligible friction the rate of rotation would depend on the frequency and on the spacing of the magnets, but in this experiment it is determined largely by the friction in the bearing, and is only of the order of one revolution a second, or less.

7.17b A rotating field

Apparatus as for 7.17a, adding:
1053 empty 35 mm film can

The two coils, each with half a C-core, are connected exactly as before (see figure 80). They are placed so as to make a right angle, as shown in figure 81, with the two cores as close together as possible. The can is supported upside down in the angle between the cores, with its solid base below the level of the top of the cores. It is convenient to make a dimple in the centre of the base of the can, using a punch, and then to support the can on a pin point, the pin being held upright in a blob of Plasticine. It will usually be best to raise the coils off the bench on wooden blocks.

Students' book

The *Students' book* contains a set of diagrams illustrating how three phase current can be used in a rotary machine and in a linear motor. It would take too long to follow up the construction of three phase machines in detail, but it seems right to point in passing to the principle, which is, after all, used more than any other if one counts power delivered electrically rather than the number of individual machines.

Interested students can follow the idea up much further, particularly in Laithwaite, *Propulsion without wheels*.

A-student could try the same pair of coils as a system for driving a plate attached to an air track vehicle.

It may be worth pointing out that, in principle, the effect could be produced by raising and lowering the currents in the coils using rheostats varied out of step, but that the slowness of such changes has a basic disadvantage. An induced voltage depends on rate of change of flux, so the faster the changeover, the bigger the induced currents and the larger the force.

7.17b **A rotating field**

The class may be asked how they would rearrange the two coils so as to spin a conducting cylinder, so making something nearer to a rotary motor. (Although the disc turns, the system of figure 79 is in essence a linear, or motion-in-a-line type of motor.) They may think of having the two coils at an angle, so producing a field which turns from one angle to another as the field in one grows and the field in the other dies away, having already passed its maximum.

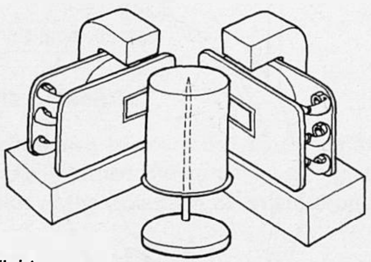


Figure 81
Rotating a can with a rotating field.

Figure 81 shows one simple way of trying the idea. The rotor is an aluminium can, supported in the angle between the two magnets, which can be placed at right angles. The can spins, and again the direction of turning is from the magnet whose phase is *advanced towards the one whose phase is retarded.* The can will also turn if a magnet is held near it and is swung round.

This is a pretty poor motor. Its torque is minute; how might one set about improving its performance? What is wanted is as much flux as possible intersecting a rotor with as low a resistance as possible. Improvements could result from using thicker aluminium, and from filling the aluminium with steel, while providing iron paths for the flux which are as complete as possible. Figure 83 shows what the improved version might be like, in principle, though not in detail.

In practice, induction motors do not use such things as capacitors to introduce a phase difference, where it can be avoided. It is easy to generate alternating currents which have phase differences just by having several coils on the generator, spaced around it and with the voltage across each rising and falling after the voltage across the coil before it. Indeed, electricity is transmitted across the country in three

7.17c The shaded pole principle

147A	demountable transformer, laminated U-core
147F	coil with 1200 turns
147I	pole piece to fit U-core
78	variable a.c. supply (Variac type)
1057	a.c. ammeter
1053	aluminium plate, 50 mm square, 3 mm thick (1052 may serve)
154/1	turntable
1061	aluminium disc
503–5	retort stand base, rod, and boss
1007	double beam oscilloscope
1039/1	search coil (axial) *2*
1000	leads

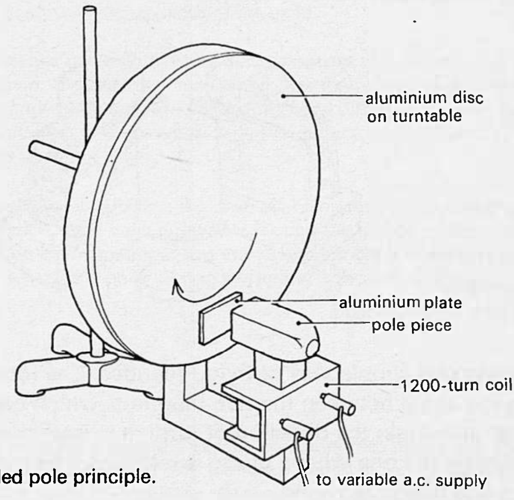


Figure 82
Turning a disc, using the shaded pole principle.

Figure 82 shows one kind of shaded pole demonstration. The aluminium disc, free to rotate in a vertical plane on its turntable, is placed facing the pole piece of the demountable transformer. An aluminium shading plate, not less then 3 mm thick, is placed so as to cover half the pole face. It may be held in place with Plasticine.

With this apparatus, an effective demonstration can be done using the 1200-turn coil supplied from a Variac. The coil is rated at 1 A, and in this arrangement would carry more than that if supplied at 240 V a.c. An ammeter is included in the coil circuit, and the Variac output raised until the current is 1 A, exceeding this value only for short times. Note that if the coil is not insulated with a polythene wrapper *it may be dangerous to touch it.* A less effective, but adequate demonstration uses the 300-turn coil and the full 25 V from the l.t. variable voltage supply.

phases, each 120° out of step with the next, and most induction motors have their coils in triples, each carrying one of the phases.

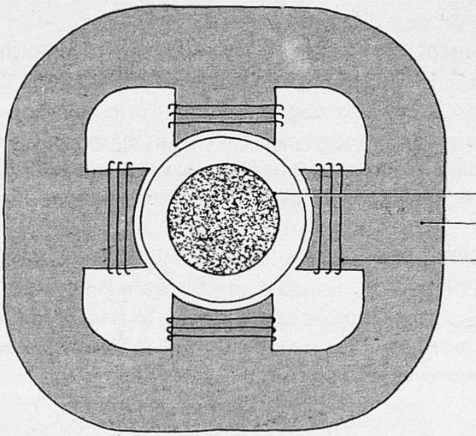


Figure 83
Some improvements to the simple model motor.

7.17c The shaded pole principle

There is another way of producing adjacent out-of-phase fields which is simple and intriguing, and uses principles studied previously in an ingenious way. Suppose a slab of conductor is put over part of the pole face of an electromagnet carrying alternating current, as in figure 84.

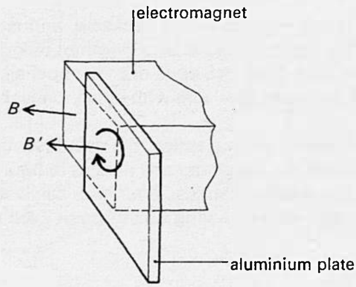


Figure 84
A shading plate over part of an electromagnet.

As the field of the electromagnet pulsates, there will be loops of current induced in the plate, such currents being large when the rate of change of flux through the plate is large. This, in an alternating field, occurs when the field is small. But the current in the plate will make some field of its own. The total effect is not simple, but it should be clear that one might expect the field B' near the plate to reach a maximum at a time different from that of the main field B of the electromagnet. That this is so can be shown by holding a pair of search coils side by side over the face of an electromagnet,

F

The phase difference between the field over and the field beside the shading plate is not large. It is best to place two search coils, one on either side of the pole face, and to start by displaying their in-phase outputs when the shading plate is absent. Then when the plate is inserted, a small phase shift can be seen.

The disc, set up as close to the shaded pole as possible, should rotate, travelling from the uncovered to the covered region of the pole face. It is best to balance the disc with a lump of Plasticine stuck to its back surface.

Students may like to investigate other shaded pole arrangements. A shaded C-core and a 240-turn coil can be used to drive an air track vehicle, for example. Possible lines of investigation include improving the magnetic circuit so as to produce a better, more powerful machine.

7.17d The gramophone motor

1078 gramophone motor

78 variable a.c. supply (Variac type) if motor is mains driven
or
27 transformer, if motor is a low voltage type

The motor can either be a low voltage demonstration type of motor, which is demountable, or – at much less expense – a standard mains voltage motor obtained from a surplus supplier or from an unwanted record player. If the latter, it is best to have two, so that one can be left intact, while the other is modified so that it can be taken apart easily, and can have its shading rings shorted or in open circuit at will. Modifications are described below.

Show first that the complete, unmodified motor runs. If, however, the shading rings are incomplete, as in figure 86 *a*, the motor will not start by itself. When the rings are completed by pinching the copper together with pliers, the rotor starts to turn. Finally, show that if the rings are left incomplete, the motor will run if it is given a start, and will run in either direction.

Modifications to a standard mains motor

The two shading rings are cut through with a hacksaw, and are removed with pliers; take care not to distort the laminations. One ring is replaced by a length of bare 14 s.w.g. copper wire bent as shown in figure 86 *a*. The motor will start if the two ends of the copper are squeezed firmly together with pliers. It may be necessary to clean the copper wire with emery paper before trying this.

So that the rotor can be removed for inspection, the rivet fastening the rotor bearings to the iron core needs modification. File away the flange of each rivet as in figure 86 *b*, so that the rivets can be withdrawn, freeing the rotor and its bearings. The motor can still be used if the rivets are held in place, as in figure 86 *c*, by a nut threaded on a long bolt through each rivet.

and then slipping a conducting plate below one of them. The outputs of the coils, displayed on a double beam oscilloscope, acquire a small phase difference.

It seems reasonable to try replacing the two adjacent out of phase magnets used in 7.17a to drive a disc (figure 79) by these two adjacent regions of field from one magnet. Figure 82 shows a suitable arrangement to try. The disc rotates, travelling from the uncovered to the covered part of the magnet. This system is called *shading* part of the iron circuit. In effect, the magnetic circuit around the magnet is split into two side by side parallel parts, and round one of these half-circuits flows induced current, which alters the phase of the flux through that half-circuit.

The device is of some practical value. One type of motor used to drive pumps for aquaria utilizes this very system: a disc driven round in the gap of an alternating current magnet, part of which is shaded by a metal plate or a copper ring round it. The system is ideal for the purpose. It will run indefinitely, having only one simple moving part, no brushes to wear out, no sparks to cause television interference, and no complicated circuit to go wrong. Its modest torque does not matter for this purpose, though this restricts the general use of the shaded pole principle. One of its main uses is in starting off other such motors. A gramophone turntable motor uses the principle in this way.

7.17d The gramophone motor

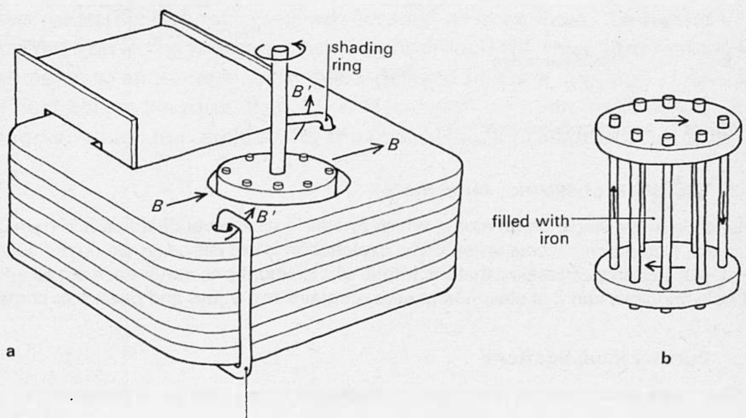


Figure 85
a Gramophone motor with shading rings.
b Rotor conductor.

Figure 85 *a* shows the motor (bearings are omitted for clarity). The rotor is a cage of conductors, as in figure 85 *b*, which is filled with iron or steel. (The steel may in practice hide most of the cage of conductors.)

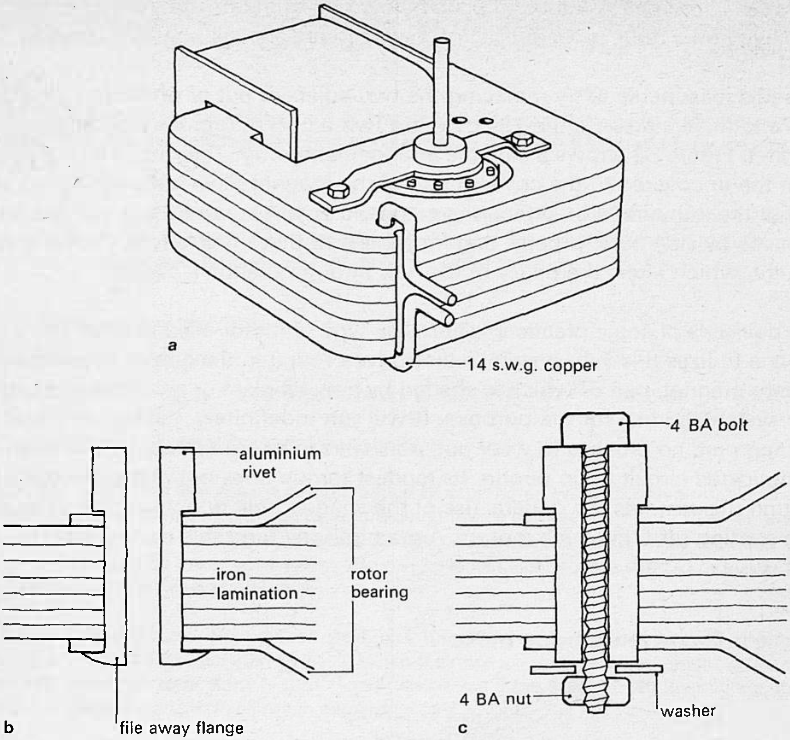


Figure 86
Modifications to a gramophone motor.

The single phase induction motor

An explanation of the single phase motor, which rotates in whichever direction it is started off, is given in Laithwaite, *Propulsion without wheels*. The explanation is not easy, and we do not suggest it should be taught. But students can realize that the torque of a gramophone motor does not *all* arise from the shaded pole principle, and that electromagnetism contains many joys and puzzles to come.

Further investigations

The subject lends itself to further investigation. Appendix C suggests some possibilities.

The rotor turns in a gap in an electromagnet driven by alternating current. If this were all, the rotor would not start to turn, and that it does not can be shown with another motor in which the shading rings have been cut through, as in figure 86 *a*. When the rings are closed electrically, the rotor turns, travelling, as did the disc in figure 82, from the unshaded to the shaded part of the magnet's poles.

The rings are placed around part of the iron, so that the field B' through the iron at the rings is delayed relative to the field B nearby. The rotor behaves as if a magnet were continually being turned from the direction of B to the direction of B' at a later moment, and turns to follow this imaginary motion.

It is fitting to conclude by noticing that there is much more to tell, and that the story of motor technology has plenty more in it for investigation or discovery. One way to do so is to show a remarkable new effect. If the shading rings are left incomplete, the rotor does not start to turn. But if it is given a start, it will go on turning. Astonishingly, it does not matter which way the rotor is started off turning; it goes on turning that way. (With the shading rings operating, it turns only one way.)

This is a genuine case of lifting oneself up by one's own bootlaces. If the rotor turns, there must be a turning field to carry it round. Since the direction of rotation depends on which way the rotor was started off, the turning rotor must itself be responsible for the turning field which keeps it turning. It seems crazy, but it is so. The currents induced in the rotor, when it turns like a short circuited dynamo in the main field, themselves create flux whose phase can be such as to maintain the rotation. Indeed, the reason the iron in the motor is carried right around the rotor (not making just two curved poles) is to encourage such phase-delayed flux in a direction at right angles to the main field across the rotor. If this seems astonishing, even magical, that would be a fitting mood in which to conclude, for the time being, a first study of electromagnetism.

Appendices

Appendix A
Problems of teaching electromagnetism

This Appendix concerns some of the problems, many of them problems of logic, of thinking through a sequence of teaching in electromagnetism. There are three difficulties in the way of such a discussion. The first difficulty is that the logic of electromagnetism happens to be particularly complicated; there are very many relationships which interlock with one another, but have to be put into some pattern.

The second difficulty is that, as elsewhere in science, there is no one 'correct' pattern; no one 'true' view. There is a complex network of relationships, and one may start where one likes, and go which way round the network one pleases. What is a definition on one view may be an empirical relationship on another. What is a measured quantity on one view may be a defined quantity on another.

The third difficulty is that logic in this sense has very little to do with teaching, in which one has to do with the gradual growth of concepts through the experience of trying to use them; not with precise definitions which are clear to the expert, but impenetrable to the learner. A scientific definition, such as that of the unit of current, is not an attempt to *explain* what one means. The ampere definition is a *prescription* for measuring current, chosen by professional physicists, not with the convenience of students in mind, but with a view to stability and accuracy of measurement. If it is ever the case that some strange new effect offers greater reliability and precision, it could well be adopted as the basis of a definition, be it never so incomprehensible at school level. Nor is science so closed and certain an enterprise that a physicist knows clearly from the start what he or she means. A definition is an end to be striven towards, not a starting point. At the least, there is no sense in 'saying what one means', until one has found out by experiment what is worth talking about. These notes are intended to clear the ground, so that in teaching, as little time as possible may be spent on logical considerations, which students are not very likely to appreciate. At the same time they may help to avoid the taking up of positions which would later on have to be abandoned.

Defining current

The SI definition of the ampere involves the force between long straight parallel wires. It is a convenient definition for professional physicists, but not a thing which means much at first to the student at school. At an early stage, it is better to use simple ammeters (and maybe current balances), trying them in circuits to see what they do. In particular, ammeter readings are the same all round a series circuit, and add up at junctions. We suggest keeping to this view until the end of Unit 7, rather than trying to abandon it at the start. At the end, the ampere is transferred, from some standard ammeter against which others could be tested, to the definition and, in practice, to current balances in standards laboratories.

Because the unit of current will in the end be the fourth primary unit added to the units of mass, length, and time in the SI, we feel free to use an ammeter to measure the strength of a B-field, via $F = BIL$, at the start of Unit 7. But because current is measured by a magnetic effect, whether in an ammeter, or in a current balance based on the definition, it is not as simple as it might be to say why one supposes the force to be proportional to IL. The essence of the matter is that magnetic forces vary linearly with whatever it is (current) that adds up at circuit junctions.

An experiment to test the point would be to place two current balances in two arms of a circuit, with a third in a wire which both arms join. The experiment will show that the force on the third balance is always equal to the sum of the forces on the other two, if all the balances are identical. This can be done with the wide current balance employed in the suggested teaching scheme. The easiest thing is to use one magnet (to avoid variations of strength between magnets) and to take it from one balance to the next. For the two balances in the parallel arms, cut weights that counterpoise these balances. Then take the magnet and both weights to the third balance fed from both arms. The two weights together should counterpoise it without further adjustment. Important as the experiment is in principle, it and others like it often make less than the expected impact on students, who care less for logic than some physicists. Moreover, it needs some skill to make it work convincingly, and if it 'doesn't work', the point is lost.

Defining B

As indicated above, B is introduced in the suggested sequence by way of the force on a current, and not by way of flux density and flux. We regard this as a free choice of tactics, and we regard as irrelevant the fact that another route, taking flux and flux density from induction experiments before using $F = BIL$, is likely to appear in schemes of logical chains of definitions in the SI. For the learner, induction has the disadvantage of being a good deal more complex than the force on a current, though the latter is not so simple as it might be, especially having regard to the directions of current, field, and force. Those who judge otherwise will do it the other way, no doubt. We only urge them to be swayed by clarity and ease of teaching, rather than by 'logic'.

A note on μ_0

In the SI, the ampere has been chosen as a primary unit. To settle upon a value for an ampere means choosing arbitrarily what force will exist between, say, two wires when one ampere is said to flow in each. Since μ_0 expresses the magnitude of such forces, an arbitrary choice of the size of an ampere is also an arbitrary choice of μ_0, which is given the value $4\pi \times 10^{-7}$ N A^{-2}. Clearly no experiment can *measure* μ_0 in this system. Such an experiment would discover what current was flowing.

Note that this is not 'the truth about the nature of μ_0', but is an artefact of a particular choice of starting point in the network of definitions and relationships. It has nothing to do with the physical realities expressed by the whole pattern of relationships.

The constant ε_0 was introduced (in Unit 3) to express the magnitude of the forces between charges. But ε_0 and μ_0 are related, through the result

$$c^2 = 1/\varepsilon_0\mu_0$$

for the velocity c of electromagnetic waves.

On a relativistic view, when charges move with velocity v, the electric force between them is modified by terms of order v^2/c^2. This modification (when both move) is the 'magnetic' force between them. The one physical measurement of a constant that it is possible to make here, is the *ratio* of the 'electric' to the 'magnetic' forces between charges at 'rest' and in 'motion'. The constant quantity c^2 expresses the magnitude of this ratio (which also depends on velocity v). This statement still holds good if one has not seen a relativistic interpretation nor come to suppose with Maxwell that $1/\varepsilon_0\mu_0$ is the square of a wave velocity. c^2 is then a constant, dimensionally the square of a velocity, whose deeper 'meaning' is unknown.

Suppose now that a new unit of current were decided upon, such that μ_0 were given half its SI value. This could not affect the magnitude of the ratio between electric and magnetic forces, expressed by the product $\varepsilon_0\mu_0$, since the physics should be unchanged by a change of unit. (We suppose that the kilogramme, metre, and second are unchanged.) Thus ε_0 would become twice as big as before. An 'experiment to measure ε_0' would give this result because the magnitude of the unit of charge would have changed along with that of the unit of current. In effect, an 'experiment to measure ε_0' measures the ratio between electric and magnetic forces, yielding the physical constant $\varepsilon_0\mu_0$.

There is much to be said for the view that one of the two quantities ε_0 or μ_0 need never be introduced. ε_0 could be replaced by $1/c^2\mu_0$, or μ_0 by $1/c^2\varepsilon_0$, throughout. Formulae for electric and magnetic forces then fall into a form in which the ratio of forces in comparable situations has the value v^2/c^2 (or v_1v_2/c^2). We have not, however, found any way of making this move which seems to us to be intelligible to a student at the time when μ_0 first appears, before any discussion based upon Maxwell's theory or on relativity suggests that the product $\varepsilon_0\mu_0$ is equal to $1/c^2$.

It is sometimes claimed that ε_0 is not a measurable constant, but is to be calculated from c^2 (measured) and μ_0 (chosen by definition). It may be so regarded, but it need not be. It was, after all, the electrical calculation of c^2 via (in effect) a *measurement* of ε_0, that gave Maxwell hopes of his electromagnetic theory of light.

The vectors *B* and *H*

Although only B is mentioned in the course, H is present, in a sense, as ampere turns per metre. Just as current turns produce flux in iron, so, for the purpose of dealing with flux in materials at a later stage, H may in some ways be regarded as the 'cause' of B.

We think, then, that the pair of quantities, B and current turns, is an adequate representation of the structure of ideas which will come later, and simple enough for a student to grasp the ideas without the confusion of introducing too many quantities, too soon.

Relativity and electromagnetism

One difficulty of teaching about electromagnetism is that one tends to treat magnetic effects as divorced from the rest of electricity. Having dealt with forces between charges at rest, the next move is advertised as 'forces between charges in motion', as if that were the most natural thing in the world, instead of the most extraordinary.

From a relativistic point of view, magnetic effects *are* electric effects, seen from a moving reference frame. More exactly, different observers assign to 'electric' and 'magnetic' effects different proportions of one multi-component electromagnetic field. An Appendix to the Teachers' Guide, Unit 8, *Electromagnetic waves*, discusses this in greater detail.

In this sense, relativity 'explains' magnetic effects; that is, it relates them to other ideas.

Relativity is involved in some of the simplest experiments in electromagnetism. It is soon found that the induced voltage in a wire moving relative to a magnet depends only on the relative motion of the two. Yet when the wire moves, the force on electrons in the wire is written as Bqv and is called 'magnetic', whilst when the magnet moves, there is no help for it but to call the *same* force on electrons in the wire 'electric', for they are at rest, and no magnetic force exists on charges at rest. One's prejudice that the name of the effect is decided by the nature of the source (a magnet) has here to be set aside. An observer travelling along at the appropriate velocity will say just the same, but will assign 'electric' and 'magnetic' in the opposite way. It is as well, in teaching the subject, to have this larger perspective at the back of one's mind.

A difficulty with the coils surrounding a space

There is a difficulty in interpreting the effects shown in experiment 7.10 g, pages 62 to 65. The flux entering and leaving the 'box' of coils in that experiment is measured using electromagnetic induction. The law of induction, however, itself requires that the result 'demonstrated' should hold, since if it did not, one could not have a simple equation linking the e.m.f. round a circuit to the flux 'through' that circuit. So the experiment, while it *illustrates* the point, cannot be said to *prove* it.

Appendix B
Long wires and solenoids

This Appendix offers an alternative route for linking the field of a solenoid and the field of a long, straight wire, which could replace the teaching suggested on pages 97 to 105, which uses the idea of the magnetic circuit.

The field of a long wire

One may start from the empirical fact that the B-field of a long, straight wire is given by

$$B = kI/r.$$

The constant k would be unknown, but for the definition of the ampere. But if a long wire carrying one ampere is to be said to exert a force of 2×10^{-7} N on a metre of straight wire, one metre from the first which carries one ampere as well, it follows at once that

$$B = 2 \times 10^{-7}\, I/r.$$

The field of a solenoid

The field of a solenoid, having N turns in length L, is given by

$$B = \mu_0 NI/L$$

and is uniform and independent of the shape or size of the cross-section of the solenoid, provided that the solenoid is much longer than it is wide. The problem is to express μ_0 in terms of the quantity 2×10^{-7} N A^{-2}, by relating the two fields to one another.

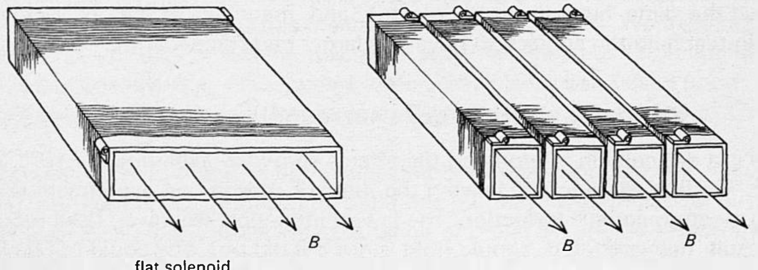


Figure 87

The field of a carpet of currents

The link can be achieved if the solenoid field is first related to the field of a large, flat carpet of current. It may be noted first that the field of a square-section solenoid is just the same as the field of a wide, flat one. This may be tested experimentally, and argued for theoretically, as suggested in figure 87. If many narrow solenoids are laid side by side, the B-field may be extended over a wide, flat region of space. The oppositely flowing currents in the adjacent sides of the solenoids would seem to be disposable, and these wires can be removed without making any difference.

If the flat solenoid is now made very wide (and very long), as in figure 88, it becomes a pair of carpets of current-carrying wires. The short, vertical, very distant edges of the solenoid have a negligible effect on the field between the two carpets.

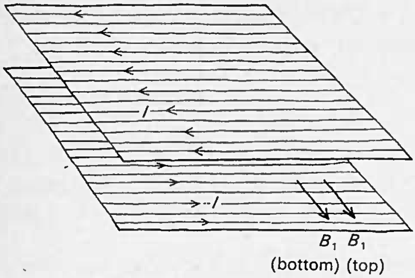


Figure 88

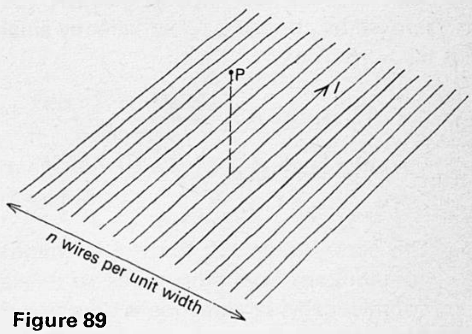


Figure 89

Current I flows in every wire, but flows from (say) left to right in the lower carpet and from right to left in the upper carpet. Clearly the carpets produce identical magnitudes of field B_1. The field B_1 *above* the bottom carpet is in the same direction as the field B_1 *below* the top carpet. If the solenoid field is B,

$$B = 2B_1.$$

Calculation of the field of a carpet of straight wires

Both carpets are made of long straight wires. The field of a carpet should be calculable from the field of one such wire, by adding up the effects of many wires. The field B_1 at a point such as P in figure 89 will be calculated, letting the carpet have n wires per unit length, each carrying current I.

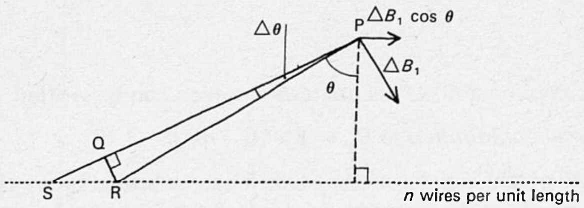


Figure 90

Figure 90 shows the arrangement, looking at the ends of the wires. All the wires make different contributions to the magnetic field at P because they are different distances away, but the wires between R and S are nearly the same distance r from P, if we imagine R and S to be very close. Then the number of wires in width RS is nRS.

total current carried by these wires $= n\mathrm{RS}I$

magnetic field ΔB_1 at P due to current in these wires

$$\Delta B_1 = \frac{2\times 10^{-7} n \mathrm{RS} I}{r}$$

It helps the calculation to work out the small distance RS in terms of the small angle $\Delta\theta$ which it subtends at P. Angle QRS approaches θ (in figure 90) as $\Delta\theta$ approaches zero, so in the limit RS becomes QR/cos θ. And QR approaches $r\Delta\theta$ as $\Delta\theta$ approaches zero, so by choosing $\Delta\theta$ sufficiently small hardly any error is made in saying that RS $= r\Delta\theta/\cos\theta$.

$$\text{Hence } \Delta B_1 = \frac{2\times 10^{-7} n I r \Delta\theta}{r\cos\theta}$$

$$\Delta B_1 = \frac{2\times 10^{-7} n I \Delta\theta}{\cos\theta}$$

This contribution ΔB_1 to the total magnetic field at P is not in the same direction as contributions from other wires, so the separate contributions cannot be added arithmetically. Its direction is downwards at angle θ to the horizontal (if the plane of the wires is horizontal). But if there are as many wires to the righthand side of P as there are to the left, then the downwards (vertical) component of ΔB_1 will be cancelled out by an equal upwards (vertical) component. This component is a contribution ΔB_1, from the wires between R′ and S′ symmetrically placed on the other side of P, as shown in figure 91. Vertical components of the field at P from all wires will add up to zero in this way, and only horizontal components of the contributions need be calculated.

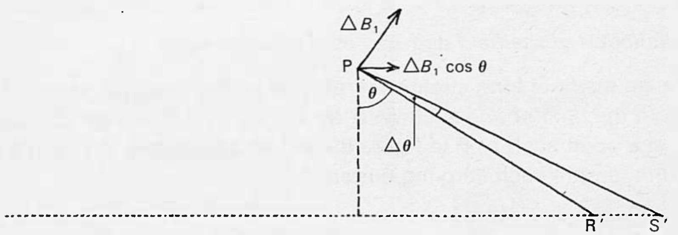


Figure 91

The horizontal component of ΔB_1 is $\Delta B_1 \cos\theta$, which can be written

horizontal contribution to $B_1 = 2\times 10^{-7} n I \Delta\theta$.

This is a very convenient expression, because it can be added up by taking all the small angle contributions $\Delta\theta$ together, since n and I do not vary from place to place.

For example, if P is close to the carpet, the sum of the angles $\Delta\theta$ from horizon to horizon is just π, so for this case,

$$B_1 = 2\pi \times 10^{-7} nI$$

and B_1 does not depend on the distance of P from the carpet. The field B inside the double carpet, figure 88, is equal to $2B_1$, as indicated previously, and B is also the field inside any solenoid with N turns over length L. Writing N/L for the number of turns per metre, n, B is given by

$$B = 4\pi \times 10^{-7} NI/L$$

to be compared with

$$B = \mu_0 NI/L.$$

It follows that if the ampere is defined in terms of a force 2×10^{-7} N on a metre of straight wire one metre from another straight wire,

$$\mu_0 = 4\pi \times 10^{-7}\ \mathrm{N\ A^{-2}}.$$

Appendix C
Suggestions for other simple induction motor investigations

Using the apparatus suggested for the course, it is easy to invent quite a number of alternative induction motor experiments, some of which may be worth trying. Figures 92 to 95 indicate some of the possibilities.

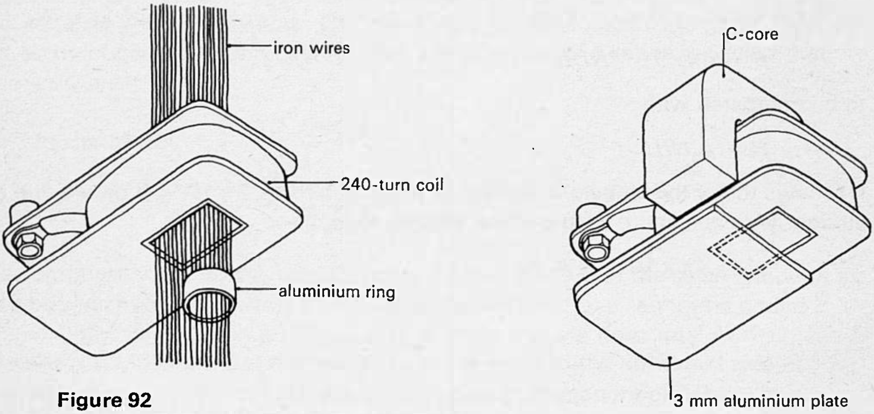


Figure 92
Two other ways of making a shaded pole electromagnet.

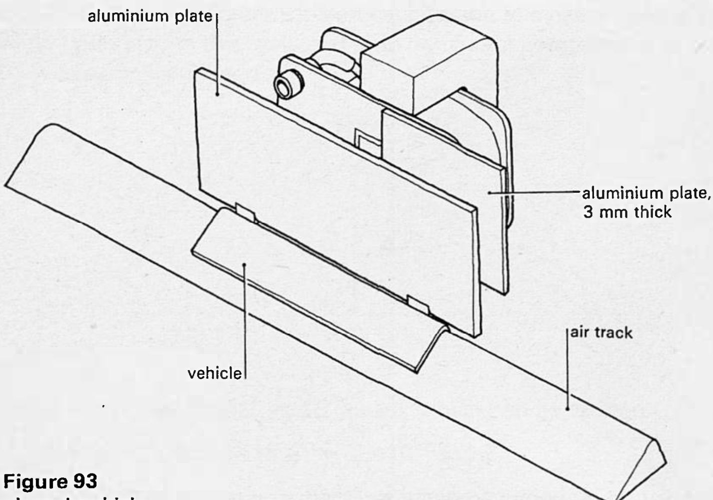


Figure 93
Driving an air track vehicle.

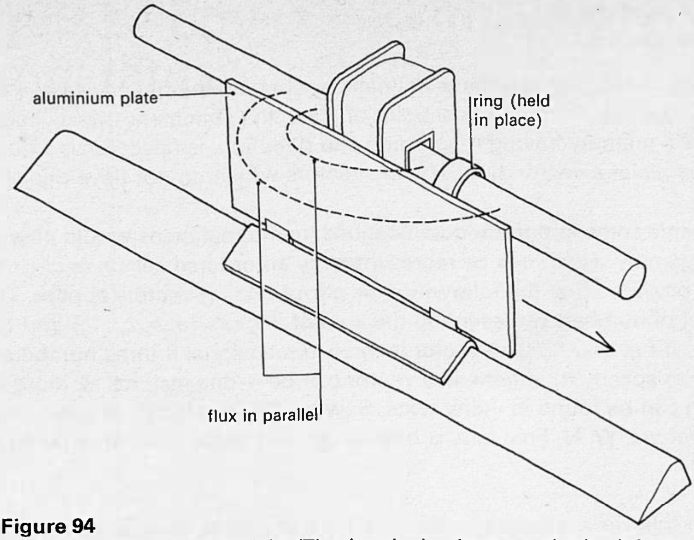


Figure 94
Another way of driving an air track vehicle. (The ring shades the magnetic circuit from end to end of the rod, which is in parallel with the unshaded magnetic circuit between parts of the rod close to the coil.)

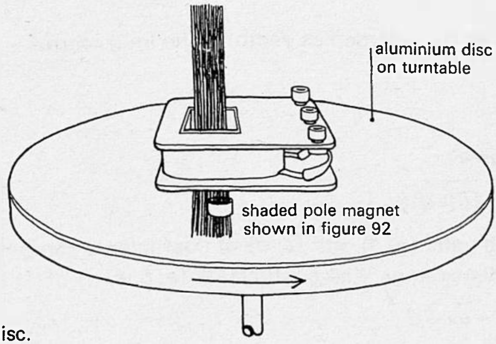


Figure 95
Driving an aluminium disc.

Appendix D
A note on vectors

In relatively recent developments in linear algebra, mathematicians have extended the notion of a vector. From this new point of view, the statement that a vector quantity is defined as a quantity having magnitude and direction, is false. Such a quantity may be an example of a vector, but there are vectors which do not have this property.

Leaving aside some important qualifications, mathematicians would now regard as a vector a quantity which can be represented by an ordered set $(a, b, c, \ldots)$ of real numbers, provided that the following rule about adding vectors applies. The rule is that the set of numbers representing the sum of vectors $(a, b, c, \ldots)$ and $(p, q, r, \ldots)$ is just $(a+p, b+q, c+r, \ldots)$. A vector is three-dimensional if three numbers are necessary to specify it; in general a vector can be n-dimensional. A more rigorous discussion can be found in many texts. Sawyer, W. W. (1959) *A concrete approach to abstract algebra*, W. H. Freeman, is brief, clear, and helpful, without being very technical.

Clearly, on this view, a magnetic field (or for that matter, an electric field) is a vector quantity, if experiment shows that it can be resolved into components and that these components add linearly when two such fields superpose. The vector is three-dimensional if it contains three orthogonal components.

Other quantities can be regarded as vectors. The linear forms

$$ax+by$$
$$cx+dy$$

can be added to give

$$(a+c)x+(b+d)y$$

so that the ordered pairs (a, b) and (c, d) of coefficients can be regarded as vectors, here having two dimensions. The coefficients (a, b, c, d) of

$$ax^3+bx^2+cx+d$$

can be thought of as making a four-dimensional vector. The idea has other applications. A wave-form which repeats itself (and which lacks sharp corners) can be expressed as a finite Fourier series of harmonic terms. The coefficients of these terms also form a vector. An analogous idea is used in modern quantum mechanics, in which a 'state vector' is used to describe the condition of a quantum system, each such condition being regarded as a superposition of basic states which play a role analogous to orthogonal unit vectors in a geometric vector. For example, the polarization of a beam of light can be given as a mixture of linear polarizations in the x and y directions. Here the state vector has two dimensions.

Lists of books, reprints, and apparatus

List of books and reprints

Page numbers of references in this *Guide* appear in bold type.

Textbooks

Arons, A. B. (1965) *Development of concepts of physics.* Addison-Wesley. **32.**
Baez, A. V. (1967) *The new college physics.* Freeman. **32, 78.**
Bennet, G. A. G. (1968) *Electricity and modern physics.* (MKS version.) Edward Arnold. **32, 78.**
Caro, D. E., McDonell, J. A., Spicer, B. M. (1962) *Modern physics.* Edward Arnold. **32.**
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Rogers, E. M. (1960) *Physics for the inquiring mind.* Oxford University Press. **32.**

Other reading

Born, M. (1951) *The restless universe.* Dover. **32.**
Classical scientific papers – physics (1964) Mills & Boon. **32.**
Laithwaite, E. R. (1967) *The engineer in Wonderland.* English Universities Press. **1, 11, 76, 120.**
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Elsasser, W. M. (1958) 'The Earth as a dynamo.' *Scientific American* Offprint No. 825.
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Van Allen, J. A. (1959) 'Radiation belts around the Earth.' *Scientific American* Offprint No. 248. **32.**
Wilson, R. R. (1958) 'Particle accelerators.' *Scientific American* Offprint No. 251. **32.**

* *Science journal* reprints are no longer available. The above titles will, however, appear in *Physics and the engineer*, a collection of these reprints to be published by Penguin in 1972 as part of the Nuffield Advanced Physics publications.

List of apparatus

10A	ball of cord	7.7
14	e.h.t. power supply	7.6
15	h.t. power supply	7.1, 7.6
27	transformer	7.10, 7.11, 7.13, 7.15, 7.17
30	slotted base	7.6, 7.13
50/1	pair of cylindrical magnets	7.1
50/3	magnet Eclipse Major	7.1, 7.9, 7.16
52K	crocodile clip	7.13
59	l.t. variable voltage supply	7.1, 7.3, 7.4, 7.8, 7.9, 7.10, 7.12, 7.17
61	fine beam tube	7.1, 7.6
62	fine beam tube base	7.1, 7.6
64	oscilloscope	7.7, 7.14
70	demonstration meter	7.3, 7.8, 7.9, 7.10, 7.12
71/1	dial for demonstration meter, d.c. dial, 1 A	7.3, 7.8, 7.12
71/2	dial for demonstration meter, d.c. dial, 5 A	7.3, 7.8, 7.9, 7.10
71/3	dial for demonstration meter, d.c. dial, 5 V	7.8, 7.12
71/8	dial for demonstration meter, a.c. dial, 1 A	7.12
72	lamp (12 V, 24 W)	7.8
74	lampholder (s.b.c.) on base	7.8, 7.11
78	variable a.c. supply (Variac type)	7.17
81	newton spring balance (10 N)	7.7
84	wire strippers	7.2, 7.9, 7.11
92	Westminster electromagnetic kit	7.2
92B	Magnadur magnet	7.3, 7.4, 7.9, 7.16
92C	reel of cotton	7.16
92G	double C-core and clip	7.11, 7.12, 7.17
92I	mild steel yoke	7.3, 7.9, 7.16
92P	aluminium ring	7.1, 7.16
92Q	aluminium ring (split)	7.1, 7.16
92R	m.e.s. bulb (2.5 V, 0.3 A)	7.12
92S	neon lamp	7.12
92T	m.e.s. holder	7.12
92X	reel of 26 s.w.g. PVC covered copper wire	7.1, 7.9, 7.10, 7.11, 7.13, 7.15
101	large Slinky	7.13
104	low voltage power unit	7.2
106/1	dynamics trolley	7.9
108/3	roll of tickertape (plain)	7.3, 7.6
130/2	photodiode assembly with light source	7.7
134/2	xenon flasher	7.7
138	deflection tube	7.6

139	set of coils and supports	7.6
140	stand for tubes	7.6
147	demountable transformer kit	7.9, 7.17
150	fractional horse power motor	7.7, 7.8, 7.9
154/1	turntable	7.9, 7.16, 7.17
158	class oscilloscope	7.11, 7.13
173	Malvern current balance kit	7.6
176	12 volt battery	7.3, 7.5, 7.7, 7.8, 7.13, 7.15
177	lamp (12 V, 6 W)	7.11
181	general purpose amplifier	7.10, 7.14
183	loudspeaker	7.10, 7.14
501	metre rule	7.6
503–5	retort stand base, rod, and boss	7.1, 7.9, 7.10, 7.11, 7.16, 7.17
507	stop watch or stop clock	7.7, 7.9, 7.10
529	scissors	7.3, 7.6
541/1	rheostat (10–15 ohms)	7.3, 7.4, 7.5, 7.6, 7.7, 7.8, 7.9, 7.10, 7.11, 7.12, 7.13, 7.15
1001	galvanometer (internal light beam)	7.4, 7.5, 7.9, 7.10, 7.13
1003/3	milliammeter (100 mA)	7.4
1003/4	ammeter (1 A)	7.5, 7.6, 7.7, 7.15
1003/5	ammeter (10 A)	7.4, 7.5, 7.6, 7.7, 7.13, 7.15
1004/2	voltmeter (10 V)	7.7
1005	multi-range meter	7.1
1007	double beam oscilloscope	7.9, 7.10, 7.12, 7.15, 7.17
1009	signal generator	7.10, 7.13, 7.14
1012	semiconductor for Hall effect demonstration	7.4
1017	resistance substitution box	7.5, 7.10, 7.12
1019	air track	7.16
1020	air blower	7.16
1027	Rogowski spiral	7.14
1029	Hall voltage apparatus for metals	7.5
1030	high inductance coil	7.3, 7.12, 7.13
1033	cell holder (with U2 cells)	7.4, 7.11, 7.12
1036	wide current balance	7.3, 7.15
1037	set of solenoids	7.10, 7.13, 7.14, 7.15
1038	Hall probe and circuit box	7.4, 7.13
1039/1	search coil (axial)	7.10, 7.11, 7.13, 7.17

1039/2	search coil (lateral)	7.10, 7.13
1040	clip component holder	7.1, 7.9, 7.17
1041	potentiometer holder	7.5
1042	magnetic field board	7.10, 7.13
1051	*Small electrical items*	
	electrolytic capacitor 500 μF, 50 V	7.17
	potentiometer 1.5 Ω	7.5
1053	*Local purchase items*	
	aluminium cooking foil	7.1
	Plasticine	7.9, 7.16
	card (e.g. postcard)	7.11
	wooden strips (to support Slinky)	7.13
	length of thick insulated wire	7.14
	aluminium plate about 40 mm by 0.2 m, 2 mm thick	7.16
	aluminium plate 50 mm square, 3 mm thick	7.17
	empty 35 mm film can	7.17
1054	*Expendable items*	
	copper wire, bare, 14 s.w.g.	7.3, 7.9
	copper wire, bare, 22 s.w.g.	7.15
	steel rod, 5 mm diameter, 50 mm long	7.7, 7.8
	rubber pressure tubing	7.7, 7.8
1055	*Small laboratory items*	
	micrometer screw gauge	7.5
	geared hand drill	7.7, 7.8
1057	a.c. ammeter	7.11, 7.13, 7.15, 7.17
1058	coil with 120+120 turns	7.1, 7.10, 7.11, 7.13, 7.17
1061	aluminium disc	7.9, 7.16, 7.17
1064	low voltage smoothing unit	7.1, 7.3, 7.4, 7.9, 7.10, 7.12
1075	electronics kit (with double beam switch)	7.11
1078	gramophone motor	7.1, 7.17
1079	flat solenoid	7.3, 7.4, 7.15
1082	coils surrounding a space	7.10

Index

Where significant information is contained in an illustration or diagram, the page reference is italicized. In general, odd-numbered page references are to the main text, and even-numbered references are to commentary material.

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There are ten Units in the Advanced Physics course. This is the *Teachers' guide* for Unit 7, *Magnetic fields*. It is intended to provide whatever information and ideas are required for the day-to-day teaching of the Unit. The book begins with an Introduction setting out the purpose of the Unit, a summary of the Unit, and a list of suggested experiments. Following this, the main text consists of three Parts, 'Forces on currents', Electromagnetic induction', and 'Flux near currents'. It contains teaching suggestions, details of experiments, and a commentary giving background information and other guidance. There are also Appendices on 'Problems of teaching electromagnetism', 'Long wires and solenoids', 'Suggestions for other simple induction motor experiments', and 'A note on vectors', and lists of relevant books, reprints, and apparatus.

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