Physics

Teachers' guide Unit 2
Electricity, electrons, and energy levels

Nuffield Advanced Science

Copy 2

Physics Teachers' guide **Unit 2**

Electricity, electrons, and energy levels

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Nuffield Advanced Science

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Electricity, electrons, and energy levels

Nuffield Advanced Science
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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 lists of apparatus and teaching aids for the Unit. These include details of books and articles referred to in this *Guide*.

Introduction

Unit 2 is about electricity and matter. It seeks to develop basic ideas about current, potential difference, and charge, and to show some of the electrical properties of materials. These ideas are then used to understand evidence for the existence of electrons within atoms (revising work from Nuffield O-level Physics) and also evidence that atoms exchange energy in lumps, having discrete energy levels.

Chemists will also be discussing energy levels (see Nuffield Advanced Chemistry, Topic 4) and the two pieces of teaching need to be planned in conjunction.

Dynamics is also revised within this Unit, as it is needed.

The ideas met in this Unit are used or developed in many later places in the course. In particular:

Unit 3 *Field and potential*
The idea of potential difference is extended to that of a potential, and the development of the idea of electric field is also based on that of potential difference. Discussion of the energy associated with an assembly of charged ions (an ionic crystal) will be helped by work in Unit 2 on stored energy.

Unit 5 *Atomic structure*
The development of the nuclear model of the atom depends both on electrical concepts met in Units 2 and 3, and on the work on atoms and electrons in Unit 2.

Unit 6 *Electronics and reactive circuits*
This uses capacitors in circuits in ways which rely on the previous experience gained in Unit 2.

Unit 9 *Change and chance*
For this Unit, the vital point is the existence of energy levels. They are made the basis of a simple model of heat exchange between solids, pictured as the random rearrangement of quanta of energy.

Unit 10 *Waves, particles, and atoms*
This returns to the energy level idea in a discussion of spectra and of photons. Much of the rest of Unit 10 shows how atomic energy levels, met as an empirical phenomenon in Unit 2, might be given a theoretical explanation.

Later use of mathematical ideas

Unit 2 contains the first encounter with numerical methods, when the decay of charge on a capacitor is discussed. Exponential decay is followed up in Unit 5, using similar methods.

These techniques are used in Unit 4, for simple harmonic motion. The use of numerical methods (simplified by much use of graphs) is an attempt to advance students' understanding of important mathematical tools.

It is part of the design of Unit 2 that the discussion moves about freely, introducing new and basic ideas, revising others, and using them to advance some of the fundamental concerns of the course. The Unit also deliberately varies the style of the problems discussed, moving from practical circuit problems to arguments about how things conduct, then to considering basic concepts, then to analysing how things change, and finally to problems of understanding the microscopic nature of matter and atoms. This variety of style is meant to show some of the important kinds of concern physicists have, and to show how a result obtained in one area can help in another.

Not all the parts of Unit 2 need to be taught together. The work on energy levels could go with Unit 5, *Atomic structure*, being used there to show how electrical concepts can be used to extend knowledge and pose new problems. This would have advantages if Unit 4 were placed between Units 2 and 3, to make an earlier break from electricity, so that Unit 5 followed Unit 3. There would then be less need for the part (on ionic crystals) that ends Unit 3, whose purpose is also to show a use for electrical concepts.

Some parts of Unit 2 must come early in the course. The analysis of exponential decay must come before that of simple harmonic motion (Unit 4), and before that of radioactive decay (Unit 5). The concept of charge as a quantity of electricity should precede charge as the source of an electric field. Potential differences in circuits seem to us to be easier to start with, and more concrete, than the notion of the potential of a field.

Summary of Unit 2

Time: up to 6 weeks, not more.

(Numbers in brackets refer to suggested experiments, listed on page 6).

Part One
Things which conduct

Time: less than a week.

This Part gives experience of the conducting properties of things, and practice in building circuits and choosing meters. It also shows how to argue about the conduction of electricity by the motion of many charged particles.

Suggested sequence

Measurement of current and potential difference (2.1). Resistivity (2.2). Temperature effects (2.3). Insulators (2.4) and semiconductors. Amount of charge conveyed by many moving charged carriers (2.5).

Part Two
Currents in circuits

Time: about a week.

This Part is about circuits and potential differences. It introduces the potentiometer as a device for varying a p.d. (needed in Unit 6) and, in passing, as a means of comparing potential differences. It gives further experience in handling and choosing meters.

Suggested sequence

Use of ammeters and voltmeters to study circuits; current and potential difference in circuits (2.6, 2.7, 2.8, 2.9). Potential difference as energy transformed per coulomb passing (2.10, 2.11). Effect of supply resistance (2.12, 2.13).

Part Three
Electric charge

Time: about a week.

Electric charge is treated as a quantity of electricity which, like a quantity of water, can be stored and can pass from place to place without getting lost. The class can make a simple, open investigation of large capacitors. The decay of charge on a capacitor introduces exponential changes, and the graphical-numerical techniques (used elsewhere) for analysing such changes.

Suggested sequence

Flow of pulses of current in capacitor circuits (2.14). Charge and capacitance (2.15, 2.16). Exponential decay (2.17) with numerical analysis of an experiment.

Part Four

Stored energy

Time: less than a week.

This Part considers the energy of a charged capacitor, partly to reinforce the idea of potential difference, and partly to assist later work on fields and energy. It also, by way of revision and comparison, considers the energy of a stretched spring.

Suggested sequence

Energy stored in a capacitor (2.18), proportional to V^2 (2.19, 2.20). Energy stored in springs and catapults, revision of work, kinetic and potential energy (2.21, 2.22). This can use the group working system, with students reporting their work to the rest.

Part Five

Electrons and energy levels

Time: rather more than a week.

After revision from Nuffield O-level Physics of evidence for the existence of electrons, and a fuller study of their charge, an attempt to understand ionization leads both to electron collision experiments and to revision of dynamics, particularly momentum. More careful electron collision experiments indicate a finite energy needed to ionize an atom and hint at the existence of energy levels. This is followed up by reading of selected extracts from papers which present clear evidence for the existence of atomic energy levels from the discrete energy losses of electrons bombarding gas atoms. Finally, the place, in a theory of atoms, of evidence for the existence of energy levels is surveyed.

Suggested sequence

Electron streams (2.23), charge on an electron (2.24, long experiment). Electrons as particles with momentum and energy (film). Ionization of air in several ways (2.25). Ionization by electron collision (2.26). Revision of dynamics of collisions (2.27). Ionization and excitation (2.28, 2.29). Elastic and inelastic collisions of a light particle with a massive one (2.30). Reading of extracts from papers dealing with energy levels of rare gases and of mercury. Facts, evidence, and theories.

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 2

Part One

Things which conduct

Time: less than a week

Discussion of teaching and aims of Part One

Part One is about electricity flowing in conductors and the relationship between current and voltage. A variety of single conductors is used, and one purpose of the Unit as a whole is to get students curious about the possible flow of electricity in conductors they meet. The ideas of current and voltage are simple but most of their value to a scientist is in their being quite familiar to him whenever he deals with situations in which electricity moves. A scientist needs an almost instinctive feeling for how current and voltage might be measured in real situations. Part One begins the work of this Unit by trying to promote this instinct and familiarity. Specific knowledge acquired about circuits and circuit elements is only a secondary object, even though for some it may be of great value.

Nearly all school time can be devoted to experience of measuring, either in small groups or in demonstrations in which members of the class participate, so that they develop a familiarity with ammeters and voltmeters.

Pieces of theory are covered by questions in the *Students' book*, so that class time can be confined to discussion of attempts at the theoretical arguments in those questions.

In teaching electricity, the very different levels of students' knowledge are often a problem. A student who can talk authoritatively about the causes of distortion in an amplifier may be at the same bench as a student who thinks that electricity is used up as it goes through a light bulb. The difference between students is lessened, and all are given a searching problem, if the contents of the boxes are concealed.

Learning to choose meters and use them sensibly

From now onwards, meters (microammeter, item 1002, milliammeters, item 1003, and voltmeters, item 1004) should be available to the class so that students can make electrical measurements whenever they see good reason for doing so. If students are unfamiliar with the instruments, their operation (accessories on basic movements, multirange meters, or others) should be briefly explained before the work of this Unit is begun. The Unit will have failed in its purpose if students cannot, after some weeks' work on electric current, make sensible judgments about what meters to use in the situations which will arise later. Practical work throughout the rest of the course depends on these judgments.

Here is an opportunity to mention commonsense precautions for avoiding damage to meters. The two obvious precautions are to use the highest range of meter first, and to use the lowest supply voltage first. But over-emphasis on precautions can be inhibiting. Meters are fairly robust nowadays.

Interpreting graphs

Making and interpreting graphs is a useful skill, practised here and in questions about voltage-current curves.

Experiment

2.1 Two-terminal boxes

1003/3 milliammeter (100 mA)

occasional access to other meter ranges

1033 cell holder with four U2 cells *2*

1047 kit of two-terminal boxes

1000 leads

1054 graph paper

Part One starts with a session of practical work in which a set of puzzles can be partly solved by making elementary measurements.

Experiment

2.1 Two-terminal boxes

Students may be told, 'Here is a set of boxes, each with two terminals, most containing something simple which you have met before. The bottom of the box is open, so you could look in it, but try to find out what is in it by electrical measurements as if the bottom were sealed up. When you think you know what is in your box, tell me, and I will tell you how I think you found out. You may put as much as 12 volts across any box and the current will not exceed one-tenth of an ampere. Assume dry cells give 1.5 volts each unless you think they need checking.' Graph paper should be available.

The object of the puzzles is not to test knowledge but to increase experience and confidence, so help should often be given and whatever a student discovers should be treated as an achievement. Ideally students would apply different voltages in both directions and plot graphs. If the voltage is not varied, a bulb cannot be distinguished from a resistor. If the voltage is not reversed, a diode cannot be distinguished from a resistor. The very high radio resistor requires a sensitive meter, and so does the diode in its reverse direction – if a galvanometer is used with the diode it is wise to check that students avoid using it for the forward direction. There is no way of distinguishing the three boxes containing 500 ohms. A student who knows that his box contains a 200 ohm and a 300 ohm resistor in series must have found out by looking. The cadmium sulphide (photoconductive) cell should give inconsistent results, and finally show that there may be factors (such as illumination) other than temperature which affect the resistance. The capacitor is to be used later and practical acquaintance with it will be useful. If students find it baffling, agree with them.

Students should have a chance to use most of the boxes, so as to get experience of different meters, and a brief discussion at the end should elicit from them the characteristics by which they recognized the devices in the boxes. The important lesson is that current-voltage curves are revealing: there is no need to try to memorize the exact behaviour of any device.

Straight line behaviour and Ohm's Law (revision)

Current-voltage graphs for several boxes will be straight lines through the origin. For good conductors, particularly metals, when the temperature is kept constant the voltage across the conductor is proportional to the current through it. This useful practical fact is known as Ohm's Law.

The ratio of voltage to current is called the resistance, measured in ohms. The ratio need not be constant, but if it is, then Ohm's Law is obeyed and calculations are easier.

Suggested contents for the boxes are:

very high radio resistor

tungsten filament lamp

germanium diode with safety resistor in series

three boxes containing marked resistors:
500 ohms
200 ohms and 300 ohms in series
820 ohms and 1200 ohms in parallel

cadmium sulphide cell with a hole in the box so that light can enter it

100 μF 50 volt electrolytic capacitor

The two terminals of each box should be different colours so as to be distinguishable, but not red and black, which might imply a direction for the current. The boxes should conceal what is inside when they are placed bottom downwards on the bench (for example, the lamp should not visibly emit light) but there is no reason to prevent students looking inside if they want to. The experiment will be duller for them if they do.

A kit of boxes from a manufacturer will not contain all the things listed above. Teachers should add whatever they think suitable. Students could make up puzzles for one another if they want to.

Students' book

See questions 1, 4, 5 about voltage and current measurements. Questions 6 and 7 deal with resistors in parallel.

Textbooks

Arons, *Development of concepts of physics*, Chapter 25, has a useful historical bias.
Bennet, *Electricity and modern physics*, Chapter 2.
Rogers, *Physics for the inquiring mind*, Chapter 32.

For details of the above and other reading recommended in this Commentary, see the list entitled 'Books and further reading' on page 127.

People as conductors

Do students obey Ohm's Law? If there are five minutes to spare, this question can be asked to emphasize that anything may conduct. Getting an answer is not profitable, but a circuit consisting of two or three students, a microammeter, and up to 8 dry cells shows conduction. The students may be in series or in parallel.

Demonstration

2.2 Conduction by wires

176	12 V battery
1003/4 *or* 79 *or* 178	ammeter (1 A)
59	l.t. variable voltage supply
1004/1	voltmeter (1 V)
1054	bare constantan wire, 24 and 32 s.w.g. (covered constantan can be used)
1000	leads

Combinations of resistors

When conductors are connected to one another in series or in parallel or both, the combination also has a voltage-current ratio, or resistance.

In experiment 2.1, the three boxes containing resistors of 500 ohms, 200 and 300 ohms in series, and 800 and 1200 ohms in parallel, illustrate this idea, for they conduct about equally well although they contain very different resistors.

The rules for calculating resistances in series and parallel circuits are useful to physicists and electrical engineers, though they are a means to an end rather than an end in themselves.

Resistivity

Some materials conduct better than others. How can one most usefully state the ability of a material to conduct? The resistivity ρ and the rule $R = \rho L/A$ need to be introduced, perhaps as follows.

Demonstration
2.2 Conduction by wires

a If the point is not evident, it can quickly be shown that long wires need bigger voltages than do short wires to drive the same current through them, and that thick wires carry bigger currents than do thin wires for the same voltage.

What would be a good way of marking on the reels of wire a quantity to indicate how well the wires conduct? (Give the resistance per metre.)

The resistance per metre for several wires is:

24 s.w.g. constantan	about 2 ohms per metre
32 s.w.g. constantan	about 8 ohms per metre
32 s.w.g. copper	about 0.3 ohm per metre.

24 s.w.g. wire has a diameter about twice that of 32 s.w.g. wire (0.559 mm, 0.274 mm). Questions about why the thick constantan conducts four times better than the thin constantan; how much better copper conducts than constantan; how to calculate the resistance of a copper bar (say 10 mm $\times$ 20 mm cross-section) carrying current in a power station; or how fine a copper wire would need to be to have a resistance of, say, 2 ohms per metre, can lead to $R \propto L/A$ and the resistivity $\rho = (R/L)A$.

Like the Young modulus, a value of the resistivity of a material is a compact way of summarizing useful information of practical value, although tables of resistances per metre, while less compact (why?), are quicker for the engineer to use.

a The ammeter can be used to measure the current through about 0.2 m of 32 s.w.g. wire when one cell is used to drive the current. The 0.2 m can be part of a longer length, more of which is used across 2, 3, and more cells of the battery, the length being increased so that the current is the same. About one metre of 24 s.w.g. can also be used.

b The wire AG can be one metre of either gauge across the l.t. variable voltage supply set to produce 1 volt. (A metre bridge can be used.)

Teachers may prefer the l.t. variable voltage supply instead of the 12 volt battery for a, but it is not quite so obvious when the voltage is being increased by equal steps.

Potential differences along a wire

Demonstration 2.2b makes explicit what has been assumed already, that potential differences across equal resistors carrying equal currents are equal, and that potential differences in a series circuit add up. The idea has been met at O-level, but needs to be presented again, at least in passing.

Involving students in demonstrations

Ideally all these demonstrations would be done by students, singly or in pairs, the teacher being merely a referee. The greater sense of involvement and the practice in communication could be set against technique being less slick. And the standard might quickly rise. The experiments which cannot be done by all students should be considered as opportunities for individual student demonstrations, but teachers will find the organization more difficult and must decide for themselves how often they can manage it.

Students' book

Questions 6 and 7 deal with the dependence of resistance on area. Questions 8 to 12 are about resistivity.

Demonstration
2.3 Effects of temperature on resistance

59	l.t. variable voltage supply
1003/4 *or* 79 *or* 178	ammeter (1 A)
1054	enamelled copper wire (3 metres of 36 s.w.g.)
512/2	beaker
1021	aerosol freezer
1051	carbon resistor ($\frac{1}{8}$ watt, 150 ohms)
1040	clip component holder
1003/2	milliammeter (10 mA)
1033	cell holder with four U2 cells
132N	thermistor (Radiospares TH3)
	hot and cold water

Connect the wire, the ammeter, and the l.t. variable voltage supply (about 2 volts) in series. Measure the current when the wire lies in a tight bundle, is laid out more loosely, and is put in hot water, in cold water, and is cooled by the aerosol freezer.

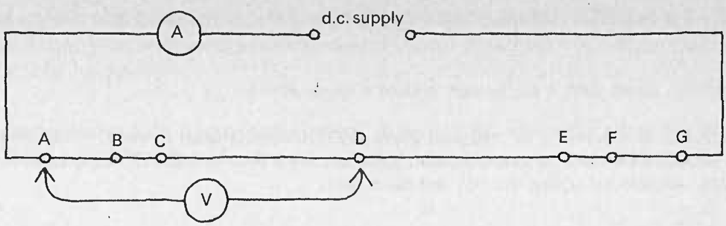


Figure 1

b Some more questions, with apparatus to hand, about the uniform potential difference per unit length in a long wire carrying current are desirable. Figure 1 shows a metre of wire, AG, connected to a supply.

What will be the reading of the voltmeter between A and G?

What will be the reading of the voltmeter between A and D? (D is the mid-point of AG.)

What will be the reading of the voltmeter between D and G?

What will be the reading of the voltmeter between B and C? (BC is roughly AG/10.)

What will be the reading of the voltmeter between E and F? (EF is roughly the same as BC.)

. . . and so on.

Effect of temperature

What conditions do, or might, affect the resistance of a wire? Temperature is one such condition, suggested by the lamp in experiment 2.1.

Demonstration
2.3 Effects of temperature on resistance

A length of copper wire is connected to a supply and an ammeter. If the wire is in a bundle, the current drops a little after a few moments, the effect being less if the wire is laid out more loosely. Immersing the wire in hot and in cold water, and cooling it with a freezer, test the suggestion that the resistance changes with temperature.

The class may be invited to speculate: why might resistance rise with temperature; must it always do so? It is fair to warn them that theories of conduction turn out to be rather complicated, and that much remains unclear about conduction in many materials. Easy questions in physics don't always have easy answers.

Show the opposite effect with the carbon resistor, using the milliammeter and a single cell. The effect is small.

The thermistor, again with a single cell, shows a larger effect.

The conduction of electricity by a heated glass rod (Nuffield O-level Physics, *Guide to experiments IV,* 146) should be shown to students who have not seen it before. D147, 'Conductivity of germanium', should be added if it has not been seen.

Aims

It is not suggested that this brief demonstration need expand into a discussion of the linearity or otherwise of resistance-temperature relationships, or that the temperature coefficient of resistance be introduced.

The intention is to make students aware that resistance need not be a constant quantity, so that they might, for instance, think of the effect later on in some investigation.

It is worth asking students to speculate, simply to make it clear to them that problems can easily be thought of but not so easily answered. Physicists do not have all the answers. Students (or teachers) interested in the matter could consult the *Scientific American* book *Materials*, particularly the articles, 'The solid state' and 'The electrical properties of materials'.

In later work, Unit 9, *Change and chance*, reasons will be given for the roughly exponential rise of conductivity with temperature of some materials.

Textbooks

Many texts discuss resistance changes with temperature. Those which say least will often be best.

Students' book

See questions 10, 11, 14, and 16.

Demonstration

2.4 Attempt to measure conduction in polythene

1001 galvanometer (internal light beam)

1033 cell holder with four U2 cells *2*

1053 part of a polythene bag

97B Aquadag

1040 clip component holder

1053 brush

Cut a few square centimetres of thin polythene sheet and paint the middle of one side of it with Aquadag. When the Aquadag has dried, paint the middle of the other side as well. When both sides are dry, use the galvanometer to measure the current passing when a supply of about 10 volts is placed between the two coatings. Caution is necessary because a small hole in the polythene could result in burning out the galvanometer. A safety resistor is needed in the circuit, for which the teacher himself is very suitable. There will be no detectable current, although the Aquadag on either side can be shown to be conducting well. A glass microscope slide instead of polythene shows no current either.

Objects for which the resistance falls with temperature can be shown: a carbon resistor and a thermistor. Glass also conducts when it is hot. Would any of these be useful for a thermometer?

A slice of germanium conducts less current than would a similar slice of copper, and the current rises with temperature, while that through copper would fall.

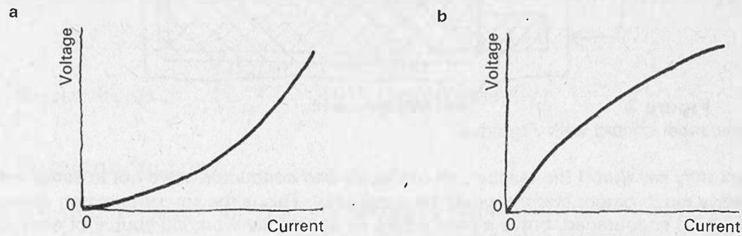


Figure 2
Current-voltage curves.
a Tungsten lamp.
b Carbon resistor.

'Conductors' and 'insulators'

What would one mean if one spoke of a perfect conductor? (A material which has a zero potential difference across it whatever current goes through it.) No material is a perfect conductor at ordinary temperatures.

What would one mean if one spoke of a perfect insulator? (A material which allows zero current to pass through it whatever potential difference is applied.) No material is a perfect insulator.

But materials differ in resistivity by much bigger factors than in most other properties, so that a thing which is called an insulator can be very different from a thing which is called a conductor.

Demonstration
2.4 Attempt to measure conduction in polythene

The class can be invited to contribute to the design of an experiment.

In demonstration 2.3, a small p.d. drove a big current through a long thin wire of copper. To detect a current in polythene, it would be best to use a more sensitive meter, a shorter distance through the polythene, and a bigger area of cross-section. Try a thin sheet. Its thickness may be 10^{-4} of the length of the copper wire, and its area of cross-section 10^3 times the area of cross-section of the wire.

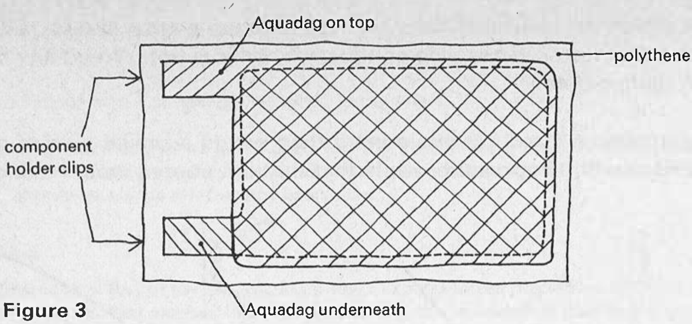


Figure 3
Polythene sheet coated with Aquadag.

A student may say that if the teacher, an obviously bad conductor, were not in series with the specimen, a much bigger current would be conducted. This is the sort of common sense approach which is to be encouraged, but is a case where an apparently worrying source of error can be shown to be quite negligible.

A trial with only the teacher in circuit shows that he conducts a current perhaps a hundred times larger than the smallest detectable current. So, when in series with the polythene, his presence reduces any current there is by less than 1 per cent.

Measuring the resistivity of polythene is very difficult, and the experiment described above does not succeed in doing it. But it illustrates the value of an experiment which might be considered exceedingly crude. Materials differ in resistivity by factors of 10^{20} or more, and to illustrate this surprising fact an experiment with a large margin of error may be good enough.

Students' book

See questions 10 to 13, which all involve insulators.

Doped germanium

Germanium can be doped with traces of elements higher or lower in the Periodic Table to give a material that behaves as if it contains extra negative or positive charge carriers, called n-type and p-type respectively. The undoped germanium slices available are not the purest possible germanium, and very pure germanium will conduct perhaps a thousand times worse than doped germanium. None of this need be mentioned now: the two types of doped material can wait for evidence from the Hall effect in Unit 7.

A logarithmic plot

Figure 4 is the first use of a logarithmic plot in the course. The resistivity scale is in powers of ten. Were the exponents written on the scale in place of the values expressed as powers, the scale would be of the logarithm of resistivity. The vast range of resistivities makes this an excellent first example of the value of the technique. A student could estimate the length needed for the PTFE 'bar' if the plot were linear and the 'bars' for metals were, say, 10 mm high. (It would reach beyond the edge of our galaxy.) Figure 4 appears in the *Students' book*, question 10.

The p.d. could be 10 times bigger and a suitable meter would detect a current of 10^{-7} A instead of 1 A. So the resistivity of polythene might be $10 \times 10^4 \times 10^3 \times 10^7$, or 10^{15} times as big as for copper, and current in it could still be detected. Will this be a big enough factor?

A trial shows that it is not: polythene is at least 10^{15} (a thousand million million) times more resistive than copper. The data below show that the factor is bigger still:

	Copper	Polythene
Resistivity/Ω m	10^{-8}	10^{15} (approximately)

Semiconductors

Figure 4 is a (logarithmic) bar diagram showing the resistivities of some materials, and the direction of the change of resistivity with rise of temperature. Certain metal-like elements share with insulators the property of conducting better when they are warmed. They appear in the middle of figure 4, having also resistivities intermediate between conductors and insulators: this property has suggested the name semiconductors. Chemists will doubtless point out their grouping in the Periodic Table.

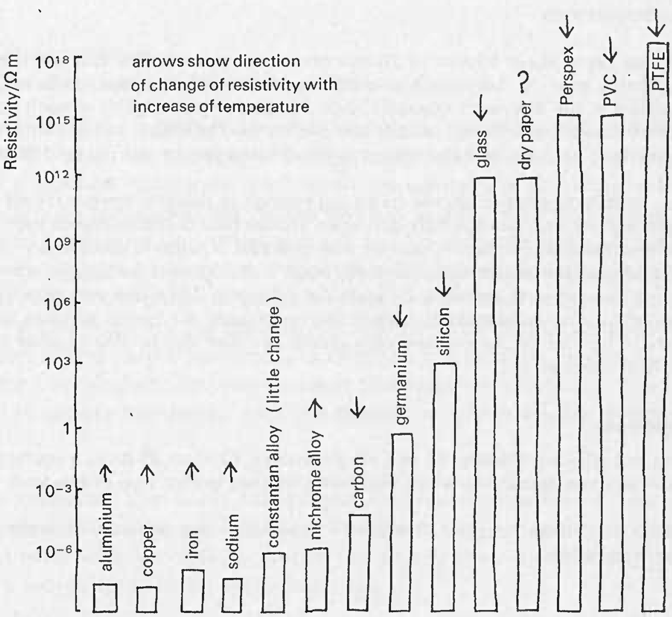


Figure 4
Resistivities of materials.

Demonstration

2.5 Conduction by coloured salts

3N	copper sulphate crystals
1056	potassium permanganate crystals
1056	ammonium hydroxide solution
1054	filter paper
3G	microscope slide
91E	large pin *2*
52K	crocodile clip *2*
15	h.t. power supply
1000	leads

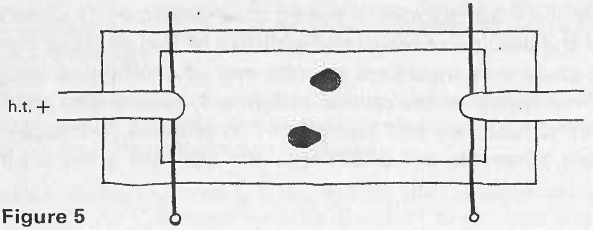


Figure 5
Movement of coloured ions.

Put a piece of filter paper about 50 mm by 20 mm on the microscope slide and wet it with ammonium hydroxide solution. Let excess solution run off if it will. Lay pins across each end of the paper and clip them to the slide with crocodile clips. Put one or two crystals of each sort on the paper, and connect the clips to the h.t. supply and switch on. The colour of the permanganate will move appreciably in a few seconds. The copper is slower, and can be spoiled by diffusion.

The ammonium hydroxide solution should be strong enough to dissolve the precipitate which it would form with copper sulphate solution, giving an intense blue cuprammonium sulphate solution. One part of concentrated ammonium hydroxide with one part of water is satisfactory. The paper should be horizontal so that the solution stays still upon it. If 200 volts are applied the colours move fairly quickly. In a class experiment using 24 volts the colours would move very slowly, and evaporation and diffusion would make the result less conclusive. H.t. power supplies are not internally limited to non-lethal currents and *care should be taken that no one touches the leads* while the supply is switched on.

Textbooks

PSSC *Physics* (2nd edition), Chapter 26 or *College physics*, Chapter 23 gives a useful qualitative survey of conductors and insulators, which also looks forward to Part Five of this Unit.

Bennet, *Electricity and modern physics*, Chapter 17 is useful for the student who wants to know more about semiconductors.

Doped germanium or silicon is the basis of the transistor and the more recent integrated circuit chip. Later work on electronics will use such devices. These materials will also be used later in the course for measuring magnetic fields. They are examples of the possibility of engineering useful electrical properties into materials, to be compared with the engineering of useful mechanical properties discussed in Unit 1.

How is electricity conducted?

Nothing about seeing or handling a piece of copper and a piece of polythene would make one expect copper to conduct enormously better than polythene. (Might one not expect it to conduct rather worse, because, as it is denser and more opaque, it might have less unoccupied space for the electricity to run about in?)

The explanation which is thought to be correct is that copper contains many electrons which carry electricity and are free to move, whereas in polythene all the electrons are fixed. And in general, better conductors contain more free electrons.

This theory has a surprising consequence involving the speed at which the 'carriers' of electricity must move. It can be illustrated by a demonstration although unfortunately the conductor must be an electrolyte.

Demonstration

2.5 Conduction by coloured salts

A strip of filter paper, moistened with ammonium hydroxide solution, is placed between two electrodes capable of being maintained at a fairly high steady p.d. The paper should be horizontal, and when the solution is no longer moving from place to place on the paper, but before the p.d. is applied, small crystals of copper sulphate and potassium permanganate are put on different parts of the paper. The crystals make coloured stains, each of which diffuses outwards symmetrically and very slowly. When the slow diffusion has been seen to be symmetrical the p.d. is applied. In a few minutes the stains have slightly extended unsymmetrically, the purple stains of the permanganate ions towards the positive electrode and the blue stains of the cuprammonium ions towards the negative electrode. The speed of the movement is minute compared with the speeds at which electrical signals normally travel.

It must be conceded that such a demonstration is not conclusive. The colours and the electricity both move, but the experiment is not direct evidence that they are linked. But even without other evidence the theory that the electricity travels with the colours would have to be taken seriously.

The speed of electrical signals

The 'speed at which electricity travels', and what one means by this, are taken up again later in the course.

In Unit 4, *Waves and oscillations*, the speed of an electrical pulse is measured as it travels along a wire, and found to be between 2 and 3×10^8 m s^{-1}. This speed is not only about a million million times faster than the drift speed of electrons in the wire, but is faster than most individual electrons travel (in contrast to the speed of sound in a gas, which cannot be greater than the speed of individual molecules because molecules exert forces only in collisions).

In Unit 7, *Magnetic fields*, there is an experiment which indirectly measures the drift speed of electrons carrying a current in aluminium, and the drift speed is found to be very small because aluminium contains so many free electrons.

In Unit 8, *Electromagnetic waves*, there is a discussion of why the speed of a pulse in a wire is so great, and the speed is linked not to the properties of electrons but to the properties of the electric and magnetic fields around the wire.

In Unit 2 there is no need to mention the later work, but when the later work comes there will be a need to refer back to what has been done in Unit 2. By the end of the course students should know the difference between individual carriers' speeds, the average (drift) speed of carriers, and the speeds of electrical pulses or signals conveyed by wires.

Students' book

Question 17 is a preparatory question, about transport. Questions 18 and 19 go through the argument leading to $v = I/Anq$. Question 20 does the same, for electrons in a metal.

Speed of particles and speed of disturbance

Teachers will need to be ready to meet students' difficulties over the glaring discrepancy between the low speed of conducting particles and the negligible delay there is between switching on a light and the lamp coming on. The difference, of course, is the difference between the time for an electric field impulse to travel round the circuit, during which time the carriers start moving, and the long time any one carrier would take to go an appreciable distance because of the low drift velocity which all carriers have then acquired.

Such an account goes too far too quickly for most students. Teachers could try a comparison with a queue of cars in a traffic jam. When the front of the queue starts moving, it may not be long before all of a queue a hundred metres long is moving. But in that time, each car may move forward only a short distance. The motion of people in a queue for meal service may be an example nearer to students' recent experience! It may be best to say little, and promise a return to this problem later on in the course (Units 4 and 8).

Speed of conducting particles

How can there be a measurable current with very small charges moving only very slowly?

How can it be that transatlantic liners and jet aircraft can carry comparable total traffic across the Atlantic despite their different speeds? (The liners carry more people per trip, the aircraft go faster and more often. Nowadays, the aircraft carry most traffic.)

The following argument is developed in questions in the *Students' book.* Consider a canal of cross-section A containing conducting liquid which carries current I. Suppose the current is carried by 'carriers' all identical to one another, of which there are n per unit volume, each carrying q and each moving with velocity v. See figure 6.

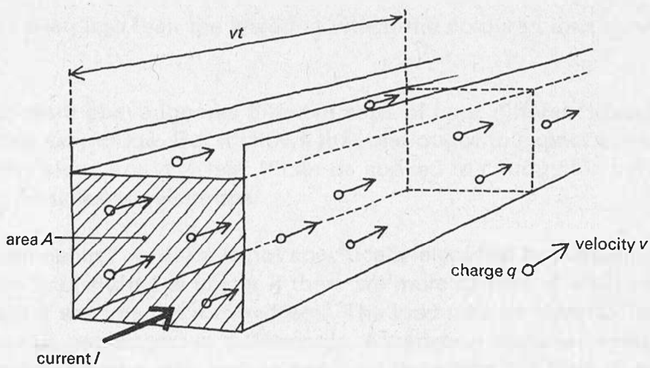


Figure 6
Current conveyed by charge carriers.

In time t the carriers in a volume Avt would cross an imaginary fixed surface perpendicular to the current.

In time t, the number of carriers crossing the surface $= Avtn$.
Therefore in time t, the charge passing $= Avtnq$.
As the current is I, this charge is equal to It.

Therefore $It = Avtnq$
and $I = Avnq$
and $v = \dfrac{I}{Anq}$.

Number of molecules

A molar solution contains 6×10^{23} molecules in 1 dm^3, so 6×10^{26} in 1 m^3. This uses the ideas of the mole and of the Avogadro constant, developed in Unit 1.

Applications to other flow problems

It is worth mentioning one or two of the other kinds of practical problem where the same analysis of transport can be applied, particularly as it applies to the urgent traffic problems of big cities. The fact that the same analysis works in many different areas is worth noting.

Students' book

Question 21 shows how the analysis of transport could be applied to the commuter traffic of a city.

If the conductor's cross-section is only 1 mm² (10^{-6} m²), a current of 10^{-4} ampere might be conducted. It is hard to guess what n and q might be, but in a molar solution there is enough solute to make 6×10^{26} molecules in every cubic metre, and this might do as a first suggestion for the number of carriers, although a molecule has no net charge and could not be a carrier itself. And the charge on each carrier might be the charge on one electron, 1.6×10^{-19} coulomb.

So as a guess:

$$v = \frac{I}{Anq}$$

$$= \frac{10^{-4}}{10^{-6} \times 6 \times 10^{26} \times 1.6 \times 10^{-19}}$$

$$= 10^{-6} \text{ metre per second, roughly}$$

which is even less than the speed at which the coloured ions moved on the filter paper.

The treatment above ignores different sorts of ions, different speeds of ions, and is altogether very crude. But it shows that one ought to expect the speed of particles to be very slow, not very fast. It can be applied to conduction by a metal, where the moving particles are electrons.

The relationship $I = Avnq$ is not specifically electrical but applies to all transport. The total load shifted is bigger if there are more carriers, if each carrier carries more load, and if each carrier moves faster. The load may be material to build pyramids or it may be passengers in a Concorde. A transport engineer trying to deal with the traffic problems of a city, and an engineer designing the flow of materials along a production line, will both use similar sorts of argument. Indeed, the flow of electricity is not unlike rush hour traffic: large numbers of slow-moving small-sized units convey a substantial total flow.

Part Two

Currents in circuits

Time: about a week

Four-terminal boxes

In their first work on electricity, students were given a chance to see something of how electricity goes through different materials. The next stage is for them to see what happens when a current divides in networks containing more conductors. A network of several conductors is more complicated, and in order to make early problems manageable we must limit their scope and consider primarily conductors which are linear in their current-voltage relationships. Eventually (Unit 6, *Electronics and reactive circuits*) students will deal with devices, such as amplifiers, which are internally quite complicated, but which can be considered simply as the unknown contents of a useful box, where the important lessons come from dealing with it as a complete thing. Partly to encourage such an approach before it becomes necessary, and partly for practical convenience, students should now be asked to find out what they can about a set of boxes, each of which has four terminals. Two terminals can (but need not) be regarded as 'input' and d.c. can be applied to them. The other terminals can be regarded as 'output' and the output from them can be measured. The boxes are all passive, that is, they contain no source of power. The only non-linear component is a diode.

The boxes A, B, C, and D in kit 1 are easier than those in kit 2, and trial experience suggests that use of both kits at once is too hard for most students. For some classes, it will be best for the teacher to replace the contents of some of the boxes in kit 2 with easier circuits, for success at an easy task will be much more valuable than failure at a hard one, in building up a feeling of confidence.

Experiment
2.6 Four-terminal boxes

1033	cell holder with four U2 cells
1003/3	milliammeter (100 mA)
1004/2	voltmeter (10 V)
179 *or* 80	voltmeter (lower resistance than 1004/2)
1048/ 1/2	four-terminal boxes, kits 1 and 2
1000	leads

The circuits in figure 7 are suggested. Teachers or students may invent other circuits.

Aims

This work is not aimed primarily at circuit analysis, though better students might get as far as that by themselves. It aims to improve their ability to think out simple electrical experiments, choose and use apparatus, and relate what they observe to what they might expect to observe. We also hope that students will afterwards use electrical instruments with greater confidence, and expect to meet and tackle similar simple puzzles at other times.

Students' book

Question 24 is a four-terminal box problem.

Further work for faster students

While investigating boxes G and H, students who are getting on well may be asked to compare the voltmeter 1004/2 with the O-level Physics voltmeter item 80 or 179. They should find disagreement between the high resistance Advanced level meter and the low resistance O-level meter. The next experiment (2.7) explores this disagreement.

Experiment
2.6 Four-terminal boxes

See figures 7 and 8. The class may be started off roughly as follows, with the boxes A, B, C, D in figure 7.

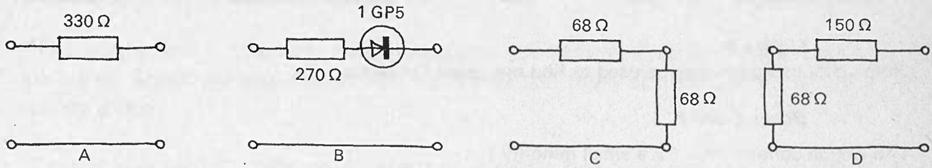


Figure 7
Four-terminal boxes, kit 1.

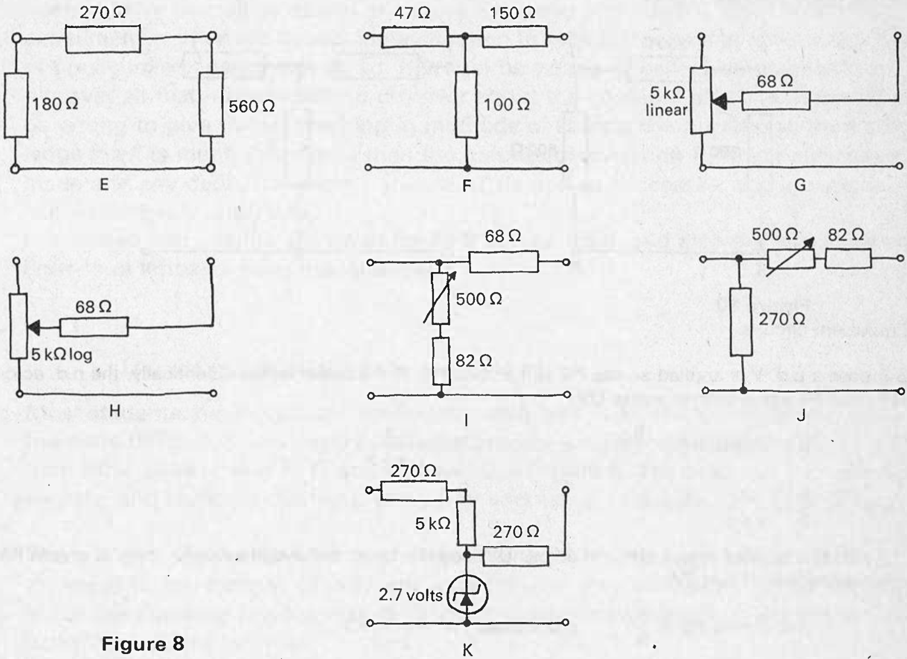


Figure 8
Four-terminal boxes, kit 2.

'Each of these boxes contains a simple circuit. In each box, as you can see, the green terminals are connected together. Find out what you can about the circuits without looking underneath, and tell me when you think you know.

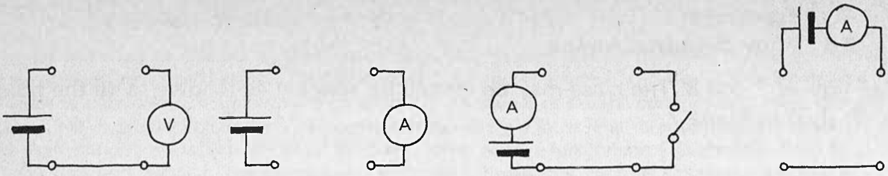


Figure 9
Some circuits which may be used to find out about the boxes.

Boxes E and F

(An option suitable only for a small minority.)

How and why these boxes are equivalent is an exercise which may interest the best mathematicians, who can be invited to consider the two circuits in figure 10 which have simpler values than those in boxes E and F. The series and parallel formulae are needed. What values of x, y, and z will make box TUVW seem like box PQRS?

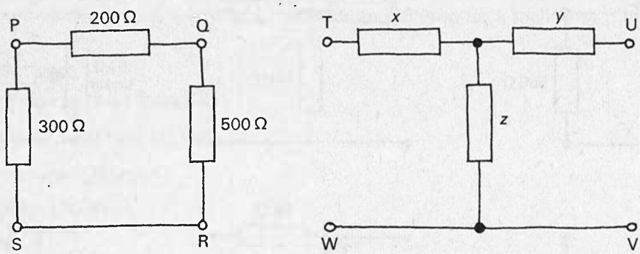


Figure 10
Equivalent circuits.

Suppose a p.d. V is applied across PS and across TW. If the boxes behave identically, the p.d. across QR must be equal to that across UV.

p.d. across QR $= \frac{5}{7}V$ p.d. across UV $= \frac{z}{x+z} \times V$

Thus $\frac{5}{7} = \frac{z}{x+z}$ **1**

If a p.d. V is applied across QR and across UV, and the boxes behave identically, the p.d. across PS must equal that across TW.

p.d. across PS $= \frac{3}{5}V$ p.d. across TW $= \frac{z}{y+z} \times V$

Thus $\frac{3}{5} = \frac{z}{y+z}$ **2**

Further, the effective resistance between Q and R, which is 250 ohms, must equal that between U and V, which is $(y+z)$.

$250 = y+z$ **3**

From equations 1, 2, and 3:

$x = 60\ \Omega, \quad y = 100\ \Omega, \quad z = 150\ \Omega.$

'If you cannot think how to start, you might try putting voltages of up to 6 volts between the lefthand pair of terminals, the green ones being at the bottom, and a voltmeter between the other two. Then you could interchange the meter and supply. You can use an ammeter to measure current anywhere. Every box contains at least 60 ohms between any pair of terminals but the green pair, so a 100 mA meter can be used with 6 volts.

'You might find a box with a non-linear component in it, so apply different voltages. Show me any circuit you think you can draw showing what might be inside a box.

'Even if you cannot think what might be inside a box, you can say how the box behaves.'

The value that a student gets from this (or any) experiment is greatest when he has been able by himself to devise or extend a method and make it work. And this experiment is intended to provide a situation in which students at almost any level of previous experience can do so. It would be wrong to expect any student to discover all that it is possible to discover about the contents of a box. It would also be wrong to give formal teaching in methods of solving the puzzles, as the knowledge itself is much less useful than the process of acquiring it. Any measurement made and any deduction from it should be treated as successes, and questions should be freely answered.
It is hoped that circuits shown in figure 9 will be used, and also the first three with right- and lefthand sides interchanged.

Use of more difficult boxes (kit 2)

Most students, having gained confidence with kit 1, can usefully be given some of the more difficult boxes in kit 2, which also take longer to investigate. Six of these form three pairs, E and F; G and H; I and J, in figure 8. The boxes of any pair differ slightly, and students may be given a pair and asked to decide how they differ.

There is no need for each student to work with all the boxes. Nor need students be expected to solve every, or even any, box they try. Any correct partial deduction about the contents is a success, as is any thought-out series of observations which reveal how a box behaves.

The voltmeters used should have high resistance, but students should find for themselves that lower resistance meters, like the O-level ones, give lower readings.

Boxes E and F are indistinguishable except that the tolerance of the resistor values will make slight differences. The equivalence of these two networks may be useful later. G and H are included because potential dividers and potentiometer circuits are to be discussed later. The non-linear angle-voltage relationship should be evident in H. With an O-level (10 mA) voltmeter, G would also appear non-linear.

Aim

There is no need to drill students in shunt calculations. They can be treated as one more interesting practical problem for which circuit ideas are needed. But certainly students ought from now on to expect to be able to find a shunt to convert a meter to a less sensitive range, and shunt problems could well appear in an examination as problems to think about.

Students' book

Questions 25, 27, and 37 to 40 involve meters.

Demonstration

2.7 Measurement of potential difference

1033	cell holder with four U2 cells	*3*
1048/2	four-terminal box G	
1004/2	voltmeter (10 V)	*3*
80 *or* 179	voltmeter (5 V d.c.)	*3*
1000	leads	

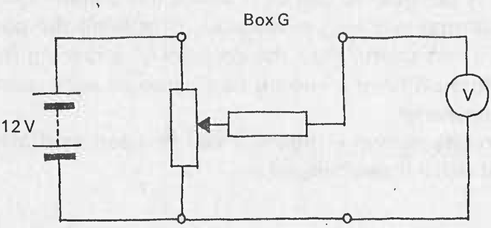


Figure 11

Connect 12 volts across the input of box G and a voltmeter (1004/2) across the output, as in figure 11. Set the box so that the meter reads 6 volts. Connect voltmeters of both types instead of (or in addition to) the first. Then connect a 6-volt battery in series with the voltmeter in the original circuit, so as to reduce the p.d. across the voltmeter, as in figure 12. Adjust the box to give zero reading. Show the effect (bigger change in meter reading for a given turn of the knob) of removing the voltmeter's multiplier and using it as a microammeter. (This may increase the voltage sensitivity 100 times and care is needed. A voltmeter giving full-scale deflection for 1 volt may be easier to use.) If students query the construction of radio potentiometers like the one in box G, teachers should be prepared to take one apart and show that it is just a small bent rheostat. Linear potentiometers or presets of small resistance are best, as they are usually wire-wound.

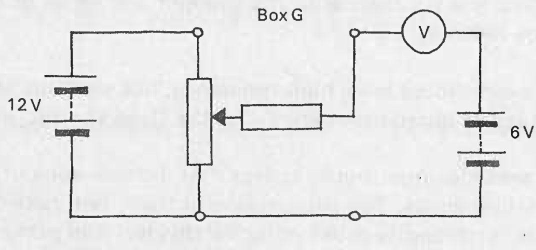


Figure 12

Box K, containing a zener diode, may be given later to a student who deals quickly with other boxes. Up to 12 volts may be put across the input side, but the output voltage is 'constant' if the input exceeds 3 volts. Apart from its usefulness in providing 'constant' voltage power supplies, it may impress students that diodes will break down if the reverse voltage is big. (No special use will be made of zener diodes in this course, and there is no reason to ensure that all the class hears of them. A useful mental picture for those who are interested is that a zener diode is simply a diode which, for a very low reverse voltage, will break down and conduct well. The breakdown does not damage the diode for moderate currents.)

Ammeters and shunts

As students have been using milliammeters or microammeters with shunts, this is a good place to discuss how such meters may be converted into ammeters, taking one or two numerical examples, especially as this is a practical problem in circuit behaviour.

Calculations can be based on the meters in use, which may have the following characteristics:

10 mA full scale at 100 mV (resistance 10 Ω)
100 μA full scale at 100 mV (resistance 1000 Ω)

The shunt resistance needed to turn each into a meter reading up to one ampere can be found. In some cases this 'resistance' is the best conductor in the circuit. Indeed, a shunt for a meter reading thousands of amperes is a substantial chunk of metal.

Potential difference

Some students should already have found that the low resistance voltmeters (10 mA movement) sometimes give lower readings than the high resistance voltmeters (100 μA movement). The next demonstration can be used to show when and why this happens, taking up ideas aired in demonstration 2.2b.

Demonstration
2.7 Measurement of potential difference

If the voltmeter in the circuit of figure 11 is of the high resistance type and a low resistance voltmeter is then connected in parallel with it, its reading falls. Both meters read the same new low potential difference. Removing the high resistance meter does not raise the reading of the low resistance meter. Two high resistance meters in parallel read very nearly as high a value as did the original one on its own. But connected directly to a battery, even several low resistance meters in parallel agree with a high resistance meter.

Students should be able to help discussion towards an explanation, and see that a high resistance voltmeter is needed in order to measure a potential difference across a circuit of high resistance without reducing the potential difference appreciably.

Aims of work on potential difference and potentiometers

Accurate potentiometric methods of measurement are not a part of the course, partly because meters have improved since the time when such methods were especially important. The use of a potentiometer as a device for varying a p.d. will appear later, mainly in the work on Unit 6, *Electronics and reactive circuits*, so it is introduced now.

Students should be expected to learn to choose voltmeters sensibly, and to think about the potential differences in simple circuits. Therefore the suggested approach takes up a problem about voltmeter readings as a puzzle to be thought about.

Certainly some students will, after they leave school, have to learn about potentiometric measurements, though a large proportion will find themselves using such devices as digital voltmeters. We think the right approach is to concentrate at school on what a potential difference is, and what a voltmeter does, rather than to drill students in a variety of special techniques before they find a clear need for these techniques. Given previous thought and experience, it should not be too hard for students to learn the techniques as and when they need them.

It is worth pointing out that the potentiometer method can bypass the inadequacies of meters by using the meter merely to indicate a null point, so that its scale may be quite inaccurate without spoiling the measurement. The accuracy of the measurement then depends on the length and uniformity of a wire or coil, or on the precision of a set of resistors connected in series.

If the school has an accurate dial potentiometer, it may be good to let students see it. Some discussion with chemistry colleagues will be needed, as they may wish to use potentiometric methods in physical chemistry, and it could be helpful to go a little further with potentiometry to meet their needs. They may need to measure the e.m.f. of one or more types of cell, and investigate changes with temperature (in a study of free energy), for which the work suggested here will almost suffice. See particularly Nuffield Advanced Chemistry *Teachers' guide II*, Topic 15, 'Equilibria: redox and acid-base systems', and Topic 17, 'Equilibrium and free energy'. See also Unit 9, *Change and chance*, Part Six.

The principle of the potentiometer as a device for measuring potential difference while drawing negligible current can be introduced by an extension of the circuit, as shown in figure 12. The output of the box can be varied so that the voltmeter gives a low reading of either sign, and the class can be asked what the output potential difference is. (Cell voltage, 6 V, plus or minus voltmeter voltage.) What if the voltmeter is made to read zero? (Output voltage is equal to cell voltage.) Would this still be true if the resistor in series with the voltmeter were taken away? (Yes.) And it can be shown that when this is done, the deflection changes more for a given change in the setting of the potentiometer. A meter that detects small currents is now best, even if it has no mark but a zero mark.

Potentiometers for measurement

Figure 13 shows the basic potentiometer circuit. The cell drives current I through the potentiometer, of which a part, of resistance r, is across the terminals A and B. A meter is in the lead to A.

If the meter shows that there is zero p.d. across itself, the p.d. across AB is Ir. The current I is not changed by altering r, so the p.d. across AB is proportional to r, so long as no current flows from A to B.

In a good measuring potentiometer r is accurately proportional to a dial reading: in a linear radio potentiometer it is roughly proportional to angle.

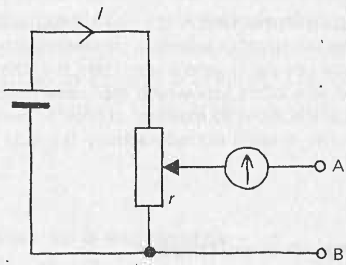


Figure 13
Basic potentiometer circuit.

Experiment

2.8 Comparison of two dry cells

1033	cell holder with four U2 cells 2
1004/2	voltmeter (10 V)
1041	potentiometer holder *with*
1051	preset, 5 kΩ *or*
1048/2	four-terminal box G
1000	leads

If the voltmeter cannot be adjusted to give greater voltage sensitivity, by removing its series resistor, a more sensitive meter is also needed.

The experiment is a problem: which of two dry cells has the greater e.m.f.? It is worth while to select pairs of cells which do not seem to differ when tested with a voltmeter.

Two cells are put in turn across the potentiometer. One cell, X, of the two cells X and Y which are to be compared, is connected as shown, and the potentiometer is adjusted to give zero deflection. Cell Y is then substituted for X. If the meter still appears to read zero, the sensitivity can be increased until it shows that either X or Y can drive current into the potentiometer when the other could not.

Before starting the experiment, students should understand that they must not use a meter in a sensitive condition before knowing that the deflection would be negligible for a voltmeter.

Later uses of the electrometer

The electrometer will be used again in this Unit and in Unit 3 to measure electric charges, which it does by indicating the p.d. across a capacitor which is connected across its input. If students are to be clear how the device measures charge, it seems important that they should first meet it as a voltmeter. Then it can be treated as a black box which measures potential differences, and adapted with a capacitor or resistor across the input to measure charge or current. The electrometer will be used to measure very small currents in work on radioactivity (Unit 5) and on the photo-electric effect (Units 5 or 10).

Demonstration

2.9 The electrometer as a voltmeter

1006	electrometer (with maker's instructions)
1003/1	milliammeter (1 mA) *or* suitable display for electrometer
1004/1	voltmeter (1 V)
1033	cell holder with one U2 cell
1041	potentiometer holder 2 *one with*
1051	preset, 1 kΩ *the other with*
1051	preset, 100 kΩ
180	galvanometer
52	Worcester circuit board kit (parts)
27	transformer
1000	leads

Experiment

2.8 Comparison of two dry cells

As a brief follow-up to demonstration 2.7, students could be asked to find which of two dry cells has the higher e.m.f., if they differ at all, using a potentiometer circuit.

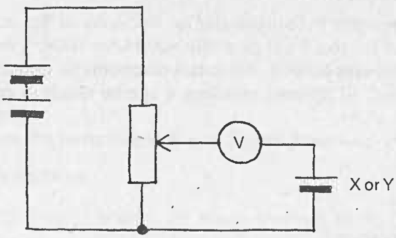


Figure 14
Comparison of two dry cells.

Some will not obtain balance points because they have not connected their cells correctly; this is an opportunity for students to find out for themselves what rules apply to polarity, using the meter as a voltmeter with the series resistor in circuit for this purpose. They need not be told what they will find. The series resistor can then be removed to detect any small difference between the cells.

Valve electrometer

Another type of voltmeter which will be useful later should be introduced now. This is the 'electrometer' or 'd.c. amplifier'. It does not depend on measurement of a small current passing through it but upon the ability of the p.d. between two electrodes in an electron tube to control a current. The current taken from the circuit in which the p.d. is measured is so small as to be negligible in most circumstances.

Demonstration

2.9 The electrometer as a voltmeter

The demonstration, which in effect calibrates the electrometer, shows that the output indication of the electrometer is proportional to the potential difference across its input.

After the electrometer has been adjusted so that its output meter gives unit reading when there is one volt across its input, it is easy to show that the output meter agrees with a voltmeter across the input for other values of the p.d.

Follow the maker's instructions for switching on the electrometer. Students can be referred to the 'Tools' section in the *Students' laboratory book.*

Set up one cell with the 1 kΩ potential divider across it, and the voltmeter to measure the output p.d. Apply this measured p.d. to the electrometer's input. Make the electrometer read zero for zero input, and full scale deflection for the maker's specified p.d.

Check that the electrometer reads proportionally for fractions of full scale deflection. If the 100 kΩ potentiometer is substituted for the 1 kΩ one, the voltmeter 1004/1 draws enough current to reduce the p.d. across the potentiometer output, while the electrometer continues to indicate an undisturbed value (when used on its own, of course) recalling a similar result in demonstration 2.7.

If the electrometer is battery-powered, check that it is switched off at the end of the experiment.

Textbooks

(Circuits and potential difference.)

Bennet, *Electricity and modern physics*, Chapter 2.10.

PSSC *College Physics*, Chapters 25, 27.

PSSC *Physics* (2nd edition), Chapters 28, 29.

Rogers, *Physics for the inquiring mind*, Chapter 32.

Potential difference in Nuffield O-level Physics

The Nuffield O-level course treats potential difference in terms of joules per coulomb, and little revision may be needed. Students whose previous acquaintance with potential difference was different may need more revision or even some remedial teaching.

See particularly Nuffield O-level Physics, *Teachers' guide IV*, pages 330–337, and experiments 120–128 and experiment 149b.

Students' book

Questions 28 and 29 ask for numerical estimates of quantities linked with p.d. Question 30 is about power-carrying circuits. Question 35, and also question 26, involve a potentiometer circuit.

Demonstration

2.10 Measuring voltages without voltmeters (crude attempts)

70	demonstration meter
71/1	d.c. dial, 1 A
9A *or* 9B	motor/generator unit 2
9F	lineshaft unit
9M	driving belt
1055	0.5 kg mass
501	metre rule
541/1	rheostat (15 Ω)
176	12 V battery
1000	leads

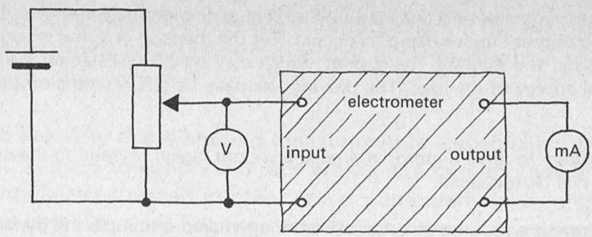


Figure 15
The electrometer as a voltmeter.

Designing voltmeters

The work of experiments 2.7 to 2.9 should have drawn attention to the series resistor which turns a moving coil meter into a voltmeter, as well as to the fact that this resistor will be larger in value the more sensitive the meter is to current. These points should be made explicit and students can try one or two examples of the calculation of suitable values for such resistances.

It is worth saying that voltmeters need not be based on moving coil meters – the electrometer is not – but that moving coil meters are cheap, robust, and reasonably accurate. The current they pass often does not matter enough to bother about it, though there are times when it must be allowed for or reduced by using a more sensitive meter as the basis for the voltmeter. Students will have seen the contrast in the performance of meters based on 10 mA and 100 μA movements.

How big is a volt?

The meaning of the potential difference between two points as the energy transformed per coulomb passing between these points may need revision, and O-level Physics experiments should be recalled or repeated. A measurement of potential difference involves measurements of energy, current, and time, or of power and current.

Demonstration
2.10 Measuring voltages without voltmeters (crude attempts)

So far as the course up to this point is concerned, a student could be forgiven for thinking that voltmeters occur naturally, complete with correctly marked scales. But, as the meaning of potential difference indicates, a voltage can be measured without a voltmeter.

As first crude attempts one or both of the following can be shown.

a A falling load turns a dynamo which is arranged to drive a current through a resistance, the p.d. across which might be roughly the ratio of the rate at which the falling load transforms energy, to the current.

Set up the motor/generator and lineshaft unit so that as the load falls the electrical output goes into the rheostat, the output current being measured. Set the rheostat at a low resistance so that the weight falls slowly, and measure the current, which may be 0.3 A. Estimate the p.d., using the rate of loss of potential energy of the load. The p.d. may actually be a few tenths of a volt, and the estimate rather bigger.

Then use the battery to drive a motor and raise a weight, again measuring the current. This time the calculated p.d. will be too small.

To illustrate energy losses, drive the motor from the dynamo or couple the dynamo mechanically to the motor.

Teachers may prefer to use the larger fractional horsepower motor (item 44), but will then have to find a way of excusing the power supply to the field coils.

'Mechanical equivalent of heat'

The methods used in experiment 2.10, and more particularly in experiment 2.11, are not unlike those of experiments formerly regarded as measurements of 'the mechanical equivalent of heat', and several of Joule's experiments were like those of 2.11. (See Nuffield O-level Physics, *Teachers' guide IV*, pages 273–302.)

In experiment 2.11, the same amount of energy is delivered to a metal block in two ways: first by passing current through a resistor embedded in it and then by mechanical means, using a friction band. If its temperature rises by the same amount each time, so does its internal energy.

There is something to be said for not invoking the word 'heat' deliberately, though there is nothing to be said for an attempt to prevent students using it, for reasons they cannot yet understand. The trouble is that no clear meaning can be given to 'the amount of heat in a body' unless 'heat' means 'internal energy', in which case one term is redundant. Later on nonsense like 'Internal energy only flows from hot to cold' will ensue or be implied. In the present experiments, energy is transferred from gravitational potential energy, or from the chemical potential energy of a battery, to internal energy of a block of metal.

Teachers in college or university courses may well prefer to reserve the word 'heat' for energy like that transferred from hot to cold as bodies reach thermal equilibrium, regarding heat as a bird of passage and not as a pool of energy, all of which could be drawn upon. On this view, there is heat flow *inside* the metal block in experiment 2.11 if its surface is hotter than its interior at some stage (or the reverse) but there is *not* heat flow from the electrical supply or the friction band to the block.

But we repeat that these remarks are not for students; they will not understand what is being said. At most, it may be wise for teachers to avoid using the word heat in more than one way in what they themselves say.

See Unit 9, *Change and chance*, Appendix A, for a fuller discussion.

Aim

The principle behind experiments 2.10 and 2.11 is what is required. Students need not be expected to memorize details of the methods, and teachers may prefer to substitute other equivalent experiments.

b A motor with a current supplied to it lifts a load. The p.d. at which the current is supplied might be roughly the ratio of the rate at which energy is supplied to the rising load, to the current.

It is not hard to see why these are bad measurements, especially if a dynamo driven by a falling load is used to supply a motor which attempts to raise another load. Too much energy is transformed in other ways, particularly in warming up the wires of the machines and also their bearings. Indeed, the crude measurements would do well to produce the correct order of magnitude for the potential difference.

All measurements that depend on keeping track of amounts of energy are difficult, but they need not be so bad as those tried so far. (Nevertheless, high accuracy is not to be expected with school apparatus or in a short time.)

The class may be led to think of turning to advantage the inevitable tendency of energy to go towards warming things up, by deliberately using the energy to heat something. Questions like, 'What has happened to the energy provided by the battery when the experiment is over and the apparatus is put away?' may help.

So a way of transferring electrical energy and keeping track of all of it is to use the energy to warm something up. Then the problem is to measure how much energy has been transferred, which is what the next experiment tries to do.

Demonstration or long experiment

2.11 Measuring a voltage without a voltmeter

1011	apparatus for measuring joules per coulomb
1003/4	ammeter (1 A)
507	clock
542	thermometer (0–50 °C in 1/5 °C)
501	metre rule
176	12 V battery
1000	leads

See *Students' laboratory book* for notes to students doing this as a long experiment. Brief details appear below. The course contains a number of long experiments, of which this is the first to appear, and is one of the less taxing examples. Notes for each appear in the *Students' laboratory book.*

We suggest that each student should be involved in one of these during the course, but not that each student need do them all. See *Teachers' handbook*, Chapter 4.

Some students profit more from having a task of their own than they would lose through missing other experiments, and such students could be given this task at this stage. Another way is to group several long experiments together and suspend or reduce other activities. Suitable long experiments at this stage, or rather later, are:

Measuring a voltage without a voltmeter (Unit 2)
Millikan experiment (charge on an electron) (Unit 2)
Measurement of ε_0 (Unit 3)
Measurement of G (Unit 3)
Velocity of light (Unit 4)
Velocity of microwaves (Unit 4).

Brief details for experiment 2.11

Warm the metal block (item 1011) electrically, from room temperature through about 10 K, stopping the current after this rise but continuing to record the temperature until it falls again. A supply of 12 V is needed. It is best to wind 5 or 6 turns of cord around the block so that conditions are more nearly the same as in the second part of the experiment.

In the second part the block is turned against the cord used as a friction band, carrying a load of about 8 kg, after bringing the block back to room temperature. So far as possible, the temperature should be made to rise at the same rate as previously, stopping after the same temperature rise. The temperature rises will not be exactly the same, but the losses will be nearly enough equal to be ignored.

Calculate the energy supplied in the first stage from that in the second stage, allowing for differences in the rise of temperature. Then the p.d. may be found from the ratio of the energy delivered to the number of coulombs that passed.

Aims

The effects of the resistance of a supply deserve a brief mention, for students will meet them from time to time. They need to know that the p.d. will fall as more current is drawn, and that it will fall more the greater the supply resistance. But a detailed analysis, though it would be good for some, is not necessary. Students should not be too puzzled when they meet such effects later.

Demonstration or long experiment

2.11 Measuring a voltage without a voltmeter

If a heating coil were placed in a metal block, then energy could be supplied to the block electrically and the only difference between the amount of energy supplied and the amount stored in the block would be any that escaped because the block was not well enough insulated.

One way of finding how much energy went into the block would be to give it an equal amount of energy mechanically, by rubbing it, and to calculate the amount of work involved from the force used. For the energies to be equal, the block must show the same temperature rise, indicating the same increase of energy within it.

With the apparatus suggested, a band brake is used to transfer energy from a mechanical source to the block. The energy transferred by work can be calculated from the forces and distances involved, and is equal to the energy supplied electrically, which is what must be known if the p.d. is to be found without using a voltmeter.

The complete absence of voltmeters from this experiment is worthy of note, emphasizing that a voltmeter is a convenient and practical means of measuring a voltage, but not an essential means. It should also be clear that high accuracy is hard to achieve, which is another reason for normally using voltmeters. It is possible to regard the experiment as one to put a mark on an otherwise unmarked voltmeter, or to check a marked meter, but it is hardly accurate enough to be presented seriously as such, and a student could then be forgiven for thinking that the experiment was a check by the voltmeter on the other apparatus. Certainly, in the event of a discrepancy, one would do better to believe the voltmeter rather than the apparatus.

The question of measuring currents without moving coil ammeters will arise in Unit 7. Students who ask could be given the definition of the ampere, but there is no need to press it on them if they do not ask.

Trials suggest that students need as much experience as they can get in connecting up simple circuits for a stated purpose. So this experiment is best presented as a simple problem, without detailed instructions. Students for whom it is too trivial need a harder problem, such as a cell and resistance enclosed in a box.

Students' book

Questions 31 and 32 are about internal resistance.

Experiment
2.12 Drop in p.d. of a supply delivering current

52	Worcester circuit board kit (parts)
1004/2	voltmeter (10 V)
1000	leads

Connect one cell to the voltmeter. Then connect first one, then two, and then three lamps in parallel across the cell, noting the falls in p.d. An ammeter may be added if desired, and students may prefer other ways of changing the current, such as a variable resistance.

Demonstration
2.13 Comparison of two supplies

59	l.t. variable voltage supply
	or
27	transformer
70	demonstration meter
	and
71/6	a.c. dial, 15 V
73	lamp, 12 V, 36 W
74	lampholder (s.b.c.) on base
14	e.h.t. power supply
1003/2	milliammeter (10 mA)
1000	leads

Set the l.t. supply at 12 V, and connect the lamp across the alternating output. Note the drop in p.d. The experiment can be repeated with a d.c. supply.

Set the e.h.t. supply to give 1000 V, switch off, and allow the output voltmeter to return to zero. Connect the milliammeter across the output and switch on again. The voltmeter should read zero, the current being a few milliamperes. Any very high resistance, such as 50 MΩ, supplied with the power pack to limit current even further, should not be in circuit. The milliammeter may be damaged by a heavy discharge from smoothing capacitors in the supply if it is connected when the output is not zero.

Sources of supply impedance

Many effects can contribute to make a supply behave as if it had an impedance, not necessarily constant. Polarization effects in cells, the slowing down of an engine driven dynamo, or magnetic saturation in the iron of a transformer are examples.

Experiment

2.12 Drop in p.d. of a supply delivering current

As a simple test of their ability to connect up a circuit and to think sensibly about what happens, students may be invited to see what happens to the p.d. across one dry cell when lamps are used to draw more and more current, and to explain what they see. There is no need to make elaborate measurements: students could be told to assume that the lamps have equal resistance. They should not be told what circuit to use nor what voltmeter to choose, these being tasks they need to practise.

A method many will use is to connect successively one, two, and three lamps in parallel, with the voltmeter across the battery. The p.d. drops as each extra lamp is inserted, but (if the cell is not on its last legs) recovers as it is removed again.

The situation is similar to those met before in which a low resistance voltmeter reads low, and students may reasonably be expected to explain for themselves that the drop in p.d. is due to resistance within the cell. The next demonstration makes the same point, and could help students who did not get there themselves.

Demonstration

2.13 Comparison of two supplies

Connect a lamp across a low voltage supply and note that the p.d. indicated by a voltmeter across the supply falls a little. The resistance of the supply can be estimated from the current (using the stated power of the lamp) and the drop in p.d.

Compare an e.h.t. supply at about 1000 V, which would pass a very large current if it had the same resistance as the low voltage supply. If a milliammeter is shorted across the supply, the largest current is only a few milliamperes and the p.d. across the output terminals falls to nearly zero. The resistance can be estimated (megohms) and the near zero p.d. explained. The dimming of car lights when the engine is started, and pressure fluctuations at taps, deserve mention.

Part Three

Electric charge

Time: about a week

Approach through capacitors

The idea of electric charge is approached through class experiments with capacitors, making use especially of high value electrolytic capacitors which can store large charges which leak away less easily than charges on insulating rods or on metal spheres. These charges are large enough to give measurable currents for appreciable times when passed through an ammeter, so that students can be clear that charge is measured in ampere seconds, or coulombs. It is important for students to see that charge is a quantity of something like litres or bucketsful, not a force or intensity. This last confusion can arise if the idea of charge is introduced along with ideas about fields and the forces between charges, so we suggest deferring these to Unit 3.

Aims

Students should become able to recall and use the idea of electric charge as a quantity of electricity, measured in coulombs (ampere seconds) in a variety of situations, some new. They should recall that charge is proportional to potential difference, and be able to calculate capacitances from $C = Q/V$. These will be used in Units 3, *Field and potential*, 6, *Electronics and reactive circuits*, and 8, *Electromagnetic waves.*

They should understand the discharge of a capacitor through a resistor, in terms of the leakage of amounts of charge proportional to the p.d., and so to the original charge on the capacitor. Later, they should come to see this as one among many instances of exponential decay.

They should recall, and be able to use, arguments leading to the energy stored, $\frac{1}{2}QV$, and be ready to compare this with the energy stored in a spring, $\frac{1}{2}Fx$.

Exponential variations appear later in the course, particularly in Unit 5, *Atomic structure*, Unit 6, *Electronics and reactive circuits*, and Unit 9, *Change and chance*. Energy changes are of importance on many occasions in the course.

Students should become able to use dynamical ideas more fluently, and expect to find them useful in situations where their applicability is not immediately obvious.

Experiment 2.14, in particular, aims to increase students' confidence in their ability to invent their own experiments and to think about what they mean, as well as to develop the idea of electric charge and to give further practice in connecting circuits.

While some students are happy to 'get down to it' with apparatus, many prefer to be told why they are doing this work, and how it fits into the rest of the course.

Destruction of an electrolytic capacitor

Some teachers may feel that it is worth while showing an electrolytic capacitor connected the wrong way round to a supply at a voltage greater than its rated value. Afterwards it will conduct electric current a little in either direction. Such a demonstration should be rapid and only serves as a warning to pupils to be careful about the connections in their circuits. A 15 V, 500 μF capacitor, used with a 0–24 V supply and a 0–5 A meter is suitable. There must be a safety screen in case the capacitor explodes. A 5 A fuse is desirable.

Experience with capacitors

This Part begins with a rather open series of class experiments, and it is suggested that after the initial introduction, students may be left to go at their own pace. Materials to occupy the faster ones are suggested. All should begin with the simpler experiments, and some may get no further than these. Apparatus can be available on a cafeteria basis, students being guided by the provision of further apparatus and the asking of questions rather than by explicit instructions. They should regard these as their own experiments, and be asked to puzzle them out for themselves. A number of short discussions about what has been done may help, and students may also be encouraged to compare notes informally.

Class experiments

2.14 Capacitors and charge

A very quick demonstration may be the best way of starting off these experiments, by making detailed instructions less necessary. See figure 16.

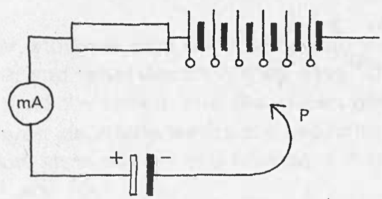


Figure 16
Capacitor charge/discharge circuit.

'Here is a capacitor. It is connected like this to a battery, through a meter and a resistor to save accidental damage to the meter. The side of the capacitor marked + goes to the positive side of the battery.'

When the circuit is completed the meter moves, then goes back to zero.

The following pages suggest how experimenting might then develop.

2.14 Capacitors and charge

Each group will need the following, but they should not all be issued at first, or confusion will result. Circuits should be checked to see that the capacitor is connected with the correct polarity.

1033	cell holder with four U2 cells (12 V)	*2*
1040	clip component holder	*3*
1051	electrolytic capacitors, 500 μF, 50 V 250 μF, 50 V 100 μF, 50 V 50 μF, 50 V	
1051	resistors, 100 Ω 350 Ω *2* 100 kΩ	
1041	potentiometer holder *with*	
1051	preset 100 kΩ	
180	galvanometer *2* *or*	
1003/2	milliammeter (10 mA)	*2*
1002	microammeter (100 μA)	
507	stopwatch *or* stopclock	
158	class oscilloscope	
1000	leads	

2.14a

Issue: 1 cell holder

1 U2 cell

1 resistor, 100Ω

1 milliammeter

1 capacitor, 500 μF

2 clip component holders

2.14b

Add: 1 milliammeter

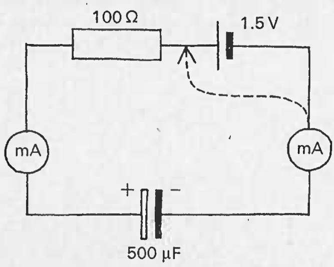


Figure 17

2.14a

When students try it themselves, they find that the meter movement is not repeated if the connection is made a second time. A reverse flick of the meter can be obtained by touching the lead to the opposite side of the cell (discharging the capacitor), and after that the original result can be obtained again. But no steady current ever flows. See figure 18.

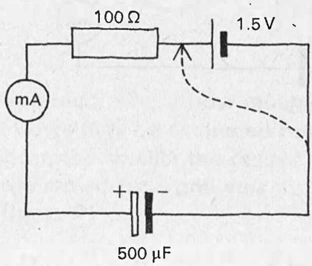


Figure 18

2.14b

Given a second meter, students may think of finding whether currents flow in both leads to the capacitor, and what direction they have. The currents turn out to go in the same direction round the circuit, and the meters give identically sized flicks, suggesting that as much electricity leaves the capacitor as enters it. (A student who thought that capacitors store charge and now says they store zero charge is doing well.) See figures 11 and 19.

Figure 19
Current to and from capacitors.

Having found that no steady current flows, the construction of a capacitor can be explained (conducting plates with insulator between), and the words charge and discharge introduced. The circuit symbol -||- will be useful for further recording of students' experiments.

2.14c

Add: 3 or more U2 cells

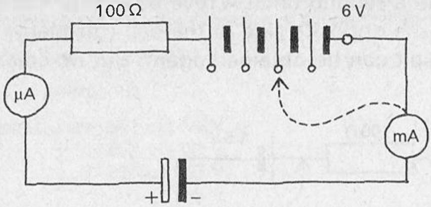


Figure 20

2.14d

Substitute:

capacitors, 250 μF
100 μF

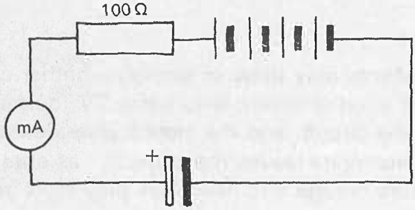


Figure 21

Guessing charges

Rough guessing is worth encouraging, especially as here it underlines a need to find better ways of estimating charges.

Students' book

Questions 41 to 49 are about charge and capacitance. Question 41 is introductory. Question 44 sums up the simpler results from experiment 2.14.

2.14e

Add: capacitors, 500 μF
250 μF
100 μF
available together

Milliammeters as ballistic galvanometers

Some milliammeters do give throws proportional to charge; others may not. If the throws in 2.14e add up correctly this might be taken to indicate something about the properties of the meter. It would be wrong to assume without evidence that the meter throw is proportional to charge, though many students would reasonably feel that such an experiment would test the point. They would be supposing tacitly that charge is conserved.

In these experiments it may reasonably be supposed that identical throws indicate equal charges.

2.14c

With more cells, larger pulses of electricity flow. Some may find that if an extra cell is added without previously discharging the capacitor, each extra cell gives an equal extra pulse. The moral, 'Equal extra voltage gives equal extra charge', can be drawn, this being about the simplest experiment to show that charge is proportional to potential difference. See figure 20.

2.14d

Other capacitors can be tried. About how much electricity flows? The current and the time for which it flows may be estimated roughly. The smaller the capacitance marked on the capacitor, the smaller the pulses of current. If students are told that the rating is the charge stored for a one volt supply, they can check the adequacy of the guesses. See figure 21.

2.14e

Two capacitors may be tried in parallel.

The pulse using both capacitors is larger than the pulse due to either on its own. Students may speculate whether the charges add up. The problem of whether the meter movements indicate charge reliably should emerge.

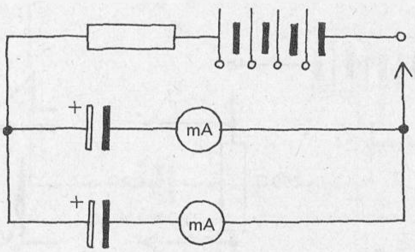


Figure 22
Capacitors in parallel.

One meter may be put into each lead to the capacitors (figure 22), or one meter can be used first with the capacitors one at a time, and then with both together. See figure 23.

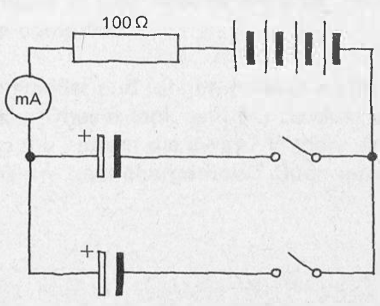


Figure 23
Capacitors in parallel.

2.14f

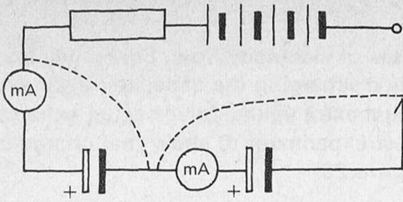


Figure 24
Capacitors in series.

Apparatus as for 2.14e

Pace

Slow students could well stop at about 2.14e or 2.14f. It is better for them to go more slowly and do less but feel that the experiments are their own, than to be rushed through a programme devised by the teacher which they do not understand. Capacitors in parallel and series will be studied in Unit 3 and can be omitted now.

2.14g

Add: class oscilloscope

2 resistors, 350 Ω or 330 Ω

Use capacitor, 500 μF, and 4 U2 cells.

The oscilloscope should be used on the d.c. setting and students can be referred to the 'Tools' section in the *Students' laboratory book*. When testing the effect of more resistance, a second resistor is best put in series without disturbing the oscilloscope connection, as in figure 25.

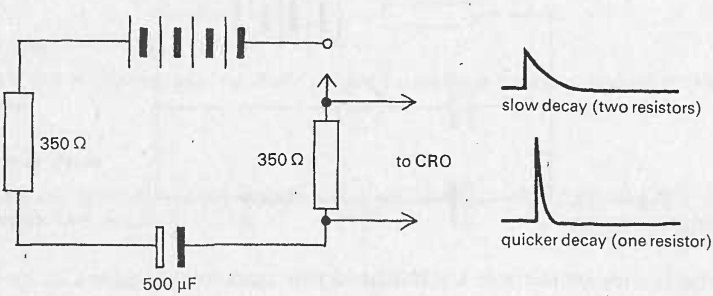


Figure 25
Effect of resistors on pulses.

2.14f

Two capacitors may be tried in series. The pulses are smaller than with either capacitor alone, and the meters show equal indications. The capacitors could be discharged independently as suggested by the broken lines in figure 24, to test whether they had equal charges.

2.14g

Faster students may be asked, 'How can you find out more exactly how the current is changing?'. It is to be hoped they will suggest using an oscilloscope to observe the rapid pulse. See figure 26.

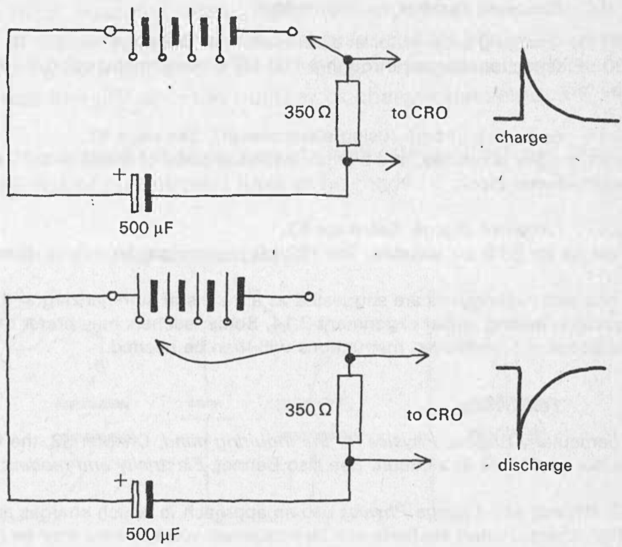


Figure 26
Charge/discharge pulses.

Students can be asked what might happen if another resistor were added, to make it harder for the current to flow. A simple arrangement is shown in figure 25. The advantage of not connecting the oscilloscope across both resistors is that the trace movement is proportional to current with the same constant of proportionality, so that readings may be compared.

The pulses are made smaller and longer. It looks as though a quick surge turns into a longer, slower trickle. Does it look as if the product of current and time might be the same? How does the current die away? Is there anything in the oscilloscope display that measures the total charge flow? Such questions will be taken up later.

Potential difference across capacitors

A fast student may think of using the oscilloscope to investigate the p.d. across capacitors in 2.14e, f, or g.

Response to pulses

Later in the course, especially in work on electronics, more will be made of the response of circuits, and indeed of mechanical systems, to sharp pulses. This early experience will be of value then. Shortly it will lead to a discussion of the slow discharge of a capacitor through a resistor. At this point it can be said, 'This is a very important kind of experiment. You can learn a lot about something by giving it a sudden jolt. Tests on a car spring might show that after a sudden jolt it bounced backwards and forwards. Suppose the spring also had a strong friction pad; what might happen then?'

Possible further experiments

2.15 Charging a capacitor at a constant rate. See page 59.
A 500 μF capacitor charged through a 100 kΩ potentiometer using a 100 μA meter is suitable. Use a 6 V battery.

2.16 Spooning charge (using electrometer). See page 61.
An e.h.t. supply is needed, and a small insulated piece of metal. A 0.01 μF capacitor is placed across the electrometer input.

2.17 Decay of charge. See page 63.
The values for 2.15 are suitable. The 100 kΩ resistor can be a fixed resistor.

The first two experiments are suggested as a means of summarizing and taking further the suggestions arising out of experiment 2.14. Some teachers may prefer to make them individual experiments, if time allows. Instructions will then be needed.

Textbooks

See particularly Rogers, *Physics for the inquiring mind*, Chapter 33, the first pages of which treat the capacitor as a break in a circuit. See also Bennet, *Electricity and modern physics*, Chapters 10 and 11.

PSSC *Physics* and *College Physics* use an approach in which charges are all seen as multiples of the electron charge. Good students will be interested, weaker ones may be confused.

Making a summary

Students may here be expected to describe what they have seen happen, and in the process to develop their powers of talking clearly.

The important ideas summarized here will be useful enough for notes to be worth while. We suggest that summary notes be prepared by one or two students, briefed beforehand. The discussion may well focus on deciding what the class want written down. The notes can then be duplicated and circulated.

The summary could centre round discussion of experiments 2.15 and 2.16, if these are demonstrations, or it could precede them.

At this first introduction, the capacitance of a capacitor should be made to seem as simple as the capacity of a milk bottle.

Further experiments for faster students

Faster students can be given experiments that will be demonstrations for the rest, and perhaps be asked to give the demonstrations. The experiments are:

2.15 Charging a capacitor at a constant rate.

2.16 Spooning charge (using the electrometer).

2.17 Decay of charge.

In experiment 2.15, a variable resistor is varied so as to keep the charging current constant for a measured time. The p.d. reached can be measured with an oscilloscope and the capacitance estimated.

In experiment 2.16, a small insulated metal object (which can even be a teaspoon) is charged repeatedly at the terminal of an e.h.t. supply, and its charge is given each time to a capacitor across the input of the electrometer. The potential difference across the capacitor rises linearly with the number of charges delivered.

In experiment 2.17, a capacitor discharges exponentially through a fixed resistor, slowly enough for readings of current and time to be made.

Summary – charge and capacitance

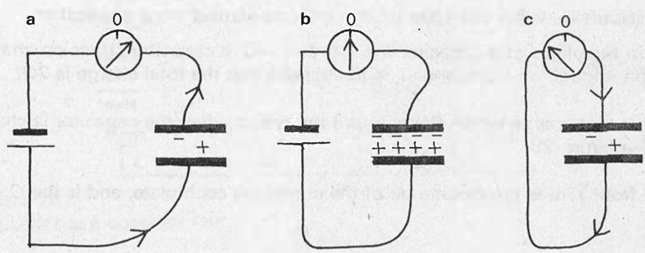


Figure 27
a Current flows.
b Current stops, plates charged.
c Discharge.

At some stage the observations made in experiment 2.14 need to be summarized. Particular points are:

1 It looks as if the rush of current onto one plate and away from the other might leave one plate charged positively and the other negatively. A rough model of the situation might be as shown in figure 27.

2 As much charge flows off one plate as flows onto the other.

3 There may be evidence that charges add up.

4 There is evidence that the charge on a capacitor is proportional to the potential difference across it.

Demonstration

2.15 Charging a capacitor at a constant rate

1033 cell holder with four U2 cells (6 V)

1002 microammeter (100 μA)

1041 potentiometer holder
with
1051 capacitor, 500 μF, 50 V

507 stopclock

64 oscilloscope

1040 clip component holder

1000 leads

This useful experiment was suggested by a teacher in the trials. It could well be demonstrated by a student.

The circuit is shown in figure 29. The oscilloscope should be set to d.c. and the sensitivity to 1 V cm^{-1}. The time base need not be in use.

Short out the capacitor with a lead across XY and adjust the potentiometer for a suitable current, say 80 μA. Remove the shorting lead across XY, start the clock, and vary the potentiometer to keep the current constant as the capacitor charges up. Times for the p.d. across the capacitor to reach 1 V, 2 V, 3 V, etc, can then be recorded.

Difficulties with the idea of the charge stored on a capacitor

The charges on the plates of a capacitor are $+Q$ and $-Q$: a capacitor stores no charge! A more likely confusion, though an illogical one, is to suppose that the total charge is $2Q$.

The charge Q is that charge which flows round the circuit when the capacitor is charged or discharged. See figure 28.

The charge Q from $\int I dt$ is the magnitude of the charge on each plate, and is the Q in $C = Q/V$.

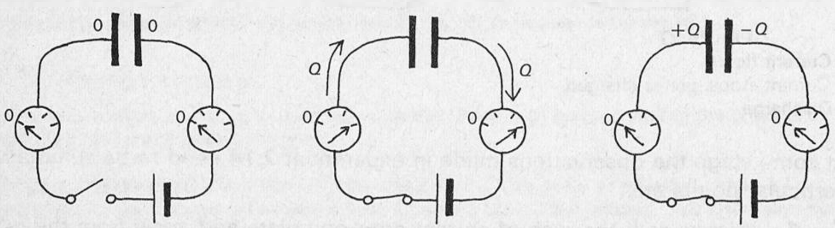


Figure 28
Charges on capacitor plates.

5 Capacitors differ in the amount of charge they store for a given potential difference. The unit of capacitance can be introduced now, but comes most naturally with the next experiment.

Demonstration

2.15 Charging a capacitor at a constant rate

This demonstration serves to clarify and link together ideas from experiment 2.14, and to bring out clearly the meaning of charge and capacitance.

A variable resistor is used to keep a steady current flowing into a capacitor for a measurable time. Having asked how many coulombs the observed current delivers in, say, five seconds, it is worth 'counting out the coulombs' every five seconds as charge goes onto the capacitor, to make the process seem as much as possible like the filling of a tank.

The p.d. across the capacitor is found, using the oscilloscope, to rise linearly with time. As twice the charge flows in twice the time, the p.d. must be proportional to the charge.

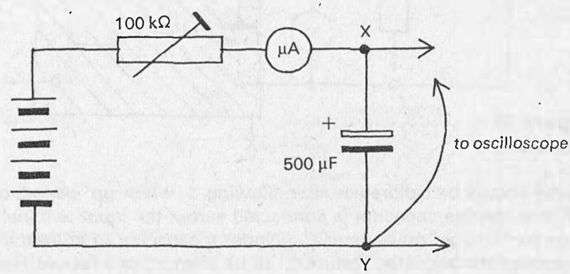


Figure 29
Charging a capacitor at a constant rate.

The number of coulombs needed to raise the p.d. by one volt can be estimated.

If the proportionality, $Q \propto V$, is written

$$Q = CV$$

then C is the quantity determined above.

The names of the quantity (capacitance) and the unit (the farad) should be given. The sub-units, microfarad μF (10^{-6} F) and picofarad pF (10^{-12} F), deserve mention.

Demonstration

2.16 Spooning charge (using electrometer)

1006	electrometer
1003/1	milliammeter (1 mA)
1004/1	voltmeter (1 V)
1041	potentiometer holder *with*
1051	preset 5 kΩ
1051	capacitor, polystyrene, 0.01 μF
14	e.h.t. power supply
1033	cell holder with 1 U2 cell
51	Malvern electrostatics kit (parts)
1000	leads

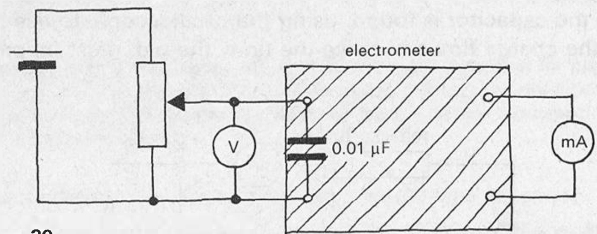


Figure 30
Calibration circuit.

The electrometer should be calibrated, after allowing a 'warm-up' period, using the circuit of figure 30. A 0.01 μF low leakage capacitor is connected across the input terminals, unless an internal switched range for 'charge' measurement includes a capacitor of at least this value. (A lower capacitance requires the insulated conductor to be charged to a low voltage, and readings are not reliable.)

Figure 31 shows the charge measuring circuit.

Small conductors with 4 mm plugs, such as may be provided amongst the accessories, are plugged into the e.h.t. positive terminal, and into the input of the electrometer. With a p.d. of 1000 V, charge is transferred from the e.h.t. supply to the electrometer by the small proof plane, the meter reading being recorded after every five transfers of charge. A graph of meter reading against number of charges transferred should be a straight line.

The p.d. used may be varied and the difference between the two proof planes shown. When the larger proof plane is used, the meter reading should be taken after each transfer of charge.

Note for teachers on incomplete transfer of charges

If the charge on an object of capacitance C, initially at V_1, is shared with the electrometer, so that it and the electrometer come to V_2, there is charge CV_2 left on the object out of the original charge CV_1.

As V_2 is of the order of 1 volt, there will be negligible error if V_1 is of the order of 1000 volts. But if C is larger, so that V_1 must be only, say, 10 volts for V_2 to be less than 1 volt, about 10 per cent of the charge will be left behind on the object.

Spooning charge

The following demonstration emphasizes that charge, like milk or sugar, is a quantity of something that can be measured out and passed from one place to another without being lost. It makes sense to ask, 'Where did that dollop of charge go to?'. There are quantities for which such a question makes no sense, such as pressure or temperature.

The demonstration also introduces the electrometer as a charge-measuring device, whereas it was used earlier (2.9) as a voltmeter.

Demonstration

2.16 Spooning charge (using electrometer)

It is first necessary to make clear that with a charged capacitor across the input of the electrometer, the p.d. can stay almost steady for a long while because the electrometer passes so small a current. (For example, 0.01 μF at 1.0 V has charge 10^{-8} C. Even if the electrometer passes 10^{-12} A, and it should pass less, the charge would last more than 10^4 seconds.)

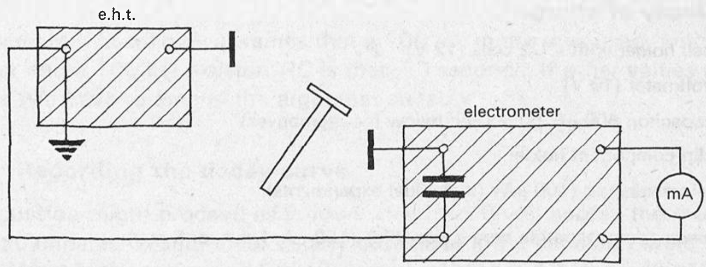


Figure 31
Spooning charge.

Take a 'spoonful' of charge from the terminal of the thousand volt supply, and carry it across to the electrometer input. The electrometer gives a small, but steady reading. Further transfers raise the indication, and the indicated p.d. rises in proportion to the number of transfers.

Try quickly a different voltage and a different size of conductor. It seems that the electrometer measures charge, and that the charge on the conductor depends on its size and is proportional to the voltage. Graphs of charge transfer and potential difference for several different insulated objects of varying size can be plotted, different students plotting different sets of results.

Show also that there is no significant charge left on the conductor after touching the electrometer, though there should be a warning that this might not be so for a larger object.

The electrometer as a tool

Students may be reminded of the 'Tools' section on the electrometer in the *Students' laboratory book*, and told that they will soon be asked to use the electrometer to investigate charges and capacitors, as well as using it later on for other purposes.

Change and decay – a piece of mathematical understanding

The analysis to come is an important, though brief, part of the course. On many other occasions, we shall want to discuss the problems of how things change, and the way in which what happens is related to physical behaviour. The job of making a piece of mathematics fit a piece of physics, and of understanding how the mathematical machinery works, as well as the fact that it works, is a difficult but worthwhile one.

Because it is important, something needs to be said to the class about how this work fits into the course, and how it may be of more general use. The passage opposite is an attempt in this direction; teachers will be able to improve upon it. Some will prefer to preface the work with a general comment; others will wait until something has been done so that it is easier to talk about it.

Exponential changes appear in Unit 5, *Atomic structure*, and in Unit 6, *Electronics and reactive circuits*, and the exponential is important in Unit 9, *Change and chance*. The numerical and graphical methods of handling differential equations are used in Unit 4, *Waves and oscillations*, Unit 5, *Atomic structure*, and Unit 10, *Waves, particles, and atoms*.

Demonstration or class experiment

2.17 Decay of charge

1033	cell holder with 4 U2 cells (12 V) *2*
1004/2	voltmeter (10 V)
1051	capacitor, 500 μF, 50 V (See below for alternatives)
1040	clip component holder
1002	microammeter (100 μA) (individual experiments) *or* meter (demonstration type if possible) (100 μA, 1 mA, or 5 mA)
1000	leads
1054	sheets of large graph paper

Component values

If the maximum meter reading is I, then the p.d., V, should be chosen so that V is as near as possible, but less than, IR. C should be chosen to make CR about 50 seconds. Suitable combinations are:

V = 9 V (or 10 V), R = 100 kΩ, C = 500 μF (50 V), meter 0–100 μA

V = 9 V (or 10 V), R = 5 kΩ, C = 10000 μF (30 V)
R = 10 kΩ, C = 5000 μF (25 V) meter 0–1 mA

V = 10.5 V, R = 2.2 kΩ, C = 25000 μF (15 V), meter 0–5 mA.

It is essential to select the components, especially the capacitor, so that the time constant has the value assumed (50 seconds). Electrolytic capacitors have wide tolerances and an unselected capacitor of the correct nominal value can give very disappointing results. A capacitor whose value is low can be trimmed by adding smaller capacitances in parallel.

A student may already have done this experiment, and be able to demonstrate it to the others. The teacher will have to judge whether combined work on a demonstration, or individual work by students, will be more effective. Much depends on the availability of a demonstration meter or on the speed and confidence with which individuals can set up the apparatus. On balance, we advise a

The exponential decay of charge on a capacitor

The next experiment is also about charge and current, but it turns out to be more important than it seems. The way in which charge leaks off a capacitor – called exponential decay – is a common pattern in much of physics, engineering, chemistry, biology, and economics. One example is radioactive decay, which will be met in Unit 5. The method used to discuss this problem is useful even more generally, whenever things change, and will be used to discuss acceleration and oscillation in Unit 4. Many physicists think that the mathematical ideas for handling rates of change (differential equations) are the most important single mathematical tool a physicist needs. That is why this first example is discussed at greater length than it seems to merit.

Demonstration or class experiment

2.17 Decay of charge

The charge on a capacitor is allowed to leak away through a resistor and meter, and a decay curve is plotted from the results of the experiment. Then, out of a discussion of the flow of charge, a theoretical prediction of the decay curve is made and theory and experiment are compared.

The argument that follows assumes that a 100 μA meter was used, with a 500 μF capacitor and a 100 kΩ resistor. RC is then 50 seconds. If other values are used, teachers will have to amend the argument suitably.

Recording the decay curve

The discussion might proceed as follows: 'With a 10 volt supply the meter reads 100 microamperes. Would there be any difference if the capacitor were removed? (Try it.) What is the resistance R?' (Potential difference 10 V, current 10^{-4} A, resistance 10^5 Ω.)

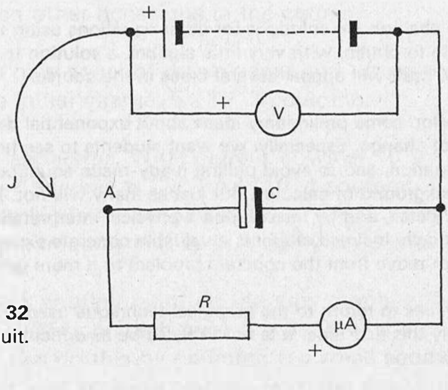


Figure 32
Charge decay circuit.

demonstration unless it will be hard for students to see the experiment. This experiment serves to introduce a piece of analysis rather than to be an individual piece of work to be puzzled over and experienced. Also, it will be very hard to find enough pairs of resistors and capacitors of the correct values.

The circuit is shown in figure 32.

Capacitor C is charged by connecting the flying lead J to A. The clock is started and J is disconnected from A at the moment the second hand passes zero. A current reading should be recorded every 10 seconds.

Choice of scales

It is important to choose simple scales, or the later numerical analysis will seem harder than it is. Large scales are needed so that a theoretical graph can be drawn easily, and accurately. This is a good place in the course to pass a comment to a class about the proper choice of graph scales.

Students' book

Question 50 is preparatory for the discussion of decay. Questions 51 and 52 consider another simple aspect of the problem.

Numerical solutions

This discussion introduces a technique which will be of the greatest service later on, and which we think will also help to develop students' mathematical grasp. They will construct graphically a theoretical curve for the decay of charge on a capacitor, by analysing the problem in a series of short steps.

In essence, the technique is that of numerical integration by finite difference approximation. Similar methods would be used to programme such a problem for a computer, and they are widely used for this purpose since it is rare, not common, for problems to have exact analytic solutions. Such methods are becoming more and more widely used in science and in industry, and students are very likely to use them in the future. Indeed, one student in the trials did programme this integration and computed a value of e to several decimal places.

Really accurate numerical work can be quite laborious, but we hope by using graphical methods to make the load of arithmetic involved quite small. This method should also help to develop skill in drawing and interpreting graphs; an important skill for a future scientist or engineer.

At later points in the course we shall obtain solutions for other equations using the same technique, and in particular we shall be able to obtain, with very little algebra, a solution for some states of the hydrogen atom. The exponential itself will appear several times in the course.

At this stage we attempt to develop some preliminary ideas about exponential decay, and the use of notation for changes and rates of change. Especially, we want students to see how the analysis actually works in a particular situation, and to avoid pulling ready-made equations out of thin air. Some will have a substantial background of calculus, but just as many will not. By choosing to discuss one physical problem in detail, and by insisting on a physical interpretation of the argument, we hope both to give mathematically inclined students a valuable concrete experience, and help those without this background to move from the concrete problem to a more general view.

There will be plenty of opportunities to return to the graphical technique used and it would be well to carry it through fairly smoothly this first time. It is not likely to be as difficult as it may seem, and confidence will soon come.

Trials teachers: 'Went surprisingly well.' 'At first doubtful . . . found it well worth while. So did the class.'

'If the supply is removed, current still flows. Why? The experiment will show what happens to the charge on a slowly discharging capacitor. At a potential difference of 10 volts, what charge has the capacitor?' (Potential difference 10 V, capacitance 5×10^{-4} F, charge 5×10^{-3} C.)

Make graph scales with at least 10 cm for the largest charge. Watch the decay and choose a scale of, say, 10 cm for 100 seconds for the time axis. A large simple graph scale will be essential later on.

'Now we will record the current I at ten-second intervals. Write down the voltage and the charge left on the capacitor at each measurement. It is always the same calculation:

$$V = 10^5 I \qquad \text{if} \quad R = 10^5\ \Omega$$

and $$Q = 5 \times 10^{-4} V = 50 I \ \text{if}\ C = 500\ \mu\text{F}$$

Plot the graph of charge left against time. Why does it have the same shape as a graph of current and time would have? (Constant multiplier.) Can you see why the *current gets less and less? It falls because the p.d. driving it falls, and that falls* because the previous current flow removed some charge. The current falls because of the current itself.

'An epidemic is like that, but growing. The more 'flu victims there are, the more infectious people there are around, so the more new cases there are – until the virus runs out of people. Why are there isolation hospitals?'

Explaining the decay curve

It is possible to do more than see roughly why the curve has the shape it has. The next step will be to explain the shape mathematically. It will be done the way a computer would do it, with numbers rather than algebra. To save on arithmetic, it will be convenient to use a graphical method, and it happens that this method will be very useful on other occasions in the course.

Give students a new sheet of graph paper and, using the same scales, mark a point to represent the initial charge, 5×10^{-3} coulomb.

Go back to the apparatus. What current flows at 10 V? (100 μA). How much charge flows in 1 second at 100 μA? (10^{-4} coulomb.) How much in 5 seconds? (5×10^{-4} coulomb.) Is the current still 100 μA all through that 5 seconds? (No, but it has not dropped much.) Is it even roughly steady for 20 seconds? (No.)

Ask them to mark another point on the new graph, at 5 seconds, showing the drop in charge of 5×10^{-4} coulomb, which is 1/10 of the original charge, 5×10^{-3} coulomb. They can do this by counting ten small squares down from the original point, since that was 10 large squares from the origin, if the graph paper is divided in tenths. See figure 33.

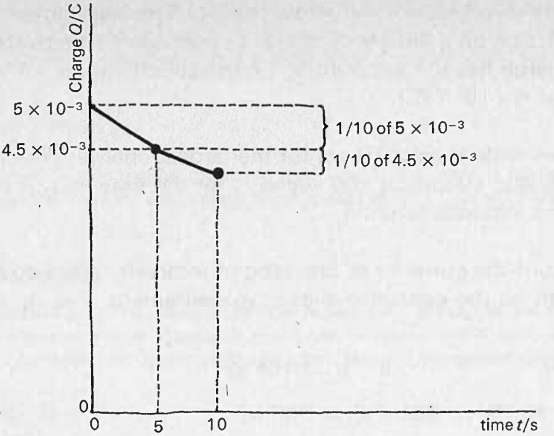


Figure 33
Charge-time graph, first two steps.

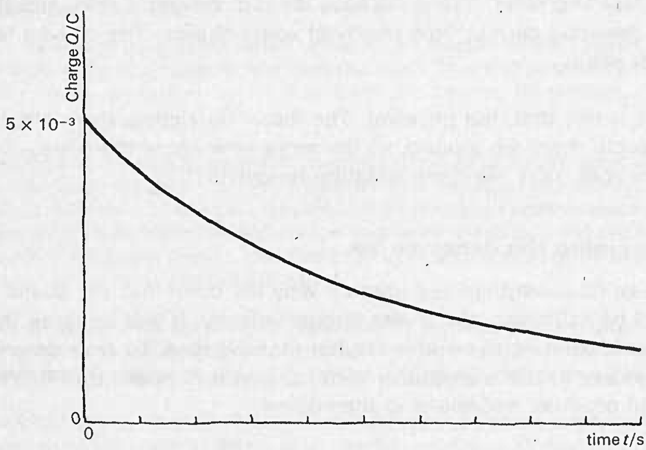


Figure 34
Charge-time graph.

'Why was the drop in charge just one-tenth of the original charge? If the charge is Q, the current is equal to Q/RC, or $Q/50$ for this experiment. But the current is the flow of coulombs every second, so in 5 seconds, a charge flow of $(Q/50)\times 5 = Q/10$ takes place. At every point on the curve, if the charge is Q, the drop in charge will be $Q/10$ after the next five seconds. Is that *exactly* true?'

There is some value in introducing the delta notation for changes, in preparation for later developments. All the changes here are finite, so we suggest using only the symbol Δ, saying that ΔQ is shorthand for 'change in Q' and Δt for 'interval of time'.

When the charge happens to be Q, the voltage V is:

$$V = \frac{Q}{C}$$

The current I is:

$$I = \frac{V}{R} = \frac{Q}{RC}$$

If current I flows for an interval Δt, which is short enough for the current to stay fairly steady, then the charge changes by ΔQ:

$$\Delta Q = -I\Delta t$$

$$\Delta Q = -\frac{Q}{RC}\,\Delta t$$

The minus sign says that this is a discharge: Q drops when current flows. 'You have to tell the mathematics *everything*; it is very nimble but also extremely literal-minded.'

For $RC = 50$ seconds, and $\Delta t = 5$ seconds

$$\Delta Q = -\frac{Q}{10}$$

'This is an equation telling us how Q changes. We are going to find a *solution*, that is, what this recipe for change leads to in the end; what the charge is after any time.'

Now ask them to draw out the curve, using this rule. Join the points with straight lines. See figures 33 and 34.

The fact that the change in charge is always one-tenth of the previous charge makes the graph easy to draw. If the charge at some moment is represented by, say, 3.5 large graph squares, then the next drop will be 3.5 *small* graph squares.

The two graphs, from theory and experiment, drawn to the same scale, can now be compared. They should agree fairly well. The theoretical graph will run downwards a little too steeply, as the current in each interval was taken from its largest value, at the beginning of the interval.

Discrepancies between theoretical and experimental curves

The numerical approximation in finite steps gives a curve which is not exactly the exponential function, though it would be were there indefinitely many infinitely small steps. In the case of the curve where the time RC is reached in ten steps, the curve will have fallen (if the plotting is accurate) to 1/2.9 of its initial value, instead of 1/e of this value (e = 2.718 . . .), an error of some 10 per cent. Theoretical and experimental time constants may therefore differ by some 5 seconds on this account, but there will also be discrepancies arising from the tolerances on the components.

Further mathematical study of the exponential function

For reasons given in the commentary above, we do *not* regard the numerical solution as an easy way of avoiding mathematical difficulties, particularly devised for students with little or no calculus. Indeed, we believe it to be a better way of developing insight into the problem than a formal algebraic treatment, and one that can succeed with more students. It represents a serious attempt to teach mathematics within physics, and to teach it for lasting understanding.

This is not to say that the algebra has no place. For many students, we think it may best be deferred, so the exponential function itself appears explicitly later on, in Unit 5, when radioactive decay is considered. But there will be students who can take it now, and some who already know it. Although the formal integration is not a part of the course, there is no need to ignore it with students who would be irritated at not being allowed to use their mathematical skill. And university teachers continually emphasize the need for such skill in students reading physics, not to mention other disciplines.

The work suggested opposite, for all students, is deliberately modest. The exponential function is regarded as the 'constant ratio' function, and the easy link with logarithmic graphs is made. The brief mention of the number e is mainly for amusement, foreshadowing later discussion. In deciding whether to go further than is suggested, teachers are advised to look at the work on exponentials suggested in Unit 5, and also at the part of Unit 4 which deals with numerical integration for the problem of the harmonic oscillator.

Textbook

Arons, *Development of concepts of physics*, is interesting in that it includes much material intended to assist understanding of calculus. It is also historical in flavour, and shows how the mathematical tools grew up alongside the scientific work that needed them. See Chapters 3 and 8, and possibly 16.

Students' book

Questions 50 to 57 cover exponential decay. Question 53 discusses the results of decay experiments. Question 54 is about testing for exponential change with a logarithmic graph. Questions 55 to 57 suggest uses for ideas about growth and decay.

The constant ratio property

In drawing the curve, the drop in Q at each time was one-tenth of Q. Thus the new charge after each 5 second interval was nine-tenths of the charge at the start.

By looking at either curve, one can see that a similar result holds for any ratio. At all points on the curve, it takes the same time for the charge to drop from Q to some fraction, say half, of Q. In this case, it takes about 34 seconds for the charge to be reduced to one half, and students should nod acquaintance again to the idea of half-life, met before in the Nuffield O-level Physics course in connection with radioactive decay. 'We have a curve that decreases by a constant ratio rule. The charge dwindles away in constant proportions. That is what you get when the rate of loss at any instant depends on how much is there at that instant.'

A logarithmic graph

A class which is managing this easily could deal with the logarithmic graph. The series

10^7 10^6 10^5 10^4 10^3

has the constant ratio property: the numbers decrease by the same factor (10) at each step. The powers

7 6 5 4 3

decrease differently, in equal steps. But the powers are the logarithms of the larger numbers.

The class could then plot a graph of lg Q against t, for the empirical or theoretical values, and reveal the linear relationship.

The number e

Students will have seen that the quantity RC decides how slow the discharge will be. It is called the 'time-constant' of the discharge. If they are asked how to measure a resistance (potential difference divided by current) and how to measure a capacitance (charge divided by potential difference), they can be shown that a measurement of RC will be in seconds.

$$\frac{\mathrm{V}}{\mathrm{A}} \times \frac{\mathrm{As}}{\mathrm{V}} = \mathrm{s}$$

They may then find the ratio of charge at one moment to charge at a moment RC seconds later, from the curve. Values will vary by 10 per cent or more, but will be in the vicinity of 2.7. This is an important number to mathematicians, who give it the symbol e. It turns up whenever there is a rate of change of something which depends on how much of that something there is. The graph has given a value of e, and in fact the only way to find e is to do some arithmetic.

Other exponential examples

Teachers who wish to illustrate the general usefulness of the exponential may find the following data helpful. They, and other examples, appear in the *Students' book* for Unit 5.

a Data for a famous epidemic – the plague of 1665 in London – survived and are shown in table 1. The rise is exponential to begin with.

Week ending	Plague deaths	Week ending	Plague deaths	Week ending	Plague deaths	Week ending	Plague deaths
May		July		Sept.		Nov.	
2	0	4	470	5	6988	7	1414
9	9	11	725	12	6544	14	1050
16	3	18	1089	19	7165	21	652
23	14	25	1843	26	5533	28	333
30	17	Aug.		Oct.		Dec.	
June		1	2010	3	4929	5	210
6	43	8	2817	10	4327	12	243
13	112	15	3880	17	2665	19	281
20	168	22	4237	24	1421	–	–
27	267	29	6102	31	1031		68596

Table 1

Deaths from plague in 1665. (Creighton, C., 1965) *A history of epidemics in Britain*, Volume 1, reprinted by permission of the publishers Frank Cass & Co. Ltd.)

b The exponential model represents the growth of demand for electricity rather well, and is used in planning ahead for generating plant.

Year	Capacity	Year	Capacity	Year	Capacity	Year	Capacity
1950	15.0	1955	22.5	1960	31.9	1965	43.9
1951	16.2	1956	24.6	1961	33.9	1966	46.2
1952	17.7	1957	26.0	1962	37.2	1967	50.0
1953	19.2	1958	28.0	1963	39.3	1968	53.6
1954	20.6	1959	30.0	1964	40.0	1969	55.1

Table 2

Installed capacity of electrical generating plant in the United Kingdom. Capacity is given in gigawatts (10^9 W). (Central Statistical Office, 1970, *Annual abstracts of statistics*, by permission of the Controller, HMSO.)

Part Four

Stored energy

Time: less than a week

Revision of dynamics

In this Part, we suggest further revision of dynamics when the need arises in connection with understanding the energy stored in a capacitor. The analogy between a spring and a capacitor can be used with profit, to show how similar ideas can be applied in different parts of physics, as well as for revision. This analogy is developed further in Unit 6, *Electronics and reactive circuits.*

As at other points, the air track can be used by students who have had enough of trolleys.

The work on stored energy also prepares for later work (Unit 5, *Atomic structure*) when the energy of an alpha particle transformed from kinetic to potential as it swings past a nucleus needs to be calculated.

Demonstration

2.18 Energy stored in a charged capacitor

1034 large electrolytic capacitor, 10 000 μF, 30 V

1033 cell holder with 4 U2 cells

1023 solar motor
or
9B small motor/generator unit (energy conversion kit)

1053 length of thin cotton thread

1053 Plasticine

1000 leads

The thread is tied to the pulley of the motor wheel and a few turns are wound on. The motor should be placed flat on the bench with the thread hanging over the edge and a small weight attached to the free end. The electrolytic capacitor is then charged up to 6 V and discharged through the motor. Most of the energy is transformed into heat, the small weight serving mainly as a marker.

If the small motor/generator unit is used, the capacitor should be charged to 9 V or 10.5 V and another cell holder with cells will be needed.

Because the energy transformed varies as the square of the voltage, the experiment is much improved by raising the voltage, but this may damage the solar motor and should only be tried with item 9B.

The temptation to make the experiment quantitative is perhaps best resisted. The motor is being used rather like a ballistic galvanometer, but with a number of ways in which energy is transformed, so that the distance the weight is lifted is obviously not a good guide to the energy transformed.

Demonstration

2.19 Energy proportional to V^2

52 Worcester circuit board kit with U2 cells *2*

92R m.e.s. bulbs (2.5 V, 0.3 A) *9*

1034 large electrolytic capacitor, 10 000 μF, 30 V

Two circuit board kits are required to obtain a 9 V supply. Note that the lamps are not the same as those supplied with the kit. The lamps should be tried beforehand, and more or less identical lamps should be selected.

The energy of a charged capacitor is worth studying, not so much because capacitors are a useful way of storing energy (they are not, except in some research experiments such as those which try to achieve thermonuclear fusion in hot gases, where the gas may be heated by a capacitor discharge) as for two other reasons.

First, ideas about electrical energy will be useful later in the course, especially in Part Five of this Unit, about the energy levels of atoms, and also in Unit 3, about electric fields, where ideas of energy will help to link up electric forces and fields. So this Part takes up electrical energy again from Part Two, which discussed it in connection with the idea of potential difference.

Secondly, there is the opportunity to think again about other kinds of energy, especially mechanical energy, which is worth taking because scientists and engineers use energy ideas almost every day of their lives. So Part Four contains a discussion of mechanical energy, to revise and clarify ideas from earlier work.

Demonstration

2.18 Energy stored in a charged capacitor

A toy electric motor which will run on a very small current will show that the energy stored in a capacitor can be transformed into mechanical energy. The motor will lift a small weight.

The motor efficiency may be as low as 10 per cent, and the weight is little more than a marker. Most of the energy goes to warm up the bearings.

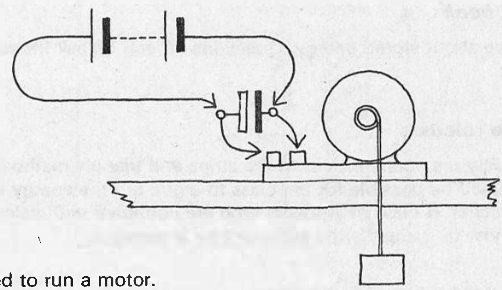


Figure 35
Charged capacitor used to run a motor.

Demonstration

2.19 Energy proportional to V^2

Discharge a 10 000 μF capacitor charged at 3 V through a torch bulb. Ask where the energy of the flash came from. Try two bulbs in parallel and two in series; they light up much less.

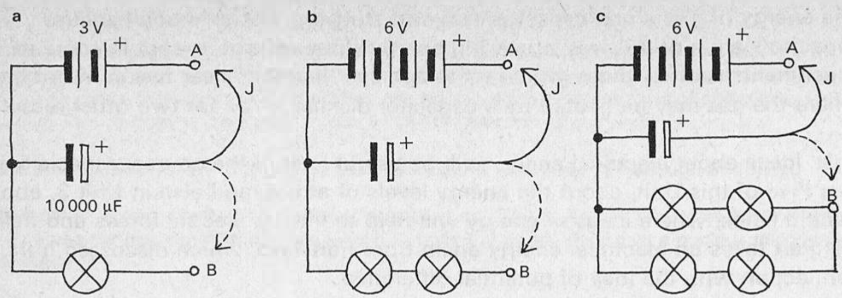


Figure 36
Discharge of capacitor through lamps.

Using circuit *a* (figure 36), the capacitor is charged (J to A) and then discharged through the lamp, the brightness of the flash being noted. Two lamps in series are substituted for the single lamp as in circuit *b*. The capacitor is again charged to 3 V and discharged. The bulbs light much less. Two lamps in parallel should also be tried.

Returning to the circuit *b* arrangement, the capacitor is now charged to 6 V and discharged. The lamps now flash more brightly and longer, than did two lamps (or one lamp) with the capacitor charged to 3 V. With 4 lamps arranged as in *c*, it will be found that the four lamps flash similarly from the capacitor charged to 6 V as the single lamp did from 3 V in *a*.

At 9 V, the capacitor will similarly light 3 parallel banks of 3 lamps in series.

It may be helpful to cover three of the four lamps, when using four, so that only one is visible and its behaviour can more easily be compared with that of a single lamp in a circuit.

Students' book

Questions 58 to 64 are about stored energy. Questions 58 and 69 ask for estimations of quantities of energy.

Use of the calculus

The Nuffield O-level Physics course has used the strips and triangle method, figures 37 and 38, more than once. It should be possible for the class to argue out the energy with little more than questions from the teacher. A class of students who are confident with calculus may profitably be shown, or be asked, how to complete the argument by integration.

Tactics for teaching about energy

The reason for teaching about energy in this course is that the idea is useful. By waiting until it is clearly needed in a new context, we hope students will see that it is useful and wish to clear their minds. In effect, the teaching tactic is to assume that the class is expert in these ideas until (as expected) the contrary proves to be the case.

Just how much revision is required is a matter for the teacher to judge. The experiments suggested below are our estimate of what may be about right for many classes, especially those whose background is Nuffield O-level Physics.

Teachers are advised to consider the experiments suggested in Nuffield O-level Physics, particularly *Teachers' guide IV*, experiments 58 to 67. Force and momentum experiments can be excluded for the moment; they appear in Part Five of this Unit.

Offer to use a larger potential difference, say twice as much. A single lamp will probably burn out, and two lamps in series would be a sensible arrangement. Looking carefully, it can be seen that these lamps flash on for considerably longer at 6 V than one did at 3 V. The energy may be doubled or more than doubled. Asking how much more charge there is at 6 V, and how much more energy each coulomb has, reach the suggestion that the energy is quadrupled.

It should be possible to light a second series pair of lamps in parallel with the first series pair. Now compare the flashes of one lamp at 3 V with those of each of the four at 6 V. The experiment can be extended to 9 V and nine lamps. The energy stored is proportional to the number of joules per coulomb passed multiplied by the number of coulombs. Is it equal to this product? (No, the p.d. falls as soon as charge is delivered. But it would be not far wrong for a car battery.)

Discussion: the energy stored is $\frac{1}{2}QV$

The experiments indicate that the energy stored is proportional both to the charge stored and to the potential difference. If the capacitor starts discharging, at a p.d. of V_0, and a small charge ΔQ flows, the energy transformed is $V_0 \Delta Q$. Potential difference is the energy transformed per coulomb flowing.

The potential difference must now be less. It will drop by $\Delta V = \dfrac{\Delta Q}{C}$ to a new value V_1. See figure 37.

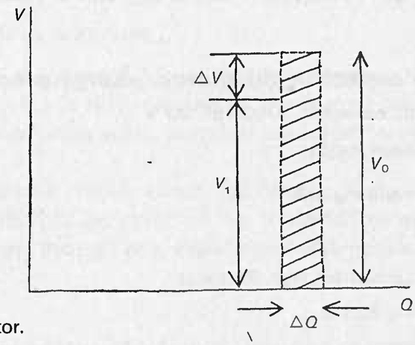


Figure 37
Drop in p.d. across a capacitor.

Students who have not used the dynamics trolleys from Nuffield O-level could use them now. Others may well be impatient with trolleys: for them the air track can give what are in essence the same experiments an air of freshness.

Organization of the energy experiments

For many classes, we think it will be enough for each pair of students to do one of the following experiments, results being reported to the class with small demonstrations where appropriate. Instructions, which the teacher will have to provide, may be needed for some experiments.

An air track can be used by more than one group of students, particularly if more than one camera is available. It may also be convenient if one group produces a number of stroboscopic photographs which are then analysed by other students.

With the number of experiments suggested, pairs of students in a normal sized class cannot all be occupied on different tasks. Either some experiments will have to be available in greater quantity or other experiments will have to be added.

One pair could be occupied with the long Millikan experiment, which appears in the teaching in Part Five of this Unit, and for which there are instructions in the *Students' laboratory book.*

There is no reason why a student who is more competent at dynamics than the rest should not tackle one of the other long experiments, such as the experiment to measure G or even the velocity of light. A good student can rise to the challenge of taking on a private task and at the same time keeping up with the classwork.

Students' book

Question 60 deals with energy stored in a spring, leading to $\frac{1}{2}Fx$. Question 61 deals with the energy of a capacitor, leading to $\frac{1}{2}QV$. Both can be used to save time in class discussing the theory.

Experiment
2.20 Heating by capacitor discharge, energy proportional to V^2

1034 large electrolytic capacitor, 10000 μF, 30 V

59 l.t. variable voltage supply
and
1064 low voltage smoothing unit
or
176 12 V battery *2*

1054 3 m insulated constantan wire, 28 s.w.g.

1054 1 m copper wire, 32 s.w.g.

1005 multirange meter

1001 galvanometer (internal light beam)

77 aluminium block

1000 leads

optional: well insulated two-way switch

Wind 2 metres of 28 s.w.g. insulated constantan into a ball about ten millimetres in diameter, starting on a 2 mm diameter rod to leave a hole into which one thermocouple junction may be inserted. Make the thermocouple from two 0.5 m lengths of 32 s.w.g. insulated copper wire and one 0.5 m length of 28 s.w.g. constantan. Put the second thermocouple junction in a large heat sink, such as the aluminium block. If possible, use thinner constantan wire for the thermocouple.

If it goes on discharging, and further charge ΔQ flows, the new bit of energy transformed is $V_1 \Delta Q$, and so on, with V growing smaller and smaller. Since $Q = CV$, the graph will run as a straight line down to zero.

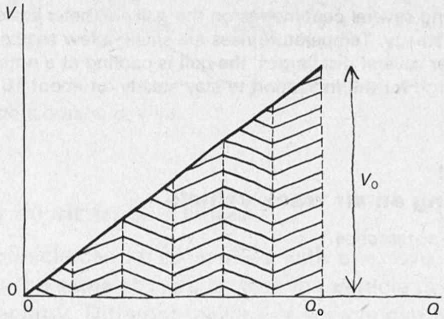


Figure 38
$V\Delta Q$ strips.

The total energy transformed is the total area of all the strips, each $V\Delta Q$, which is the area $\frac{1}{2}Q_0V_0$.

This total energy is also equal to $\frac{1}{2}CV_0^2$ (and to $\frac{1}{2}Q_0^2/C$). If there is confusion with the decay of charge curve, teachers will prefer to make the same argument, but for the charging up of the capacitor.

Energy stored in a spring

If the analogous case of the energy $\frac{1}{2}Fx$ stored in a spring which obeys Hooke's law at tension F and extension x is now discussed, the formal parallel can be brought out. Arguments in physics often work, suitably modified, in more than one problem.

But uncertainties in students' minds about the concepts of work, potential energy, and kinetic energy are likely to be revealed. So there follow some mainly dynamical experiments about energy, though one experiment attempts a check on $\frac{1}{2}QV$.

Experiment
2.20 Heating by capacitor discharge, energy proportional to V^2

A short calculation can indicate that the 10 000 μF capacitor stores about 4 joules at 30 volts, enough to warm a small object appreciably. The capacitor is discharged through a small bundle of wire and temperature changes are indicated by a thermocouple. The galvanometer rise after one discharge can be plotted against V and against V^2. See figure 40.

If this is used as a demonstration, it is effective and economical to show that four discharges in succession at, say, 10 volts, give the same temperature rise as does one discharge at twice the voltage.

The capacitor is connected so that it can be discharged through the bundle of wire, which has a resistance of about 10 Ω, the time constant being about 0.1 second. The polarity of the capacitor must be correct.

The thermocouple should give measurable temperature rise indications for voltages above 10 volts, the rise for 30 volts being several centimetres on the galvanometer scale. It takes about 5 seconds for the reading to become steady. Temperature rises are small, a few tenths of a degree, so that cooling effects are small. If, after several discharges, the coil is cooling at a noticeable rate, it is best to wait until it has cooled enough for the indication to stay steady for about 10 seconds before taking further readings.

Experiment

2.21 Catapulting an air track vehicle

1019	air track and accessories
1020	air blower
133	camera *and*
171	photographic accessories kit *and*
134/1	motor driven stroboscope *and*
1054	developer, fixer, printing paper *or*
130/1	scaler *and*
130/2	photodiode assembly with light source
501	metre rule
1053	card, Sellotape
529	scissors
106/2	elastic cord for accelerating trolleys
31/1	weight hanger with slotted weights (10 g)
42	lever-arm balance
4A	drinking straws
	a light source, such as a slide projector, is needed for photography

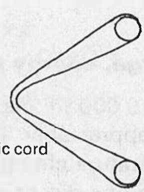


Figure 39
Catapult.

An elastic catapult is made from a rubber band by stretching it lightly between two supports about 0.2 m apart, at such height that it will project a vehicle along the air track. The band should be firmly fixed at each end. The band is then pulled back a measured distance x with the air track vehicle. The vehicle is released and its velocity measured. This is repeated for various extensions of the catapult.

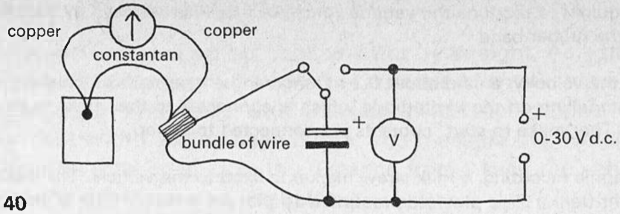


Figure 40
Capacitor discharge through a bundle of wire.

Experiment

2.21 Catapulting an air track vehicle

a An air track vehicle can be catapulted with one, two, or three elastic bands or threads all at the same stretch, so that the vehicle is given one, two, or three units of kinetic energy. Different masses of vehicle can be used, and the equation kinetic energy $= \frac{1}{2} mv^2$ tested.

This will probably be an unnecessary repetition for some students who have taken the Nuffield O-level Physics course.

b Using a single piece of elastic as a catapult, the force needed to pull it back to several measured distances is recorded. Then the vehicle can be released from each distance, and its velocity can be measured by stroboscopic photography or with the scaler-timer and a lamp and photodiode. Teachers may want students to compare these methods for reliability.

Questions in discussion should bring out that the energy of the vehicle could be expected to be less than that stored in the catapult, for when the vehicle leaves the catapult the rubber itself is moving and has some kinetic energy. The error is small because the rubber has a much smaller mass than the vehicle. This is why a steel spring is not a good device to use in this experiment, but is suited for use with trolleys, as in experiment 2.22.

The force required to produce the various values of x can be obtained by hanging various slotted weights on the rubber band.

To measure the velocity, a card about 0.1 m long can be mounted on the vehicle so that it interrupts the light beam falling on the photodiode which is connected to the 'make to stop' contacts of the scaler-timer. The 'make to start' contacts are connected together.

For photographic recording, a milk straw marker is fixed to the vehicle. The marker is illuminated by means of light from a slide projector, mounted so that the beam of light is along the length of the track. The camera faces the track. The stroboscopic disc (6 slits) mounted on its motor (which turns at 5 revolutions per second) is placed so that the slits rotate across the camera lens. It may be necessary to cover alternate slits to obtain images suitably separated. A scale should be incorporated in the field of view.

Notes on photographic technique appear in the 'Tools' section of the *Students' laboratory book*. See also Nuffield O-level Physics, *Guide to apparatus*, page 150 and *Guide to experiments IV*, Appendices I and II.

Students' book

Question 62 uses the result for the energy of a capacitor. Question 63 is a problem about a catapulted vehicle.

Textbooks

For the energy of a charged capacitor, see:

Bennet, *Electricity and modern physics*, Chapter 11.3, and many other texts.

For stored mechanical energy, see:

PSSC *College physics*, Chapters 17, 18

PSSC *Physics* (2nd edition), Chapters 23, 24.

Rogers, *Physics for the inquiring mind*, Chapter 26 (very good).

Experiment
2.22 Energy stored in a spring

107	runway
106/1	dynamics trolley
2A	expendable steel spring
81	newton spring balance (10 N)
503–6	retort stand base, rod, boss, and clamp
44/1/2	G-clamps, large and small
108/1	ticker-tape vibrator
108/2	carbon paper disc
108/3	ticker-tape
27	transformer

Calculation: the stored energy

The graph of force and distance pulled back will not be straight. As with the capacitor, the area below the graph is treated as a series of small strips, but this time it has to be found by arithmetic. Students can divide their graphs into narrow strips, of a convenient width Δx, perhaps 5 mm, and measure the average force F in each interval. Then the total area up to the distance from which the vehicle was released measures the energy stored, in joules.

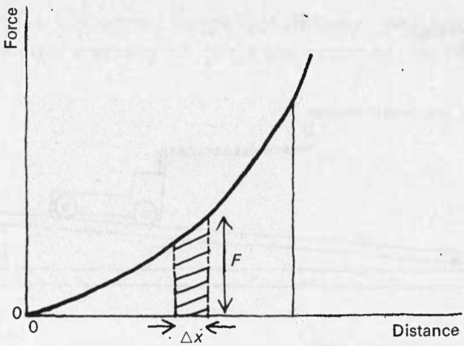


Figure 41
Area under the force-distance graph.

It would be wise to point to the curvature of the graph, and ask if the energy would be equal to $\frac{1}{2}Fx$. Then when students see that it would be so only for a straight graph, they may wish to try it for a good steel spring.

Experiment
2.22 Energy stored in a spring

The steel springs used in the Nuffield O-level Physics course can be used to test the prediction that the energy should be equal to $\frac{1}{2}\times$ (tension in spring at release) $\times$ (distance pulled back). Students may want to check that the force-distance graph for the springs is straight, but this should be done very rapidly.

A spring is convenient for catapulting a trolley. A spring from the Nuffield O-level Physics elastic materials kit may be stretched against a stout tethered thread, or the spring may be held on a downward facing peg so that it drops off when it is slack. Students may well find other arrangements. See figure 42.

Having measured the trolley velocity, students can compare the values of $\frac{1}{2}mv^2$ with $\frac{1}{2}Fx$, and test whether they are equal within the limits of the experiment. A plot of velocity v against spring extension x should be a straight line, since $F \propto x$ so that the stored energy goes as x^2, the kinetic energy going as v^2.

133	camera
	and
171	materials for strobe photography
	and
1054	developer, fixer, printing paper
	and
134/1	motor driven stroboscope
	or
130/1/2	scaler with photodiode assembly and light source
501	metre rule
42	lever-arm balance
1000	leads

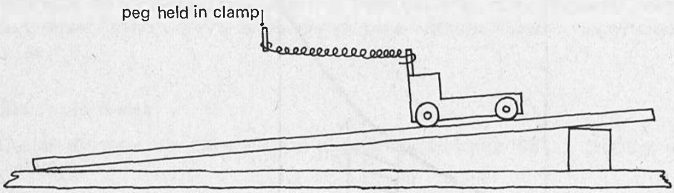


Figure 42
Apparatus for a spring accelerated trolley.

The trolley runway is carefully compensated for friction so that the trolley, when given a push, runs down it with a steady speed. The stand is securely G-clamped near the track centre and a trolley peg is held as shown so that its lower end is a few millimetres higher than the peg in the trolley. The spring is hooked over the two pegs and a check made that the spring drops off the clamped peg when the trolley moves underneath it.

A metre rule is clamped along the runway near the trolley but positioned so as not to interfere with the movement of it. The position of the trolley as the spring *just* begins to stretch is noted so that the stretch of the spring can be obtained from a knowledge of the trolley's position relative to the ruler. The spring is now stretched by a known amount, the trolley is released from that position, and its velocity, after the spring has dropped from the clamped peg, is measured. This is repeated for other values of the extension (up to 120 mm). The forces corresponding to these extensions may be measured with the spring balance. The mass of the trolley may be varied by loading it (1 kg). It will be necessary to weigh the trolley.

Students' book

Question 64 is about energy in general, and confusion between force and energy in particular. It is useful as practice for comprehension questions.

Capacitors and springs

The analogy may be brought out by comparing the equations:

$F \propto x$ $\qquad$ $V \propto Q$

$(F = kx)$ $\qquad$ $\left(V = \dfrac{Q}{C}\right)$

Energy $= \frac{1}{2}Fx$ $\qquad$ Energy $= \frac{1}{2}VQ$

Two capacitors can have the same charge but different energies. Is there a parallel with springs? What would a spring of 'large capacitance' be like: weak or strong?

Part Five

Electrons and energy levels

Time: rather more than a week

The purpose and timing of teaching about energy levels in the course

Part Five offers evidence, early in the course, for the existence of atomic energy levels. The treatment is entirely empirical, with theoretical ideas being deferred until Unit 10 at the end of the course.

Students usually like to know how the work to come fits into the total pattern, and the survey opposite is an attempt in this direction.

Students doing Nuffield Advanced Chemistry will meet similar work on energy levels at about the same time, in Topic 4. This is one reason for an early introduction in the Physics course, and there is much to be said for joining forces with the chemists at this point. Certainly there should be consultation as to how the two accounts can complement each other.

There are other reasons for placing this work at this point, though teachers will feel free to fit it in elsewhere if they prefer. It provides a use for the ideas in the rest of Unit 2, and a use which illustrates again how physics moves backwards and forwards between the large scale and the small scale, constantly trying to extend explanations of the large scale in terms of new understanding of the small scale. The ideas of charge and potential difference are revised in considering evidence for electrons, and again in discussing the energy level evidence. The latter demands some revision of dynamics, needed in other Units.

The evidence for energy levels is a nice example of the interplay of fact and theory. Such interplay is crucial to an understanding of the nature of atoms. So energy levels are here presented as a fact to be explained, as part of the build-up of this aspect of the course. The fact of their existence is used in Unit 9.

The work of Part Five could be amalgamated with that of Unit 5, *Atomic structure*, thus shortening the time spent on electricity, or it could be used in place of Unit 3, Part Four, on 'Ionic crystals', as a bridge between Units 3 and 5. This would be especially appropriate if Unit 4 were placed between Units 2 and 3 in order to break up a long stretch of electricity, though the dynamics in Unit 4 would then need stronger attention.

Structure of Part Five

Part Five is necessarily a little complicated, weaving together evidence for electrons, for energy levels and dynamics. The following map may be helpful.

Revise ideas about electrons, Millikan experiment,
calculations on electron bombardment.

↓ ↓

Ionization of air; ionization of gases by electron bombardment. Energy needed to ionize gases.	Collision dynamics; elastic/inelastic collisions; momentum conservation

↓ ↓

More careful ionization and excitation experiments; reading about energy level evidence.
Evidence and theory.

Revision by discussion

The dangers with revision are boredom and a tendency of students to think that 'What I tell you three times is true', the latter being disastrous for teaching which is concerned with what the evidence does and does not support.

Both may be countered to some extent if students present and explain the demonstrations, while the teacher joins the class and tries to exemplify a critical attitude. In this way, individual students have the valuable experience of defending their explanations in discussion, and the teacher is freer both to encourage contributions and to comment on the discussion.

Survey of Part Five

Unit 2 so far has been concerned with the bread and butter of the study of electricity: ideas about current, conduction, charge, and potential difference. In Part Five these ideas are used to understand something new and important about atoms: the fact that atoms accept or reject energy only in lumps.

This is an important fact about atoms for physicists and for chemists, and it is also something that asks to be explained. But this will have to wait until Unit 10, *Waves, particles, and atoms*, and for now the course concentrates on the evidence that it is so.

Understanding the evidence will require revision of other ideas, particularly the idea that electric charge also comes in lumps carried by particles like electrons.

This Part will also include some extracts from original scientific papers which present some of the evidence. It will be found that these papers assume some understanding of dynamics, for they are about what happens when electrons collide with gas atoms. So this Part also revises the dynamics of collisions. The dynamics revised here will be useful elsewhere in the course, as it so often is, especially in Unit 4, *Waves and oscillations*, which at first sight seems to have nothing to do with collisions. The idea of energy levels will be used in Unit 9, *Change and chance*, which is about how large numbers of atoms in lumps of matter exchange energy with each other, and especially about how it happens that heat flows by itself always from hot things to cool things.

Unit 5, *Atomic structure*, will follow up the ideas about electrons and energy levels in this Part, when it discusses evidence that an atom is an assembly of electrons around a nucleus.

Electrons and electron streams

Most physics books mention electrons, but no physicist has ever seen one. So what does it mean to say that matter contains electrons? What evidence is there, what does it tell us about electrons, and which of our imaginings (electrons like small hard spheres?) are or are not supported by the evidence? This Part will almost all be concerned with this aspect of a physicist's thought: what does the evidence suggest about what he can't see directly?

Asking the question can introduce a discussion of the evidence for electrons, which will be mainly revision for students who come from the Nuffield O-level Physics course. Others will need more direct teaching, based on Nuffield O-level Physics *Teachers' guide IV*, Chapter 6, pages 362–366 and 375–384.

The evidence is of two kinds: evidence from electron streams, and evidence from the Millikan experiment. The first can be the subject of demonstrations by students.

Students' book

Questions 65 to 70 are about electrons. Question 69 deals with the Millikan experiment.

Textbooks

Bennet, *Electricity and modern physics*, Chapter 17.

Caro, McDonell, and Spicer, *Modern physics*, Chapter 2.

Millikan, *The electron,* Chapter 5.

Rogers, *Physics for the inquiring mind*, Chapter 36.

Demonstration or student demonstration

2.23 Electron streams

27	transformer
14	e.h.t. power supply
140	stand for tubes
136	Maltese cross tube
137	Perrin tube
138	deflection tube
139	pair of coils
51A/B	gold leaf electroscope
15	h.t. power supply
176	12 V battery
61	fine beam tube
62	fine beam tube base
92B	Magnadur magnet
541/1	rheostat (10–15 Ω)
70	demonstration meter *with*
71/12	d.c. dial (100 mA)

A selection from Nuffield O-level Physics Year IV. See *Guide to Experiments IV.*

160	stream of electrons making a shadow of an obstruction (Maltese cross)
161	stream of electrons coming through a slit to make a straight splash across a screen *and*
161	deflection of stream of electrons by electric fields
162a	fine beam tube, raising and lowering gun voltage
162b	deflection of beam (fine beam tube) by electric field
163	deflection of fine beam by magnetic field
164	electrons hitting a target and heating it
165	electrons collected to determine the sign of their charge (Perrin tube)

Cathode ray oscilloscope

If necessary, the construction of the cathode ray oscilloscope should be explained at this stage.

Demonstration or student demonstration

2.23 Electron streams

The experiments can show tubes in which electron streams strike an obstacle, make a streak, are bent by fields, heat a target, and are shown to carry negative charge. The extent to which the experiments do *not* give evidence for some points is worth attention, and a sceptical attitude towards the interpretations offered is to be encouraged. Some points worth noticing are:

1 None of the experiments point directly to particles of charge.

2 There is evidence for the negative sign of the charge carried by the electron stream.

3 The stream bends in electric and magnetic fields, and the question 'Why does it bend just the amount it does?' can lead to discussion suggesting that the stream may carry charge and mass.

Long experiment

2.24 The Millikan experiment (charge on an electron)

1043 Millikan apparatus
14 e.h.t. power supply
1005 multirange meter
1000 leads

The *Students' laboratory book* includes a section on the Millikan experiment, which is intended to help the student acquire the skill he needs as he goes along, and gives very full practical details.

Figure 43 shows a Millikan cell developed by the Project which fits onto the O-level Physics microscope, item 23. See apparatus section of *Teachers' handbook.*

Oil drops or latex spheres

The Millikan film (see below) uses a suspension of uniformly sized latex spheres, which have the advantage over oil drops that the size and weight can be taken as known data.

The latex is manufactured for calibrating electron microscopes by Dow Chemicals, and has been supplied to distributors of PSSC and Harvard Project Physics apparatus in the USA. It is hoped that apparatus firms in this country will be able to arrange for its distribution here. The particle size required is about 2 microns (10^{-6}m) diameter. The latex is expensive, but only a few cubic centimetres are needed, although this will still cost several pounds.

The practical advantage of the latex is that arguments using viscous forces on falling drops are avoided. The *Students' laboratory book* achieves the same for students using oil drops by printing a graph of the weight of a drop against the time taken to fall freely a standard distance (1 mm).

Long experiment

2.24 The Millikan experiment (charge on an electron)

Free use of the word 'electron' in 2.23, as earlier in this Unit, should have raised the question as to the evidence for the grainy, particulate nature of electric charge, and for the size of the charge $e = 1.6 \times 10^{-19}$ coulomb. It is Millikan's experiment that offers evidence on these points.

If, as suggested, not all students do the experiment, the principle needs to be discussed and the apparatus shown. This can be done in conjunction with the film of the experiment, referred to below. Note that the electric field between the plates need not be mentioned explicitly. An energy argument can make it seem reasonable that the force on a coulomb of charge between the plates is the ratio of the potential difference to the distance between the plates, equating the energy transformed in moving a charge from one plate to the other with the product of force and distance. This argument helpfully reinforces the meaning of potential difference. It will appear again, and the connection with electric field will be made explicitly, in Unit 3, so it may be treated quite lightly now.

One pair of students could begin work on this long experiment now, results being discussed later, perhaps at the appropriate place in Unit 3.

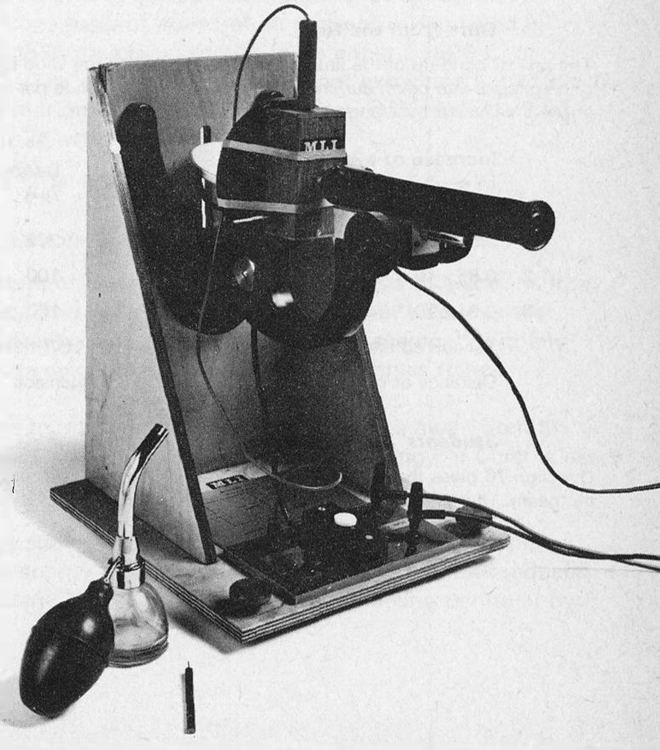


Figure 43
Millikan apparatus.
Photograph, Michael Plomer.

Film and film loop

The film 'Are there electrons?' may be hired and the loop purchased from Rank Audio Visual. See the list of films for this Unit on page 126. The film was made, in conjunction with the Nuffield Advanced Physics Project, for use in the Advanced or Ordinary level Physics courses, or for use with Advanced Chemistry or Physical Science courses.

The PSSC film, 'The momentum of electrons', is available on hire. For details see the list of films and film loops at the end of this book. It is not easy to hire films for just the time when they are needed, mainly because the distributors carry too small a stock of copies. This film could, however, be shown at many points in the course, whenever atomic particles or dynamics are being discussed. It could fit into Units 3, 4 (less naturally), or 5, and could even go with the discussion of accelerators in Unit 7. However, it fits well now, because it suggests that one can calculate the effect of electrons hitting things, which is exactly what is wanted for the energy level work.

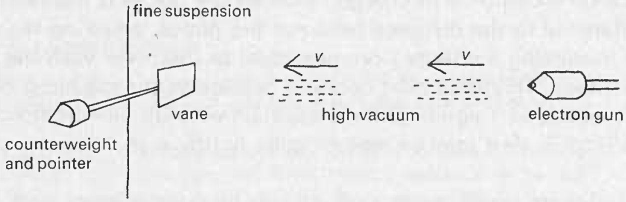


Figure 44
Electron gun and vane used in film 'The momentum of electrons'.

Data from the film

The rate of build-up of the amplitude of oscillation of the vane is measured in the film, for various gun voltages and beam currents. The increase of amplitude per oscillation is proportional to the impulse delivered by a burst of electrons.

	Increase of swing in each oscillation /radians per oscillation	Gun voltage/V	Beam current /μA
1	1.5×10^{-3}	2500	200
2	0.86×10^{-3}	2500	100
3	0.67×10^{-3}	1250	120

Torsion constant of vane suspension $= 5.9 \times 10^{-7}$ newton metre per radian

Distance of point of impact of beam from suspension $= 1.2 \times 10^{-2}$ metre

Students' book

Question 70 gives the above data and asks the questions on pages 93 and 95 about the forces from the beam. The question can be done at home, saving class time for discussion of difficulties.

Film and film loop

The film 'Are there electrons?' assumes that students have seen the apparatus and understood the point of the experiment. It shows first the evidence for the grainy nature of the charge, and can be stopped here on a first showing or in use at O-level. The last part offers a calculation of the charge on an electron from the data obtained.

The film loop 'Are there electrons?' does not stand by itself, but should be used in conjunction with apparatus. It shows only the process of obtaining data in the experiment, and could be used by a student who had difficulty in producing enough results.

Calculations on charged particles and on electrons as bullets

The idea that lumps of charge can be carried on particles that also have mass is still remote, lying beneath the surface of the evidence. Some calculations can make it seem less tenuous.

1 *Ions and electrolysis*

Chemists in the class should be able to say something about evidence that ions carry charge in lumps. When one mole of atoms of an element is deposited in electrolysis, the charge passing in the circuit proves to be either 96 500 C, or $2 \times 96\,500$ C or $3 \times 96\,500$ C. (The case for expecting or not expecting $4 \times 96\,500$ C could be argued.) Recalling that one mole is 6×10^{23} atoms, one might think of ions having charges e, $2e$, or $3e$, where

$$e = 96\,500/(6 \times 10^{23}) = 1.6 \times 10^{-19} \text{ C}.$$

2 *Force produced by a beam of electrons*

The PSSC film 'The momentum of electrons' shows short bursts of electrons from a gun striking a suspended vane and deflecting it, suggesting that electrons are particles real enough to behave like bullets. The film is worth seeing, but in any event calculations can be done using data drawn from it. Examples follow.

The gun bursts are fired so as to hit the vane each time it swings away from the gun, building up the swings in this way. The increase in angle of swing per burst is used as a measure of the impulse delivered by a burst of electrons.

Which of the data (opposite) shows that halving the number of electrons per second at the same speed or energy halves their impulse? (Beam current reduced from 200 to 100 μA, at constant 2500 V, reduces increase of swing per burst by about a factor of 2.)

Introducing ionization experiments

Some teachers may prefer to start the experiments first and talk about why afterwards. In this case, the only excuse needed may be that of looking at the conduction of electricity by air, having previously looked at conduction by other things. But the reasons opposite are nearer to the true reasons for studying ionization, though they avoid anticipating the result – that energy is transferred to atoms only in lumps.

The conception of 'physics as gunnery' is surprisingly general. It covers nuclear physics, and also spectroscopy and X-ray crystallography once one remembers that 'looking at' something involves bombarding it with photons.

Demonstration

2.25 Ionization of air

65	metal plate with insulating handles	*2*
503–6	retort stand base, rod, boss, and clamps	*2*
1033	cell holder with 4 U2 cells	*2*
1006	electrometer with $10^9\ \Omega$ and $10^{10}\ \Omega$ resistors	
1003/1	suitable meter for electrometer, if not incorporated	
1054	nichrome wire, 28 s.w.g., 0.3 m length	
59	l.t. variable voltage supply	
16	radium source (5 μCi) with handling tongs	
52K	crocodile clip	
1053	matches, candle	
1000	leads	

The plates are mounted parallel to each other, in a vertical plane and no more than 20 mm apart. They are connected to two cell holders in series and the electrometer with a $10^9\ \Omega$ input resistor, as shown in figure 45. The electrometer should be carefully zeroed.

Ionization of the air between the plates is detected by the p.d. across the input resistor due to the ionization current through it. Ionization may be caused by:

The flame of a match or a candle held immediately below the plates.

A coil of wire heated bright red by an electric current. The coil can be made from 0.3 m of 28 s.w.g. bare nichrome wire wound tightly into a coil about 5 mm in diameter and about 3 mm long. The coil may be held between the plates (axis parallel to the plane of the plates) in crocodile clips, or soldered to stout copper leads for a more permanent arrangement. It is supplied directly from the l.t. variable voltage supply, whose output should be slowly raised until the coil glows bright red.

The radium source held pointing into the space between the plates. There may be advantage in reducing the separation to about 10 mm or in changing the input resistance to 10^{10} ohms.

In doing these demonstrations, the presence of a charged object may disturb the meter reading and it is advisable to keep away from the plates if possible. The variations can be smoothed out somewhat by switching to the 'C+R' position on some electrometers.

Reducing the gun voltage from 2500 V to 1250 V halves the energy of each electron. By what factor does it reduce the momentum? ($\sqrt{2}$.) Find the increase of swing per burst at 1250 V for a current of 100 μA (multiply the value for 12 μA by 100/120) and compare with that for 2500 V at 100 μA. (Ratio 1.43, expected value $\sqrt{2}$.)

Ionization and collision experiments

The main new work of this Part now begins, after the necessary preliminaries about electrons.

Physicists are great bombardiers, because they have to be. Those who use high energy accelerators (of which more in Unit 7) use them to fire high energy particles, including electrons, at atoms and nuclei to see what happens, and often to see how much energy is transferred. Because atoms and nuclei can't be seen, one has to do something to them to find out about them, and bombarding them is one of the best ways of getting information. (Unit 5 has another example, bombarding nuclei with alpha particles.)

In this Part, atoms will be bombarded with electrons, and the energy transferred will be studied, to find out about how atoms exchange energy. Electrons are a convenient tool because the energy to which they are accelerated can be controlled accurately, using a definite potential difference across an electron gun. But before looking at electron collisions (and at collisions in general, to revise the needed dynamics) some simpler demonstrations can suggest what may be worth studying.

Demonstration

2.25 Ionization of air

Three ways of ionizing air can be shown with one basic arrangement, as in figure 45.

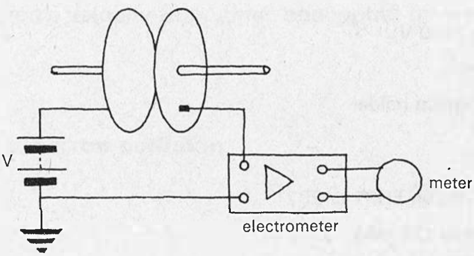


Figure 45
Ionization of air.

Group of experiments on ionization and on collisions

It is suggested that the class should be divided among ionization experiments with gas-filled tubes and momentum experiments on collisions. Each pair or group of students would do one experiment, and report to the rest, with demonstrations if necessary. The practical work may occupy a double period, followed up by reports and further discussion. The dynamics experiments can be reported as part of the discussion of the interpretation of the ionization experiments.

Brief notes on the ionization experiments appear in the *Students' laboratory book*, so that work may start without delay. Because the selection of dynamics experiments will vary according to the previous experience of students and the resources of the laboratory, teachers will have to produce their own notes for these, if they feel that notes are needed.

Introductory questions

The teacher should aim here to indicate that the electron collision experiments will be a piece of applied dynamics, and that for this purpose, it will be necessary to have the dynamical principles clear. Most classes will not provide complete answers; that is the point of asking the questions, to reveal the need for further work.

Students' book

See question 75.

Textbooks

See PSSC *Physics* (2nd edition), Chapters 26–9, 34–1, and PSSC *College Physics*, Chapters 23–9, 33–2, on ionization.

Experiments

2.26 Ionization by electron collision

a Xenon, b Argon, c Helium

1049	thyratons and thyratron base
59	l.t. variable voltage supply *and*
1064	low voltage smoothing unit
1005	multirange meter (25 V range) *or*
1004/3	voltmeter (100 V)
27	transformer
1040	clip component holder
1000	leads
a	
	xenon thyratron EN91 *or* 2021
1003/2	milliammeter (10 mA)
1051	protective resistor, 1000 Ω *or*
1017	resistance substitution box

a Alpha particles crashing through the air between the plates make the air conduct and a current flows. Are air molecules being ionized? If so, how – because of violent collisions? Such questions are mainly speculative. Students may recall cloud chamber tracks of alpha particles, seen in O-level Physics.

b A flame between the plates also produces a current. Is this because the flame is hot, or because the flame reaction produces ions? With care, ions can be blown downstream of the flame into the space between the plates and still produce a current.

c A red hot coil of wire will ionize air enough to give a current. Could heated air become ionized because of more powerful collisions between fast moving molecules?

Introducing the ionization and collision experiments

Ions can be made by having electrons knocked out of atoms, as a result of a collision. Ask some questions about how one would use dynamics to calculate what may happen if one particle hits another. (This will bring out the need to know masses and velocities and to use conservation of momentum and possibly conservation of energy.) Such questions are likely to reveal uncertainty or confusion about these dynamical principles, and serve to introduce the next group of experiments, in which some students look again at experiments on the conservation of momentum.

Other students can, at the same time, pursue the study of ionization by collision. Electrons make a good tool for this purpose, for they can be accelerated to a known energy by making them pass between places of known potential difference.

This is a good point to calculate the energy acquired by an electron of charge 1.6×10^{-19} C passing across potential differences of, say, 15 V and 1 V. The latter amount of energy is called one electronvolt and is 1.6×10^{-19} J. The former is 15 electronvolts. An electronvolt is a convenient energy unit, much used by physicists. But to calculate an electron's velocity from $\frac{1}{2}mv^2$ one would have to put the energy in joules, of course.

Experiments

2.26 Ionization by electron collision

a Xenon

b Argon

c Helium

Electrons from a hot filament can be accelerated by a potential difference, and the larger the p.d. the higher is the kinetic energy of the electrons. A diode containing gas as well as a hot filament would pass a current of electrons and then, if ions were formed by collision between electrons and gas atoms, there would be an extra

b

argon thyratron 884

1003/3 milliammeter (100 mA)

1051 protective resistor, 100 Ω

c

helium thyratron 6K25

1003/4 ammeter (1 A)

541/1 rheostat (protective resistor 10–15 Ω)

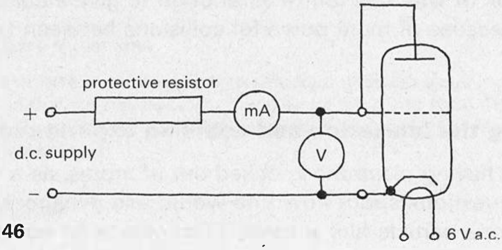


Figure 46
Thyratron circuit.

The grid and anode are connected together, the tube being used as a diode. As the d.c. voltage supply is raised, the current shows a sharp change in the rate of rise at the ionization potential. The voltmeter should preferably have a 100 μA movement. The protective resistor is essential to prevent damage to the tubes. Two of each type of tube are recommended so that students may exchange types and to allow for the possibility of tubes being damaged. The thyratron base (1049) is suitable for all the tubes suggested.

The helium-filled thyratron (6K25)

There are difficulties associated with the use of this tube, and it could be omitted. The tube is opaque so that no glow is visible at ionization. The thermionic current is large, so that the onset of ionization is not so clear as with the other tubes. The ionization potential is high (24.6 V) and at the top of the range of p.d. available from the power supply, so that the current-voltage curve stops just as it gets interesting. Most high tension power supplies are unsuitable because they will not deliver the current (up to 0.5 A) needed and would be dangerous if they did. It is possible to raise the p.d. of the low voltage supply by adding dry cells in series with it.

Students' book

Question 78 is about the ionization of air.

Further work for fast students

A pair could go on to experiment 2.28 now, for later demonstration to the class.

Students' book

Questions 71 to 77 deal with conservation of momentum. Question 71 is a hard but interesting problem for discussion. Questions 72 and 73 are detailed step-by-step problems to revise ideas about momentum. Question 74 is about Newton's Third Law. Questions 76 and 77 suggest uses of conservation of momentum.

ion current. So the experiment is to use the tube as a diode and raise the p.d. across it slowly, looking for a rise in current due to the extra ions.

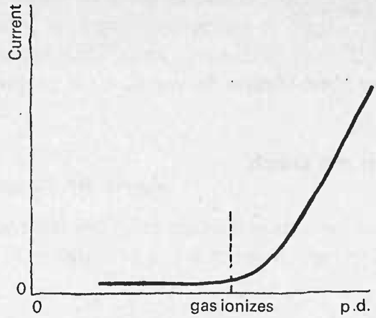


Figure 47
Current-voltage graph for a thyratron.

Figure 47 shows the result. At some fairly definite voltage, the current in the tube suddenly rises sharply. This could be understood if, above this voltage, there were a new source of charge carriers in the tube. It seems likely that the gas atoms are ionized by collisions with electrons in the tube only when the electrons have at least the energy corresponding to the voltage at which the current first starts to climb more steeply.

The gases ionize at different electron energies, the critical voltages being about:

24.6 V for helium

12.1 V for xenon

15.7 V for argon

But for each gas there is some one electron energy below which the gas atoms are not ionized. Too feeble a collision will not chip an electron off an atom.

It may be desirable to have a vacuum diode available so that the current-voltage curve obtained with no gas in the tube may be looked at again. (See Nuffield O-level Physics *Guide to experiments IV*, 158.)

Textbooks

Dynamics (momentum). Most books are useful, among them:

PSSC *Physics* (2nd edition), Chapter 22.

PSSC *College physics*, Chapter 16.

Rogers, *Physics for the inquiring mind*, Chapter 8.

Experiment
2.27a Collisions on an air track

1019 air track

1020 air blower

4A drinking straw

529 scissors

134/1 motor driven stroboscope (2 slits open)
or
134/2 xenon flasher

133 camera
and
171 photographic accessories kit

1054 developer, fixer, printing paper

slide projector (if 134/1 is used)

The *Students' laboratory book* has a section on photography, which describes the use of this tool and suggests techniques for stroboscopic photography. Teachers can also refer to Nuffield O-level Physics, *Guide to experiments IV*, Appendices I and II, and to *Guide to apparatus*, section C, page 150.

The important points about the set-up of apparatus are:

Shine the light along the length of the track.

Have a white or a shiny marker on the vehicles.

Have a dark background. (For the xenon stroboscope, the room must be fully blacked out.)

Place the camera looking at right angles to the track.

The track and vehicles need to be kept clean, and vehicles should be stored and handled in such a way that they do not become deformed. Vehicles can be fitted with nose-pieces, elastic bands, needles, corks, or Plasticine, so that elastic or inelastic collisions may be achieved. The loads on a vehicle should balance, or it will lift at the less loaded end and be driven along by the air from the track.

Some air tracks have a long narrow shutter which can be swung so as to cover the space above or below the vehicles. Milk straw markers can be placed so as to project above and below the vehicle, and the shutter is swung over at the collision. The one part of the marker indicates the motion before collision and the other part indicates motion after collision. Such a device is needed only if the vehicles change direction on collision.

Dynamics – momentum conservation

One possible way, for revision, is to 'forget' previous knowledge of Newton's Laws of motion, and to start again looking at collisions empirically. By observing velocities before and after collision, students can arrive at conservation of momentum as an empirical fact. Here the air track is an invaluable tool. Given the briefest of instructions, students could try a series of experiments somewhat as follows.

Experiment
2.27a Collisions on an air track

1 Make two identical vehicles collide with a springy buffer between them. One may be at rest to start with. Is it the same if the other one moves? Then both may be tried moving.

2 Make two identical vehicles collide and stick together. Again, both may move or one may be at rest.

Given a clue, 'Look at how the velocities change', students can find one rule to cover all these cases. The rule is that the velocity changes of the two vehicles are always the same, and are opposite. One must count a reversal of velocity direction as a change, for this to work.

3 The collisions so far have involved the maximum or minimum energy loss. The rule $\Delta v_1 = -\Delta v_2$ can be tested for an in-between collision if desired.

4 Collisions between one vehicle and another of double the size (maybe two linked together) suggest that now $\Delta v_1 = -2\Delta v_2$ if vehicle 2 is twice as massive as vehicle 1.

Determined and sceptical pupils might try with masses of 1:3, or might load one vehicle with Plasticine and check whether the mass ratio found by weighing agrees with that from the velocity changes.

The change of the quantity mv for one vehicle, written $m\Delta v$ since m is fixed in these cases, is equal and opposite to the change $m\Delta v$ for the other. That is:

$$m_1\Delta v_1 = -m_2\Delta v_2$$

or $m_1\Delta v_1 + m_2\Delta v_2 = 0$

or Total of mv remains fixed.

Because mv stays constant, it is useful and has a name – momentum. The difference between momentum and kinetic energy can be emphasized by calculating the net change of kinetic energy in joules for a collision in which it does change, while the total momentum stays the same.

Experiment
2.27b Collisions with trolleys (optional)

See Nuffield O-level Physics *Guide to experiments IV*, experiments 41a, 41b, 42.

Experiment
2.27c Collision with pucks (optional)

See Nuffield O-level Physics *Guide to experiments IV*, experiment 43 and Appendices I, II.

Teachers will have to make their own selection of experiments and apparatus, according to the background of their students.

Other apparatus, such as the air table, is now becoming available and some may prefer it to either the air track or the dry ice puck system or both. Useful experiments can be done with long pendulums carrying massive steel ball bearings, collisions between such ball bearings being photographed or analysed from the distances the pendulums swing sideways. See experiment 2.30.

Some teachers may prefer to have a few students producing data in the form of photographs, while several others analyse them.

We urge only that the class sees evidence for the conservation of momentum, and that students are kept interested.

Conservation laws

This is a good moment to point out the importance of conservation laws in physics. Because the quantity *mv* is conserved, it is interesting and worth naming, as opposed to momentum being something interesting which, it just happens, is also conserved.

'Elastic' and 'inelastic'

Students should know these words well enough for a teacher (or an examiner) to be able to use them freely in discussion or problems.

While discussing the point, Unit 9, *Change and chance*, could usefully be anticipated, as below.

A collision in which a vehicle comes in from the left, say, and hits another initially at rest, in an elastic collision, after which the second vehicle moves off and the first stops (if they have equal masses) can nearly happen. So can a collision which would be what one would see if a film of the original collision were projected backwards. (The 'second' vehicle would move in from the right . . . and so on.)

But an inelastic collision is different. Say the vehicles of equal mass approach at equal speeds, collide, and stick together, coming to rest. The kinetic energy goes from twice $\frac{1}{2}mv^2$ to zero. A film of the collision shown backwards would present vehicles springing apart spontaneously and cooling at the same instant. Such events, though they conserve momentum and energy, do not ever happen. If one saw such a thing, one would be sure either that one was dreaming, or that there had been potential energy locked up in an unseen spring or explosive charge between the vehicles.

The impossible event would defy the Second Law of Thermodynamics.

Students should be able to say that the missing kinetic energy has not vanished, but is now spread out among the atoms of the vehicles.

In discussing electron collisions, it will be of interest to distinguish those where energy does go into something other than kinetic energy of the particles and those where it does not. The name 'elastic' collision is given to the latter, which at best are only nearly attained with large lumps of matter, while collisions in which kinetic energy is transformed to other forms (warmed-up vehicles or energy needed to remove an electron from an atom) are called 'inelastic' collisions.

Experiment
2.27b Collisions with trolleys (optional)

This is an alternative to 2.27a.

Students who have never used trolleys or the ticker tape timing technique could try some collision experiments with them. See Nuffield O-level Physics *Guide to experiments IV*, 41 a, 41 b, 42.

Experiment
2.27c Collisions with pucks (optional)

Students who are more confident than average might try the O-level Physics demonstrations in which collisions between low friction pucks are photographed and analysed. See Nuffield O-level Physics *Guide to experiments IV*, 43.

Ionization energy and excitation energy

Discussion of students' findings in experiments 2.26 and 2.27 should aim to clarify what may be happening inside the gas-filled tubes in terms of electrons colliding with gas atoms, and to summarize the results in terms of the finite energy needed to ionize an atom. The argument then expands, with more evidence from experiment and from reading, into reasons for thinking that atoms take in or give up internal energy only in lumps.

The next demonstration is a variation on experiment 2.26.

Demonstration or student demonstration

2.28 Detection of ions

1049	thyratrons and thyratron base
59	l.t. variable voltage supply
1064	low voltage smoothing unit
1005	multirange meter *or*
1004/3	voltmeter (100 V)
27	transformer
1033	cell holder with two U2 cells
1001	galvanometer (internal light beam) *or*
1002	*or* microammeter (100 μA)
1040	clip component holder
1051	resistor, 10 kΩ
1000	leads

See 'Critical potentials in gases', *Educational electronic experiments* No. 7, Mullard Educational Service, Mullard Ltd, Torrington Place, London W.C.1.

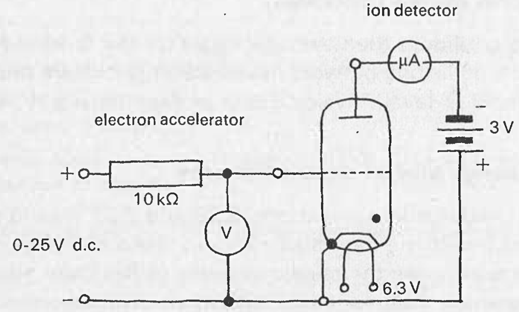


Figure 48

The two cells are used to make the plate negative with respect to the cathode, so that no electrons reach the plate. As the grid is made more positive, no current flows in the microammeter until, beyond the p.d. at which the gas ionizes, a current of ions begins. See figure 49.

The light beam galvanometer is better than the 100 μA meter, but should be used on the ×0.1 range at first.

Demonstration

2.29 Excitation of xenon

Apparatus as for 2.28.

The light beam galvanometer is essential, and is used at its full sensitivity. The flow of current through it keeps the plate slightly negative with respect to the accelerating grid. A 1.5 V dry cell may be connected in series with the galvanometer, with its negative terminal joined to the plate of the thyratron, to emphasize the role of this p.d.; it does not improve the results.

Demonstration or student demonstration

2.28 Detection of ions

In this variation on the ionization experiment with a thyratron, the plate is made slightly negative with respect to the electron source so that only positive ions (and no electrons) reach the plate.

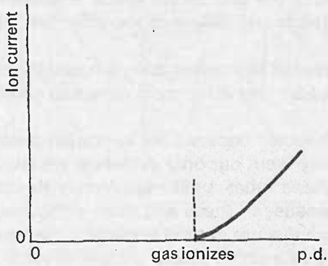


Figure 49

The point is that until the bombarding electrons have a certain energy, they do not break the atoms up into an ion and an electron. It seems that a gentle 'knock' is not enough: an atom has to be hit hard enough if an electron is to be removed from it.

Demonstration

2.29 Excitation of xenon

A small modification of the circuit for experiment 2.28 can advance the discussion by suggesting that at energies of less than 12.1 electronvolts (for xenon) it is possible for bombarding electrons to give xenon atoms energy without ionizing them.

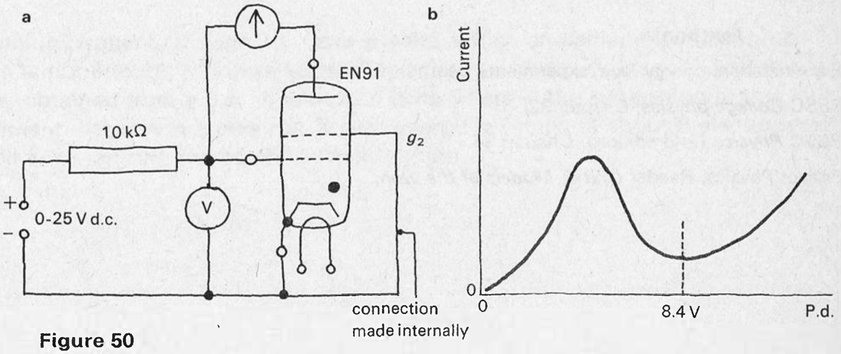


Figure 50
a Excitation circuit.
b Current-voltage graph.

Choice of commercial tubes

The processes occurring in a gas-filled tube are not simple. In addition to ionization by electron bombardment there may be photo-electrons ejected from cathode, grid, or anode, by ultra-violet photons emitted from excited atoms. It is also possible that some atoms will be excited or ionized by collision with the hot cathode surface. The tube geometry greatly influences the sharpness of any current variations, as does the gas pressure. If the pressure is low, there will be little probability of collisions, while if the grid is close to the cathode and far from the anode, electrons may have a larger chance of making collisions in the grid anode space. The existence or otherwise of a space charge of electrons round the cathode will influence the effective geometry.

For these kinds of reasons, commercial thyratrons do not normally indicate the onset of excitation and may indicate ionization potentials that differ from accepted values by appreciable amounts.

The tubes suggested have been selected because the ionization potentials they indicate happen to fall close to accepted values. If they were our only evidence, we would be guilty of fraud, and pupils ought in honesty to be told that these tubes, unlike apparently similar other ones, happen to give good answers. At a later stage, because of these and other difficulties, we shall suggest the use of extracts from original papers which discuss careful research experiments. These are not only honest experiments, but also happen to give a rather clearer picture of what happens in electron collision experiments than do any available school experiments.

Analogue

Teachers may like to discuss an analogue. A ball accelerated down a slope will run along a flat track and will then easily rise up a small hill at the other end (figure 51). But if the ball loses energy in the flat part (perhaps it runs over sandpaper) it will not be able to climb the small hill to the detector.

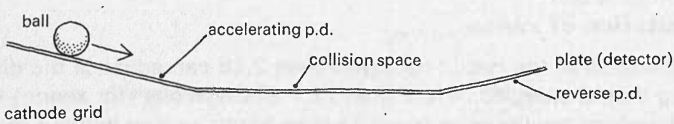


Figure 51
Analogue.

Textbooks

For excitation, energy level experiments, see:

PSSC *College physics*, Chapter 32.

PSSC *Physics* (2nd edition), Chapter 34.

Project Physics, Reader *Unit 5, Models of the atom.*

In this circuit (figure 50 *a*) the galvanometer detects electrons which have enough energy to pass beyond the accelerating grid. If any lose energy, the current to the plate will fall. Figure 52 shows the geometry of the electrodes. g_2 forms a space within which collisions may occur.

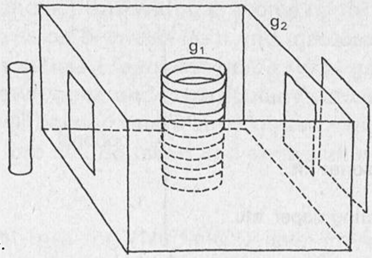


Figure 52
Electrodes in the EN91 tube.

Electrons travel from the cathode k towards the grid g_1, whose voltage is varied. g_1 is inside a box g_2, which has slots to define the electron beam, which then passes out of g_2 towards the plate p. The flow of electrons to p, and then through the galvanometer back to g_1, keeps the plate slightly negative with respect to the grid g_1.

If an electron did give most of its energy to a xenon atom it would not have enough energy to reach the plate from the grid, because of the reverse potential difference between them.

The minimum current thus corresponds to the voltage at which such collisions occur. If this were all, there would be a sharp dip in the current at 8.4 V, since there is an energy level of xenon at 8.4 eV above the lowest level. In fact, the minimum is at about the right voltage but it is very broad, for a variety of reasons.

Something happens, though, at about 8 volts, which an earlier experiment has shown is not enough to ionize xenon. Ionization needs electrons with collision energy obtained from a p.d. of about 12 volts. There is the suggestion in this experiment that xenon atoms can accept energy in lumps of about 8 electronvolts, as well as in ionizing lumps of 12 electronvolts.

Demonstration

2.30 Collision of light and massive objects

131B	steel ball with hook (50 mm diameter)	
131D	steel ball with hook (about 10 mm diameter)	
1055	twine or string	
134/1	motor driven stroboscope *or*	optional
134/2	xenon flasher	optional
133	camera *and*	optional
171	photographic accessories kit *and*	optional
1054	developer, fixer, printing paper, etc.	optional
	slide projector	optional

This is a demonstration from Nuffield O-level Physics *Guide to experiments IV* 44d. The small and large balls are hung on strings of equal length from the same point so that, when one is pulled aside and released, it collides with the other.

Observations of the collision when each mass swings against the other stationary one are made. They may be photographed if desired.

A 1 kg slotted weight is an acceptable alternative to the larger ball.

Other energy level demonstrations

The xenon experiment seems to show that there is just one energy level, and that it is broad: in fact there are many and they are sharp. It is very hard to make tubes which show this, though there exist tubes containing mercury or helium which have been designed for the purpose. They tend to be expensive, and have only this one use, so we do not recommend that schools buy them.

In our judgment, the combination of rough experiments with the commercial xenon tube and the reading from papers which report more adequate experiments will serve quite well, and have besides the positive virtue of helping students to learn from secondhand evidence, and of showing them some examples of physicists in action.

Students' book

See the section, 'Evidence for the existence of energy levels'. Questions 79 and 80 deal with points made in the papers from which the extracts are taken.

Aims and value of reading of extracts from papers

When students learn in the future, it will very often be from the printed word, and practice in this task may well be of later service. So this work contributes to our general aim of assisting learning in the future.

Students often wonder what the daily work of the scientist is like, and some have strange images of improbably talented people performing superhuman tasks of cogitation or experiments of amazing accuracy. Science has produced a few men of giant stature, but most scientists are talented, ordinary people tackling problems that seem to them interesting. And these extracts report relatively 'everyday' work by competent men, not 'great' experiments by geniuses. The extracts have the everyday virtues of scientific writing: clarity and honesty. We hope that there will be some valuable freshness in this contact with original work.

Demonstration
2.30 Collision of light and massive objects

The ionization and excitation experiments will raise the problem of what happens when a light object hits a much more massive one. There will now be the suggestion that the collisions of electrons with gas atoms might be elastic or inelastic. The problem of an elastic collision between light and massive objects is discussed in the Nuffield O-level Physics course (*Teachers' guide IV*, pages 115–116). Similar experiments may be shown now, and a particularly valuable one is a collision between a small steel ball bearing and a large massive one, both hanging on long strings. A multiflash picture can be taken and analysed, or the collisions may simply be observed.

The fable of the elephant-in-a-fog (Nuffield O-level Physics, *Teachers' Guide IV*, page 116) may be told now, to pupils who have not heard it. The important point is that if an object of small mass, like an electron, collides elastically with a much more massive object, like a gas atom, practically no kinetic energy is transferred from the electron to the gas atom. Thus, in electron collision experiments, elastic collisions result in electrons with undiminished energy, while inelastic collisions can be detected by the reduced kinetic energy of the scattered electrons. This is the principle underlying experiment 2.29 and the other energy level experiments which are described below.

Extracts from papers describing energy level experiments

The *Students' book* contains extracts from three papers, with a commentary linking them and notes explaining some technical terms. The extracts are reproduced below.

The first paper, by J. H. McMillen, concerns helium. Electrons bouncing off atoms are collected and their energy is measured, it being found that they either lose no energy, or lose energy in one of several definite sized amounts, of 21, 23, or 24 electronvolts. There are other closely spaced levels beyond 24 electronvolts which are not resolved.

The second extract pays honour to G. Hertz, who did the earliest energy level experiments with Franck. This one re-introduces (from experiment 2.29) the idea of a small reverse p.d. to detect electrons which have lost energy. Results for three inert gases are given. The extract consists wholly of diagrams. The same technique is used in this and the third experiment: a small reverse p.d. is switched on and off and the change in current is noted. Since a large change corresponds to the detection of an energy level, it is the peaks, and not the troughs, of the graphs of experimental data that indicate energy levels.

The third extract, by J. C. Morris, reports an experiment on mercury vapour, and the experiment is sensitive enough to detect many of the 'rungs' of the 'ladder' of energy levels possessed by the mercury atom.

Students should be told that they ought to try to get from these extracts what any generally interested scientist would want: a general idea of the methods used and an overall understanding of the meaning of the results. Only someone interested in repeating the experiments would pay minute attention to details of technique, and only someone concerned with using the data in calculations would remember or write down the full data obtained. Students need attempt neither of these.

The important point is that electrons can be detected losing energy to gas atoms, and that the energy transfers are found not to be of any possible size, but to be lumpy. Atoms accept energy in lumps. Each atom can have one of a series of energies, and the lumps of energy are the amounts that jump an atom from one level to another.

McMillen's helium experiment

This extract is confined to a description of the experimental details, and presentation of the results. Much of the remaining discussion (more than half the paper) has been omitted.

Students should be encouraged to look through, but not to puzzle unduly over, the description of practical detail. It is included more to give a concrete sense of reality than for its own sake. This experiment appears first because the parts of the apparatus in which the energy losses are made, and the parts in which the loss is detected, are quite separate. In later extracts, the apparatus is simpler but the distinction between these two parts of it is not so clear.

Notes on technical points

The *Students' book* has notes on:

Faraday cylinder

oxide coated filaments

bevelling of slit edges

Compton electrometer

mercury diffusion pump

adsorption by charcoal

palladium tubes

use of calcium to purify argon.

The McLeod gauge is also mentioned in the extract. Students who ask may be told that it is a mercury pressure gauge adapted to measure very low pressures. Details appear in many books.

An energy level experiment with helium

The following extracts are reproduced from 'Angle and energy distribution of electrons scattered by helium, argon and hydrogen' by J. H. McMillen (*Physical Review*, **36**, 1034, 1930) with permission.

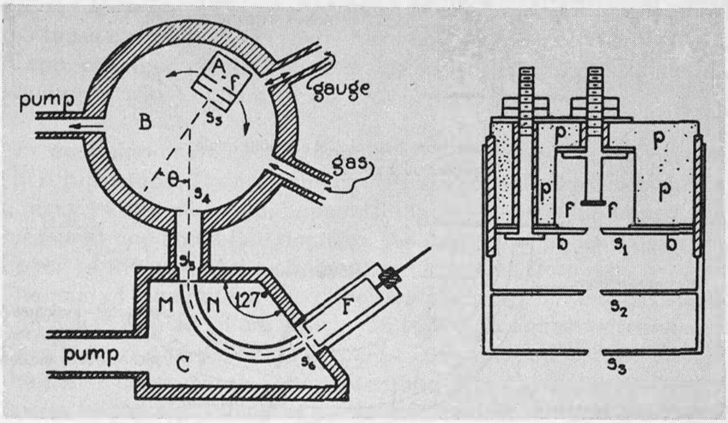


Figure 53
From McMillen, (1930).

Description of apparatus

The apparatus used in this investigation may be briefly described as consisting of an electron projector *A*, a collision chamber *B* and an analysing chamber *C*. A diagram is given in Fig. 1 [53]. Electrons leaving the projector *A* were scattered by the gas molecules in chamber *B*. After single collisions in *B*, the electrons passed through the slit s_4 into the analyser *C*. The two cylindrical plates, *M* and *N* in *C*, when set at the correct potentials, deflected the electrons into the Faraday cylinder *F*.

The projector, as shown in Fig. 1 [53], consisted of an oxide coated filament *f*, a grid *b* with slit s_1, a final grid with the two slits, s_2 and s_3, and a back plate *p*. All parts were made of brass, with the exception of the plate *p*, which was constructed of aluminium alloy. A glass cylinder and mica sheets were used as insulators. The potential on the final double slits, s_2 and s_3, determined the energy of the electrons projected through the slit. The potentials on *b* and *p* were fixed so as to give the maximum emission from the projector, or gun, as it is sometimes called. The slits of the gun play an important part, since they are the chief source of slow electrons. Their lips were sharply bevelled and sooted to eliminate slit-scattering. The dimensions of the slits were $s_1 = 1$ mm × 15 mm, $s_2 = 0.8$ mm × 14 mm, $s_3 = 0.4$ mm × 14 mm.

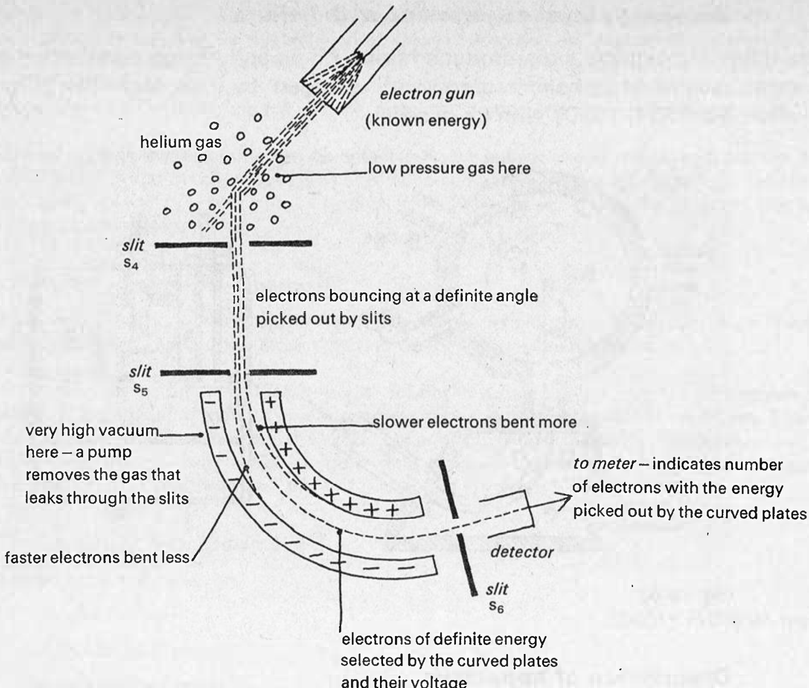


Figure 54
Diagram to show the principle of McMillen's experiment.

General principles of McMillen's experiment

Figure 54 appears in the *Students' book*. Electrons rebound from gas atoms at many angles and at many places in the chamber through which the beam passes. The slits s_4 and s_5 select those which happen to rebound at a certain angle. The curved metal plates then select those of a particular energy by allowing them to reach the detector.

Results

A peak in the graph (figure 55) indicates that many electrons have the corresponding energy. Thus many lose no energy (elastic collisions) as shown by the peak on the right. No electrons lose, say, 15 electronvolts energy, but many lose about 21 eV. Peaks can be seen corresponding to levels at about 21 eV, 23 eV, and 24 eV. Theory says that there is an infinite number of levels before the ionization energy, which is about 25 eV. The experiment cannot resolve more than the first three.

The projector could be rotated about the axis of the cylindrical chamber B. In B the electrons collided with the gaseous molecules and were reflected at various angles. Only those electrons which were reflected at an angle θ entered the analysing chamber. This angle was determined by the gun-setting. The gun was fastened to a brass tube which fitted into a ground glass joint. The ground glass joint was waxed into the back end of the brass chamber B. On to the front end was fastened a thick glass plate. A copper screen placed on the inside surface of the glass plate insured the equipotentiality of chamber B.

The analysing chamber was connected to the collision chamber B by a short brass tube. The two chambers were separated by two slits; s_4, 2 mm $\times$ 14 mm and s_5, 0.3 mm $\times$ 10 mm. The angle subtended at s_5 by s_4 measured one and a half degrees. The cylindrical plates M and N were bolted to the wall of the chamber and insulated from it by sheets of mica. The radii of curvature of the plates were 50 mm and 60 mm respectively. The plates formed an arc which subtended an angle of 127° 17′. It has been shown, and predicted by theory, that the potential difference between the plates necessary to deflect electrons from s_5 to s_6 is proportional to the energy of the electrons. The particular chamber and the properties of the electrostatic analysing method have been described by Hughes and Rojansky and Hughes and McMillen. The Faraday cylinder was connected to a Compton electrometer.

The gas to be investigated flowed into chamber B through a small capillary and was pumped out by a mercury diffusion pump. This arrangement maintained a steady pressure and a fresh supply of pure gas in the collision chamber B. The pressure was read on a McLeod gauge. To secure high pumping speeds, a glass tube of large diameter connected the analysing chamber with a Gaede two stage steel diffusion pump. The gases used in this experiment were helium, hydrogen, and argon. Helium was purified by slow passage over charcoal at liquid air temperature. The hydrogen was obtained by heating a palladium tube. A discharge in the presence of calcium vapour was employed to purify the argon. To freeze out the mercury liquid air traps were inserted. The following pressures in mm of Hg were used with the following gases: helium, 0.008 mm; hydrogen, 0.006 mm; argon, 0.004 mm.

Energy losses in helium

To measure the energy losses, the projector was set at some fixed angle and the electron current to the Faraday cylinder noted for each set of potentials on the deflecting plates. The energy of the deflected electron is readily obtained from the potential on the deflecting plates when the ratio of the energy of the deflected electron to the deflecting potential is known. This ratio was established when no gas was in the apparatus. One can then obtain a set of curves plotting the number of electrons against their energy.

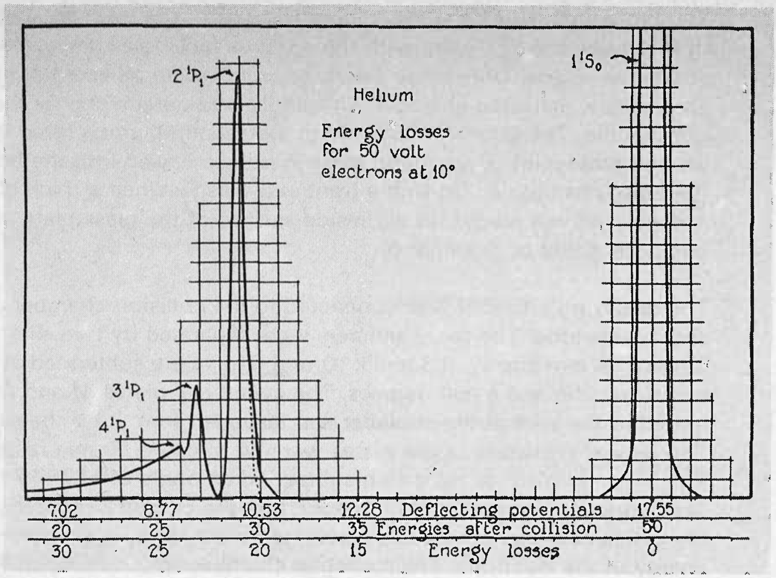


Figure 55
From McMillen, J. H. (1930) 'Angle and energy distribution of electrons scattered by helium, argon and hydrogen.' Physical Review, **36**, *1034.*

Hertz's experiments

The same method of detection of energy loss of electrons is used in this and in the last extract. Electrons from the filament D are accelerated to known energy by a p.d. between D and the gauze N_1, which forms part of a box R inside which the potential is constant and which contains a gas. The sides of the box R are of gauze, N_2, and close round this gauze is a collecting conductor P. The space between N_2 and P is small so that there is little chance of an electron collision in this space. Electrons that bounce off gas atoms in the box R can reach P. Suppose their original energy is close to some energy level spacing of the gas atoms. Then there will be electrons which have almost no energy reaching P, if P is at the same potential as N_2. But if a small p.d. is switched on between N_2 and P, these electrons can be prevented from reaching P and the current to P changes by a large amount. The graphs show these *changes*, so that peaks (large changes) correspond to energy levels of the gas atoms. The p.d. plotted in the graphs is that between D and N. The method can only resolve levels further apart than the magnitude of the small p.d. between N_2 and P.

Note that the neon and helium mixture shows levels at the same places as those for neon alone, but with two more levels presumably attributable to helium, whose values agree generally with those from McMillen's (later) experiment. Argon shows levels which are not the same as those of helium or neon. Results may be compared with those from class experiments with gas-filled tubes.

Franck and Hertz were the pioneers of this type of experiment. They began much earlier, at about the time of the Bohr theory, and set out to show that Bohr's idea of quantized energy levels might be an experimentally observable fact. Boorse and Motz, *The world of the atom*, Volume I, page 766, reproduces a paper of Franck and Hertz in translation, with a commentary, which may be of interest to teachers.

Unfortunately, because of excess scattering of the slits and other unaccounted for defects in the apparatus, the original curves had to be modified by subtracting from them spurious peaks and background scattering which were also present in the absence of any gas.

In Fig. 2 [55] can be seen an energy loss curve for helium. This curve was taken with electrons of 50 volts energy and indicates the energy losses for those deflected at 10°. The abscissa measures the energy of the electrons after collision, while the ordinate measures the number of electrons having that particular energy. The energy loss is also indicated in the diagram. The main peak at 50 volts, comprised of electrons making elastic impacts, is many times higher than the remaining peaks and extends off the figure. A group of peaks is seen near 30 volts energy region, indicating losses of the order of 20 volts. In this group there are three distinguishable peaks. The obvious lack of symmetry of the main energy-loss peak suggests a smaller peak, or peaks, overlapped by the main peak. One notes, too, on the low energy side of the last peak, that there is a gradual shading off in intensity.

Hertz's experiments with neon, helium, and argon

Figure 56 is taken from Hertz's paper in *Zeitschrift für Physik* (**18**, 307, 1923).

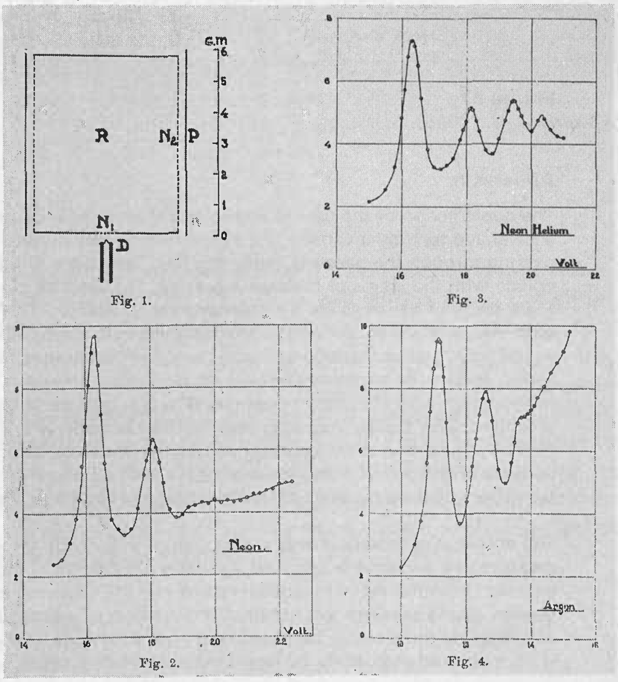


Figure 56

From Hertz, G. (1923) 'Uber die Anregungs-und Ionisierungsspannungen von Neon und Argon und ihren Zusammenhang mit dem Spektren dieser Gase.'

Morris's experiment

The extract quoted opposite gives only the results of the experiment. Morris refined Hertz's technique so that he could use a very small detecting p.d. and thus resolve many levels. The main problem was to achieve a very small p.d. across the heated wire emitting electrons, and to find the right dimensions for the parts of the apparatus. A further extract giving practical details appears below, for the interest of teachers.

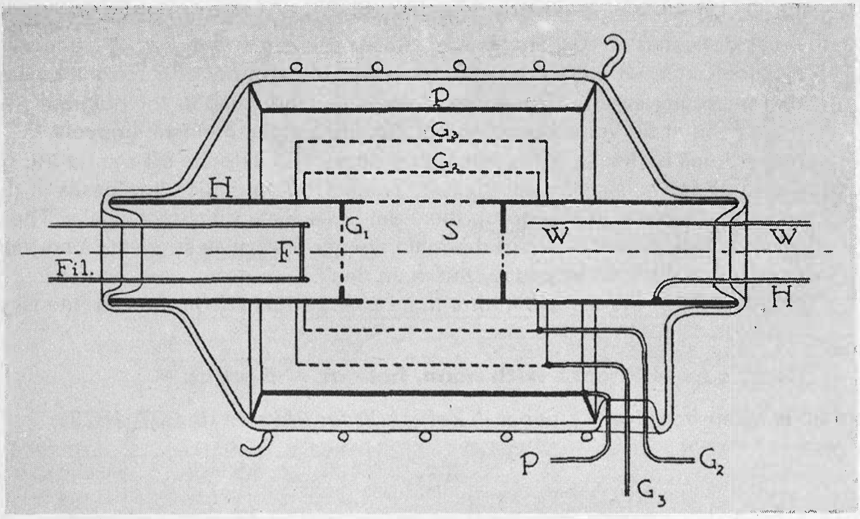


Figure 57
From Morris, J. C. (1928).

Apparatus

The construction of the tube is shown in Figure 1 [57]. Electrons from the filament *F* are accelerated to *H* by a variable, measured, electromotive force. Some of these electrons passing through the gauze G_1 enter the field free space *S* where a number of them will collide with the atoms or molecules present. The sides of the cylindrical electrode *H* about *S* are made of gauze as are the coaxial grids G_2 and G_3. The plate *P* is cylindrical, coaxial with the grids and mounted at some distance from the sides of the containing glass vessel. In the final form of the tube all metal parts mentioned thus far except the filament are of nickel. In an early experimental tube an aluminium plate was used. Filaments of molybdenum and of tungsten were used at first but later a Wehnelt cathode was employed with greatly improved results. The electrode *W* is a thin platinum wire mounted in *H* as shown and removed as far as possible from any direct radiation from *S*. The purpose of the coil of a few turns of heavy wire wound around the tube will be explained later. The usual precautions of 'baking-out' and degassing the metal parts were observed.

The accelerating potential was varied uninterruptedly by steps (0.02 to 0.1 volt) and measured by a voltmeter checked against a potentiometer. In all cases the electron emission from the filament was measured and the observed effect divided by the emission thereby giving readings proportional to the effect of a constant electron stream. The effects produced by the electron bombardment – photoelectric, production of positive ions, etc. – were measured electrically by high sensitivity electrometers or galvanometers.

Morris's experiment with mercury vapour

The following account is taken from 'Comparison of measurements of critical potentials of mercury vapour' by J. C. Morris (*Physical Review*, **32**, 447, 1928) with permission.

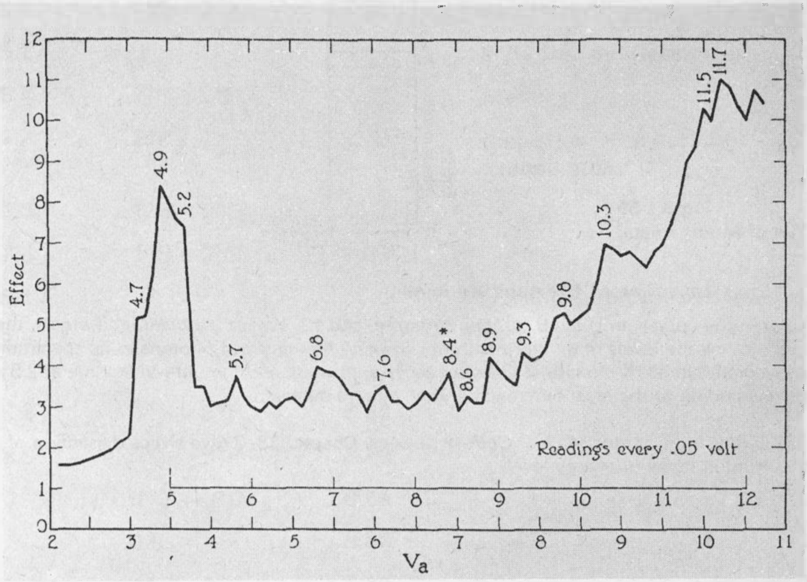


Figure 58
From Morris, J. C. (1928).

Hertz method

Using again a small retarding potential of 0.1 volt and arranging switches so that this could be made 0 or 0.1 volt at will, and plotting the difference of the galvanometer readings for these two cases as ordinate against the accelerating potential as abscissa, the tube was used according to the Hertz method for determining the critical potentials of inelastic impacts. This was by far the most efficient method of all used for determining critical potentials below ionization. Figure 5 [58] shows a set of the results obtained with this method and gives the values of the more prominent potentials noted. The accompanying table [3] shows the interpretation placed on the various potentials. The curves obtained with this method could be reproduced without difficulty.

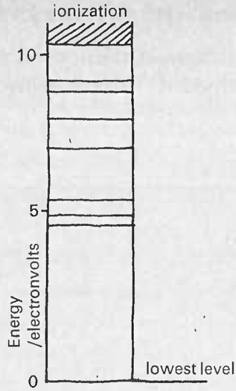


Figure 59
Plot of Morris's data.

Later use of the mercury levels

Later in the course, in Units 5, *Atomic structure*, and 10, *Waves, particles, and atoms*, there will be a need to link the levels of an atom with the size and frequency of photons in its spectrum. Mercury is convenient: some of the visible lines are easily explained, and the ultra-violet line at 2.5×10^{-7} m corresponding to the level difference 4.9 eV, can be detected.

PSSC *Physics*, Chapter 34–2 or *College physics*, Chapter 33–3 give a nice dissection of the mercury spectrum in terms of energy levels.

Potential observed (volts)	Interpreted from Theory	Calculated from Theory	Remarks
4.7	$1^1S—2^3P_0$	4.66	Metastable state
4.9	$1^1S—2^3P_1$	4.86	2537
5.2			5.25 obs. by Messenger
5.4	$1^1S—2^3P_2$	5.43	Metastable state
5.7	2^3P_0	5.73	Ionization of metastable excited atom
6.8	$1^1S—2^1P$	6.67	
7.6	$1^1S—2^3S$	7.69	
8.1			8.0 and 8.05 obs. by Messenger
8.4			8.35 obs. by F. & E. 8.3 obs. by Messenger
8.6	$1^1S—3^3P_{0,1}$	8.58	
8.9	$1^1S—3^1P$	8.79	
	$1^1S—3^3D_{1,2,3}$	8.82	
	$1^1S—3D$	8.80	
	$1^1S—3^3P_2$	8.80	
9.3	$2(1^1S—2^3P_0)$	9.32	Successive impact
9.8	$2(1^1S—2^3P_1)$	9.8	Successive impact
10.3	1^1S	10.39	Ionization
	6.7+4.9		
11.5	6.7+4.7		

Table 3
Results obtained using Hertz's method.
From Morris, J. C., 1928.

Many levels

This experiment shows what the others were too coarse to reveal; that there is for any one atom a whole series of energy levels arranged in quite a complicated way. The ladder is there all right, but has many rungs spaced out unevenly.

Questions about atoms

This Part deliberately closes on a quizzical note, raising problems rather than solving them. These are problems that recur in the course (Unit 5, *Atomic structure* and Unit 10, *Waves, particles, and atoms*) and we want them emphasized early. The teaching can also illustrate more of what physics is like.

Two points can be made. New information leads often to new puzzles and problems, while itself coming very often from a use of earlier knowledge which, once obtained, suggested a new idea or experiment. Thus, having found electrons, physicists use the idea to press further on. When they have done so, new questions arise about atoms.

Also, advance in physics is a blend of fact and theoretical model making. This point is expanded on page 122.

Elastic collisions in kinetic theory

See question 78 in the *Students' book* which leads to order of magnitude estimates.

Teachers will note that the argument is about electronic energy levels, which are too widely spaced to be excited by thermal collisions at normal temperatures. Of course at high temperatures gas molecules will ionize by collision and form a plasma of ions and electrons. At high enough temperatures, nuclear levels can even be excited.

At room temperature, a molecule will, by chance, very occasionally acquire enough energy to excite an electronic level, or ionize an atom. But this is so rare that the number of ions is pretty well undetectable. However, at flame temperatures (as shown in experiment 2.25) ionizing collisions are frequent enough for ions to be detected, even though only a small fraction of atoms acquire sufficient energy to ionize.

Even at room temperature, energy levels of molecular vibration or rotation can be excited, for these are narrowly spaced. Thus vibration and rotation can contribute to the specific heat capacity of a gas, though for some molecules the levels are too widely spaced for this to happen appreciably.

More knowledge, and more questions about atoms

The energy level experiments have yielded more information about atoms, by using electrons as a tool and analysing the results in the light of understanding of energy and potential difference.

Knowledge of atoms is a mixture of facts and of pictures to tie the facts together. So far in the course there is a suggestion that atoms may contain at least one ingredient in common – electrons. No clear model of how the electrons are contained or arranged can be supported so far. But the rough size of an atom is known from experiment (Unit 1 and Nuffield O-level Physics).

The existence of energy levels helps resolve one problem, that of why gas atoms or molecules may be pictured in the kinetic theory as making elastic collisions. A rough estimate of gas molecule collision energies at room temperature shows them to be much smaller on average than the spacing between energy levels: the collisions are too feeble to excite the molecules.

But many questions remain open, and the evidence stimulates still further questions. For example:

> Why should an atom have a definite size; what holds the parts together?
>
> Why do atoms have the size they do, about 10^{-10} m, and not some much larger or smaller size?
>
> Why do they have definite, sharp energy levels, accepting energy in lumps?
>
> Why does a helium, or a mercury, atom have just the levels it does have, and not others?
>
> Why is there a lowest possible energy level for any one atom?
>
> Why are atoms so alike, if they are just collections of charged particles? What tells a newly minted atom from a nuclear reactor to assemble itself to have the same chemical behaviour as that of an atom of the same element that has existed since the Universe began? In other words, why do elements exist?

These are questions without answers; a programme for further study. Some will receive partial answers in the course.

Evidence and theory

We want students to grasp a little better the nature of physics and this seems a good point to reflect briefly about facts and theories. The wave-particle theory that turns out to explain energy levels is perhaps the leading example of theory in the course, so the need for it deserves emphasis.

Teachers will have to vary the amount that is said here to suit the class. Some classes can debate these matters for hours (are there really electrons?) while others see no profit in it. This particular issue will come up again, so a few brief questions and a short discussion will amply suffice, at this point.

Other examples may occur to teachers. 'Facts' in physics are pretty well always loaded with theoretical interpretation. To a Greek, 'What goes up must come down', must have seemed a summary of tendencies of things to attain their 'natural' place. But we see it as part of a story about the gravitational pull of the earth. Today, theory says it isn't generally true. So do the new facts about the motion of space probes. But the Greek theory would incline one to think of it as a generally true fact.

Some facts can be exactly the same, but look different, according to the theoretical picture they are supposed to fit. The following example comes from Hanson, *Patterns of discovery*. Two men might watch the sun rise at dawn, and observe exactly the same events. But one might 'see' or 'feel' the earth turning below him as the horizon falls across the sun's surface, while the other may 'see' the sun move upwards across the horizon in its circular path across the heavens.

'Facts' are rarely so simple as the phrase, 'the simple facts' might suggest. When a mass is released, the pull of the earth accelerates it at a constant rate. Why do we say there is a pull, for people have not always done so? Because it accelerates. Why is it acceleration that is the symptom of force? Use Newton's Laws. Why believe them? And so the argument can develop. Even the fact that a mass is accelerating is more than a simple fact, and depends on making time and distance measurements and combining them. And what is time?

Behind even simple facts lie layers of other fact and theory, and perhaps even prejudice. It is well to remember this from time to time, though it is also well to ignore it, for the complex ideas physics uses are designed to enable one to think without having all the time to go back to grass roots.

Textbook

See Chapters 13 to 15 of Holton and Roller, *Foundations of modern physical science.*

Evidence and theory

Is the existence of energy levels a fact or a theory, or is it something else?

If there is evidence that energy levels exist, then any theory about atoms will have to explain why they exist. But notice that the situation we have arrived at in this section isn't a simple one. A simple situation would be 'Here is a fact – now find a theory to explain it'.

The difficulty is that 'energy levels' isn't a *simple* fact. One couldn't say to a friend in the arts sixth 'Come in here and look at these energy levels'. In order to understand the evidence we have had to put together other things, for example, the existence of electrons (is that a fact?), and other theories, for example, our ideas about dynamics, momentum, and collisions. So the real situation is more like: 'The interplay of previous theories, models, evidence, together with some new experiments, has produced evidence of a new fact – now find a theory to explain it'.

Nevertheless, the existence of energy levels is based on experimental fact, and is a fact demanding a theoretical explanation.

Lists of films, books, symbols for circuit diagrams, and apparatus

Films and film loop

16 mm films

(Both useful, not essential.)

'Are there electrons? (The Millikan experiment)'. 13 minutes, colour, sound. Rank Film Library, Rank Audio Visual Ltd, PO Box 70, Great West Road, Brentford, Middlesex. No. 21.7772.

'The momentum of electrons'. 10 minutes, colour, sound. Central Film Library, Government Building, Bromyard Avenue, London, W3. No. V 661.

8 mm film loop

(Optional; simply yields data.)

'Are there electrons? (The Millikan experiment)'. Rank Film Library. No. 290316.

Books and further reading

Page numbers of references in this *Guide* appear in bold type.

For students

Arons, A. B. (1965) *Development of concepts of physics*. Addison-Wesley. **12, 68.**
Baez, A. V. (1967) *The new college physics: a spiral approach*. W. H. Freeman.
Bennet, G. A. G. (1968) *Electricity and modern physics* (MKS version). Arnold. **12, 20, 38, 56, 80, 88.**
Caro, D. E., McDonell, J. A., and Spicer, B. M. (1962) *Modern physics*. Arnold. **88.**
Holton, G., and Roller, D. H. D. (1958) *Foundations of modern physical science*. Addison-Wesley. **122.**
PSSC (1968) *College physics*. Raytheon. **20, 38, 56, 80, 96, 100, 106, 118.**
PSSC (1965) *Physics* (2nd edition.) Heath. **20, 38, 56, 80, 96, 100, 106, 118.**
Rogers, E. M. (1960) *Physics for the inquiring mind*. Oxford University Press. **12, 38, 56, 80, 88, 100.**

Background reading

Feather, N. (1959) *Mass, length and time.* Penguin.
Millikan, R. A. (1963) *The electron.* Phoenix Science series. University of Chicago Press. **88.**
Project Physics (1971) Reader, Unit 5 *Models of the atom.* Holt, Rinehart & Winston Inc. **106.**
Scientific American (1967) *Materials.* W. H. Freeman. **16.**

For teachers

Boorse, H. A., and Motz., L. (1966) *The world of the atom.* Basic Books, Inc. **114.**
Nuffield O-level Physics (1968) *Guide to apparatus.* Longman/Penguin. **80, 100.**
Nuffield O-level Physics (1967) *Guide to experiments IV.* Longman/Penguin. **16, 80, 88, 89, 100, 102, 103, 108.**
Nuffield O-level Physics (1966) *Teachers' guide IV.* Longman/Penguin. **38, 40, 74, 109.**

Pamphlet

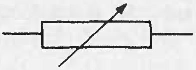
'Critical potentials in gases'. *Educational electronic experiments,* No. 7. Mullard Educational Service. Mullard Ltd, Mullard House, Torrington Place, London, WC1. **104.**

Symbols for circuit diagrams

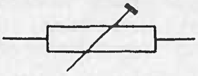
Some of the symbols for circuit diagrams used in this book are shown below. They follow British Standard 3939, *Graphical symbols for electric power, telecommunications and electronics diagrams* (1966–70).

Resistor general symbol

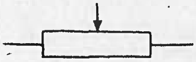
variable resistor



resistor with preset adjustment



resistor with moving contact

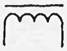


Capacitor general symbol

polarized electrolytic capacitor

Inductor general symbol

inductor with core



Battery primary or secondary cell

battery with tappings

pn diode

npn transistor

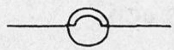
Measuring instruments

voltmeter 

ammeter 

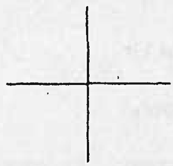
galvanometer 

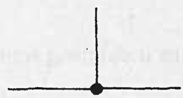
Signal lamp 

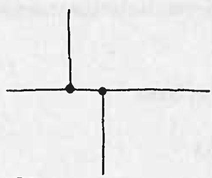
Lamp for illumination 

Wires, junctions, terminals

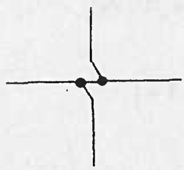
crossing of wires, no electrical contact

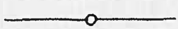


junction 

double junction 

or



terminal 

Apparatus

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Editor **Jon Ogborn**

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A *Teachers' guide* has been produced for each of the ten Units forming the Advanced Physics course. This is the *Guide* for Unit 2, *Electricity, electrons, and energy levels.* 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 five Parts, 'Things which conduct', 'Currents in circuits', 'Electric charge', 'Stored energy', and 'Electrons and energy levels'. It contains teaching suggestions, details of experiments, and a commentary giving background information and other guidance. There are also lists of relevant films, books, symbols for circuit diagrams, and apparatus.

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