Physics

Students' book **Unit 2**

Electricity, electrons, and energy levels

Nuffield Advanced Science

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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

To the student

This book contains some of the things you need to help you to understand the work of this Unit, and some reading which we hope will help you to see how the work is relevant to the practical, everyday world. It does not contain all you need: you will have to consult textbooks and other more general books as well, working through theoretical arguments, reading about experiments, and finding out more about how the ideas can be put to practical use.

This book contains many questions; more than you will be able to do while working on this Unit. Later on, you may wish to use some of them for revision. You will find questions which take you step by step through the theoretical arguments in the course; students who took part in the trials have said that these questions are a good way to understand a piece of theory. You will have to pick and choose, according to your needs and tastes, amongst the other questions. A few give you simple practice in calculation. More invite you to argue about or discuss a problem, and some of these – usually marked *'For discussion'* – are not suited to formal written answers. They are meant to start off a discussion, which may then wander far from the question.

There are a few harder questions to challenge the clever, and you should not expect to be able to tackle every question easily. But most are meant for ordinary human beings, not for budding geniuses. If in doubt, try the obvious answer: usually there is no catch! Most questions have some kind of answer in the section headed 'Answers', though some of these suggest where you might find the necessary information, instead of giving it. We have tried hard not to give wrong answers, but, being fallible like yourselves, may not have succeeded.

Some questions ask you to guess, speculate, or give your private opinion: obviously they have no one right answer.

What you are being asked to learn to do

This course aims to help you to become more like a physicist. Most of you will not become physicists, but will use physics or learn more of it in one of a variety of scientific jobs or in further education. Physics, and the world with it, are changing so fast that no one can tell what bits of physics you will use in, say, ten years' time; however, one can be pretty sure that there are some basic ideas that will be relevant to the new problems of tomorrow. We have tried to build the course around what we believe to be these basic ideas.

So one thing the course aims at is to help you to become able to learn, in the future, the new ideas in physics you may meet, and to help you to become able to use the physics you have learned. It does this because these are the tasks that will face you.

In the future, you will need to be able to learn from books and articles; that is why the course contains a good deal of reading (in a list at the end, you will find details of books referred to in the text). To use the physics you have met, you need to understand it – that is, to be able to use it in new kinds of problems. That is why so many questions in this book ask you to make up arguments about new problems, using what you know.

What is 'understanding'? That is, how does one recognize that someone understands a piece of physics? We think it is something like this. Suppose a group of people are talking about a problem in physics. Very rarely, even among research workers, will anyone immediately see an answer. More often they each have some ideas which they try out in discussion with colleagues. Those who 'understand' their physics are the ones who can offer sensible, relevant ideas that would help towards clearing up the problem. A reasonably competent physicist expects himself and others to be able to draw on their knowledge and use it to make sensible contributions to the discussion of problems.

So to test whether you understand a piece of physics, it is asking too much to expect you to solve a new problem completely and correctly; few – if any – experts can do that. The test should be that of physicists talking together: can you produce sensible ideas that are relevant and would help a bit towards clearing up a problem? This is the test that will be used in the examination, and is the way to decide how well you have managed a question or problem in the work of the course.

The course also aims to show you what doing physics is like, and this is another reason for encouraging plenty of discussion of problems, for that is the way physicists work. It tries to show what kinds of questions physicists ask themselves and what sorts of ways they use to tackle them. We think this is important because to use physics successfully and to judge its claims and achievements you need to understand what it can, and what it cannot do. That is why several questions ask you about such things as how theories, models, experiments, and facts fit together. Physicists also guess, estimate, and speculate, so other questions ask you to do these things too, to find out what doing them is like and to become better at doing them.

There are a lot of misunderstandings about what physics is like. Some say it is all facts; others that it is all theory, having little to do with what happens in practice. Many are puzzled; asking whether what physics says is true or not, or how physicists arrive at their ideas. We hope you will find chances in this course to think about such matters, and that you will form your own views.

Some of the questions ask about how physics can be used in engineering and technology, and the articles in this book are also about that, because we think that you will rightly want to know when what you learn is of practical value.

Finally, one of the main reasons we want to offer you some physics is that we like the subject and get excited about it. So we hope you enjoy it too.

Summary of Unit 2 Electricity, electrons, and energy levels

This Unit is about electricity, about its practical importance and about the ideas like current, charge, and potential difference which are used throughout physics and engineering. It is also about why electricity is of fundamental importance in physics, because atoms turn out to be *electrical* in nature.

Electrical energy cannot be understood unless one understands energy, so this Unit contains some revision of energy ideas from dynamics. The work on atoms also involves dynamics, for it discusses experiments in which electrons collide with gas atoms. So the dynamics of collisions and momentum is revised too.

Part One

Things which conduct

Using meters

Measuring currents and voltages, sensible use of ammeters and voltmeters.

Laws

Ohm's Law.
Resistance.

Useful quantities

Resistivity, and the variety of electrical behaviour of materials.

Simple theory

How fast electrons or ions need to move to carry electric current.

Part Two

Currents in circuits

Thinking about circuits

'Puzzle' boxes containing hidden resistors.

An important basic concept

Potential difference (p.d.); how to measure it and what it is.

Practical problems

Sources of p.d. which have resistance.

Part Three

Electric charge

Another basic concept

Electric charge, an amount of electricity conveyed by a current in a certain time. Simple experiments with capacitors to find out about charge and capacitance.

A mathematical idea and a mathematical technique

The decay of charge on a capacitor, an important type of change (exponential change). A graphical method for handling rate of change equations.

Part Four

Stored energy

Uses of energy

The energy stored on a capacitor, the energy stored in a spring.

Part Five

Electrons and energy levels

Evidence (and lack of evidence) in physics

Revision of reasons for thinking that there may be electrons. Millikan experiment (a long experiment where accuracy matters).

Evidence about atoms

Ionization of atoms by collision.

Usefulness of dynamics

Collisions and momentum.

Reading – evidence about energy levels

Selected passages from papers discussing electron collision experiments showing that atoms have definite energy levels.

Questions

Part One

Things which conduct

Questions 1 to 5 Electrical resistance and current–voltage graphs

1 *Suppose you are in charge of a laboratory technician* whose job will be to measure the resistance of sample resistors which are occasionally delivered. The resistors are unmarked, but vary in resistance from 10 Ω to 100 000 Ω. The laboratory has the ammeters, voltmeters, and supplies of potential difference available in the teaching laboratory you now work in.

Write out a list of rules or notes to help make sure that the technician connects the meters correctly, chooses his meter sensibly for the job in hand, and is unlikely to damage a sensitive ammeter by passing too large a current through it.

2 Repairs to cars, drainpipes, and many other jobs are sometimes done with a paste which has a slightly metallic appearance, can be spread with a knife or shaped into any form, and sets hard with a smooth finish in about an hour. How would you set about testing its electrical properties?

3 Guess or estimate your own electrical resistance, say from hand to hand. (If you want to make an experimental check, make sure you have a safe arrangement – p.d. not more than 12 volts – and that any meter you use will not be damaged.)

4 Figure 1 shows the results of measurements of the current I through and the potential difference V across four different electrical components, each concealed inside a box having only two terminals. What can be said about the contents of the boxes, using only the information conveyed by the graphs? The graphs are all drawn to the same scale, even though no markings are shown.

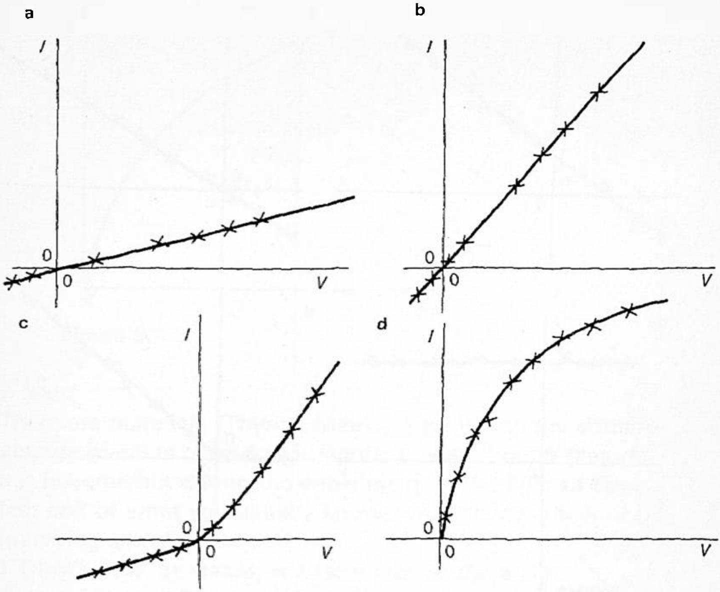


Figure 1

5 Part **a** of this question is about interpreting graphs, which is a useful thing to be able to do. Part **b** is about making graphs to test a suggested rule. Part **c** is more philosophical, and considers when it is reasonable to discuss laws and whether they need always be true.

Here is a statement of Ohm's Law.
'The current between two points in a conductor is proportional to the potential difference between these points, provided that physical conditions such as temperature remain constant.'
a Which of the graphs of experimental results in figure 2 could be taken as agreeing with the Law as stated?

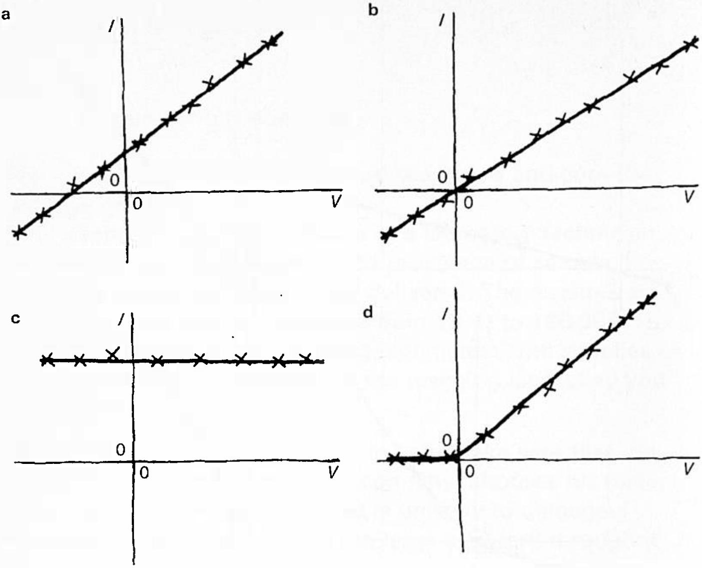


Figure 2

b Here are some results taken for a sample of a new material. Does the relation between current and potential difference agree with Ohm's Law?

Current/mA	Potential difference/V
1.0	14.5
1.5	21.8
2.0	29.0
2.5	36.2
3.0	43.5
3.5	50.7
4.0	58.0

Table 1

Can you think of any other ways, apart from the one you used, to make this test? What is the resistance of the sample when the current is 2.0 mA? Is the resistance the same when it is 4.0 mA?

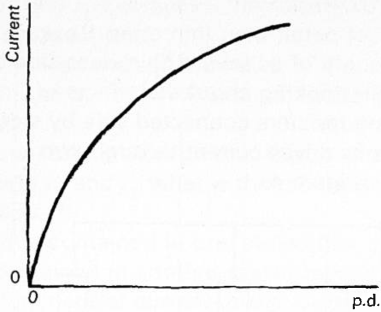


Figure 3

c *Hard*

There are materials (Thyrite, Metrosil) for which the current–voltage graph is curved as in figure 3, even though they do not become hot during the experiment. In the light of this fact and of what you already know, what do you think of the following statements?

1 Ohm's Law, as stated, is a false law, as there are exceptions to it. The Law should be rejected.

2 Ohm's Law is a useful summary of the behaviour of some materials, but not all.

3 There are materials that do not obey Ohm's Law, and it would be best to keep the word 'conductor' only for those that do. Then the Law would always be true.

4 Over small enough ranges of current, even a curved current–voltage graph will be approximately straight. So it would be better to say that, experimentally, Ohm's Law is true over small ranges of current only, to a good approximation. (Look at figures 2*a* and *b* before making up your mind.)

5 I would prefer not to call it a 'law' but to keep that word for statements that always work exactly.

Questions 6 to 10 Resistivity

6 Thick wires conduct better than thin ones. Because a thick wire could be thought of as several thin ones side by side, it is useful to begin thinking about the effects of thickness by considering resistors connected side by side, in parallel. A p.d. of 12 volts drives current through two resistors in parallel as in figure 4.

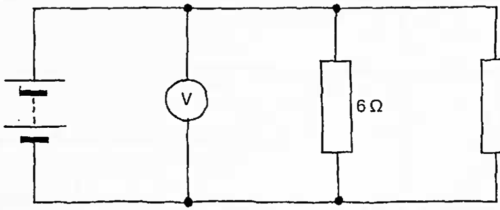


Figure 4

a What current goes through the 6 Ω resistor?
b What current goes through the 3 Ω resistor?
c What is the total current taken from the battery?
d If the two resistors were replaced by a single resistor, which conducts the same current as the total through the 6 Ω and the 3 Ω resistors together, what would be its resistance?

7 This question is an algebraic version of question 6. A p.d., V, drives current through two resistors, r_1 and r_2, in parallel, as in figure 5.

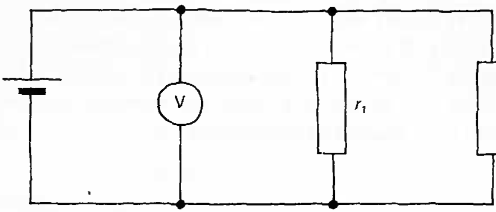


Figure 5

a What current passes through r_1?
b What current passes through r_2?
c What is the total current passing through r_1 and r_2?

d If r_1 and r_2 are replaced by a single resistor R, what current passes through it?
e Why does the equation $V/R = V/r_1 + V/r_2$ represent the case where the current in R is equal to the total current in both r_1 and r_2?
f If the current through R is the same as the total current through r_1 and r_2 what is the relationship between R, r_1, and r_2?
g If R is contained in one sealed box and r_1 and r_2 in parallel are contained in another sealed box, can you think of any measurement of current or p.d. outside the boxes which could distinguish between them?

8 A tube containing a column of mercury passes a current of 0.1 A when connected to a source of p.d. of low resistance. If all of this mercury is now put into a tube which has twice the radius of the first tube, what current will flow with the same p.d.?

9 *Fairly hard*
You have to erect a power line but don't know whether to use copper or aluminium wire. Assuming that the resistivity of aluminium is 1.6 times that of copper, that copper is 3.2 times as dense as aluminium, that the cost of 1 kg of copper is the same as the cost of 1 kg of aluminium (which it is not), and that the line has to be of the same resistance whichever metal you use, which would you choose? What other advantages will you derive from your choice?

10 Figure 6 shows the electrical resistivity of a number of materials, and whether the resistivity rises or falls with a rise in temperature. The height of each bar represents the resistivity.

a Notice that the scale is a peculiar one, with equal *multiples* of resistivity spaced out evenly along it. The difference in the height of the bars for silicon and germanium is roughly the *same* as the difference between those for germanium and carbon. What can you say about the relative sizes of the resistivities of carbon, germanium, and silicon?

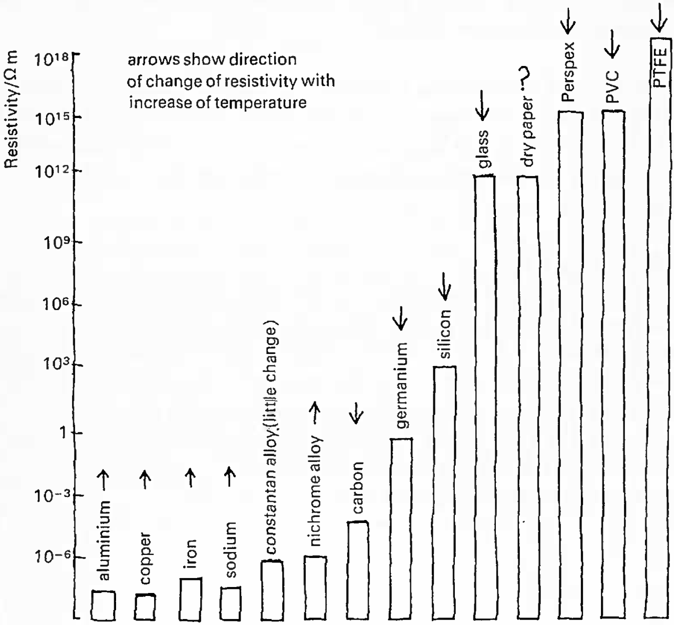


Figure 6

b Suppose the printer had not put 10^{-6}, 10^{-3}, 1, 10^3, 10^6, etc., along the scale but had printed the powers -6, -3, 0, 3, 6, and so on, instead. What quantity would now be plotted on the vertical scale?

c Estimate roughly how high the bar for PTFE (polytetrafluoroethylene) would be if the scale were conventional, with each millimetre representing an increase of resistivity of 10^{-8} ohm metre (so that the bar for copper would be about 1 mm high).

Questions 11 to 16 *Conductors and insulators*

11 Table 2 shows three groups of materials, X, Y, and Z. There follow some suggestions about the possible nature or uses of such materials. For each suggestion, pick the group or groups to which it *might* apply, on the information given.

Group	Material	Resistivity at 20°C/Ω m	
X	silver	1.6×10^{-8}	all increase with rise in temperature
	copper	1.7×10^{-8}	
	aluminium	2.7×10^{-8}	
	mercury	69×10^{-8}	
Y	graphite	$350–6500 \times 10^{-8}$	all decrease with rise in temperature
	germanium	0.47	
	silicon	2.3×10^{3}	
Z	Pyrex glass	10^{12}	all decrease with rise in temperature
	paraffin wax	10^{14}	
	polystyrene	10^{15}	

Table 2

a They contain many electrons which are free to move.
b Practically no charged particles at all are free to move.
c When it becomes hotter, increased atomic vibrations somehow free more charged particles so that they can move.
d Increased atomic vibrations somehow get in the way of moving charge and obstruct its flow.
e The number of charge carriers free to move is much less than for a metal, but is more than for a typical 'insulator'.
f Some might be useful as the wrapping for a submarine cable.
g A piece the size of a pea will pass a current between 10 μA and 10 mA under a p.d. of one volt (one of the group might pass less).
h Electrical properties would be significantly affected by surface moisture.
i Some could be used to make high-current shunts for meters.

12 The large insulators carrying high voltage lines on pylons have the ribbed shape shown. Can you think of a good electrical reason for using this shape?

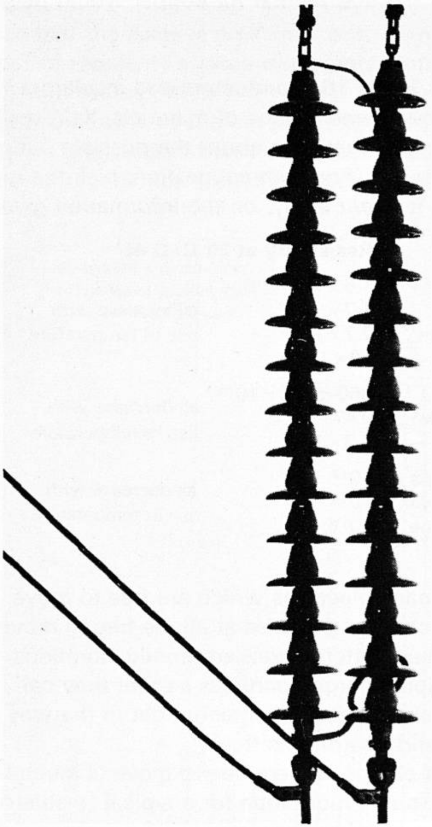


Figure 7
Photograph, Central Electricity Generating Board.

13 The heater of an electric iron is made of a nickel chrome alloy (nichrome) ribbon wound over a flat mica sheet, and sandwiched closely between two more sheets of mica. The arrangement is shown 'exploded' in figure 8.

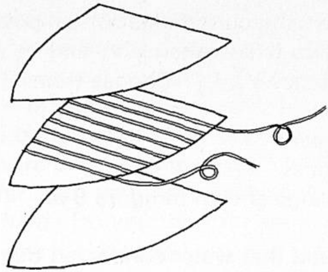


Figure 8

Suppose the supply of mica ran out. What desirable properties would you ask for in a replacement material to do the same job in the same way?
(*Hard*) Can you think of any other ways of providing safe and effective heating for an iron?

14 Semiconductors have a resistance that decreases as they become hot. If you connected a specimen of such a material incautiously to some power supplies, the specimen could rapidly be destroyed. Can you explain why?
(*Harder*) Can you think out what you can do to the circuit to make this less likely?

15 *Hard*
This question is about reading information from graphs. The set of curves in figure 9*a* shows how the current through a device varies with p.d. at various temperatures. The curve

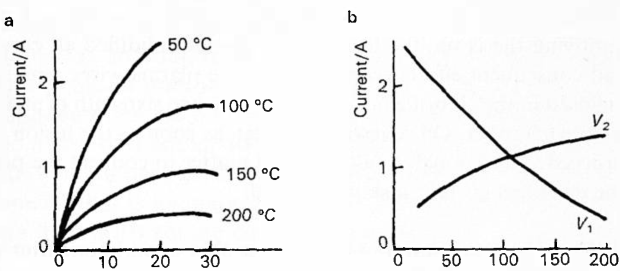


Figure 9
From Nedelsky, L. (1965) Science teaching and testing, *Harcourt Brace Jovanovich, Inc.*

in figure 9*b* shows the current against temperature for the same device, at two fixed voltages V_1 and V_2.
What are the voltages V_1, V_2? Choose from:

about 10 volts
about 20 volts
about 30 volts
not in the range shown in figure 9 *a*.

16 Faraday found that water conducted but that ice did not. He then went on to some other experiments, the first of which is reported in the extract below from his *Experimental researches in electricity* (1839) Articles 380 to 417.

As it did not seem likely that this *law of the assumption of conducting power during liquefaction, and loss of it during congelation*, would be peculiar to water, I immediately proceeded to ascertain its influence in other cases and found it to be general. For this purpose bodies were chosen which were solid at common temperatures, but readily fusible; and of such composition as, for other reasons connected with electrochemical action, led to the conclusion that they would be able when fused to replace water as conductors. A voltaic battery ... was used as the source of electricity and a galvanometer introduced into the circuit to indicate the presence or absence of a current.

On fusing a little chloride of lead by a spirit-lamp . . . and introducing two platina wires connected with the poles of the battery, there was instantly a powerful action, the galvanometer was most violently affected, and the chloride rapidly decomposed. On removing the lamp, the instant the chloride solidified all current and consequent effects ceased, though the platina wires remained inclosed in the chloride not more than the one sixteenth of an inch from each other. On renewing the heat, as soon as the fusion had proceeded far enough to allow liquid matter to connect the poles, the electrical current instantly passed.

a What *fact* did Faraday know after this experiment that was not known before it?
b Draw a circuit diagram of the apparatus he describes.
c Why did he try the comparison of conducting powers that he describes?

d Why did he choose lead chloride?
e He begins by suggesting a law, having only tried the ice and water comparison. Do you think he could be sure of the truth of this law before the experiment described? After it?
f Why does he bother to mention that the wires in the solid lead chloride were only 1/16 inch apart? Why does he *not* mention how far apart they were in the fused lead chloride?
g (*Optional – hard*) Do you think if Faraday had tried a metal like tin, which conducts both as a solid and when melted, he would have rejected the 'law' he states as false? Is there evidence that he deliberately chose a substance that he thought would support his 'law'? What do *you* think of Faraday's 'law'
1 on the evidence above?
2 in the light of what you know about electrical conduction?

Questions 17 to 22 The current conveyed by moving charged particles

17 This is about transport by rail or road. The problem of the current conveyed by moving charged ions or electrons is of essentially the same kind, but the familiar case of travel by train or road may be easier to think about.

a Suppose that, on average, 200 passengers arrive in London from Manchester by train every hour. The journey takes $2\frac{1}{2}$ hours, averaging 100 kilometres an hour. About how many passengers would you expect to be travelling by train at any instant? If the same number of people arrived in London each hour having walked from Manchester at an average of 5 kilometres an hour, roughly how many people would you expect to be on the road at any instant?
b Suppose there are 5×10^{26} doubly charged positive ions in a cubic metre of a liquid, and all are moving west with a speed of 10^{-5} metre per second. What is the direction of the current? What is its magnitude in amperes if the cross-section of the fluid is 10 square centimetres (10^{-3} m^3)?

18 Question 19 is the same as this one, using algebra. Do the algebraic version straight away if you want to, but do calculate the numerical answer to part **e** of this question. Together, these questions take you through a useful piece of theory.

Think of a tube containing liquid which has a cross-section of 1 square centimetre (10^{-4} m^2). Suppose the liquid conducts a current of 10^{-2} ampere. For simplicity, think of the current being carried by a lot of charged particles, all moving along at the same speed, v, which you will be able to calculate if some more assumptions are made about the charged particles.

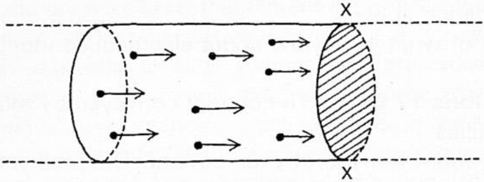


Figure 10

Suppose there is a counting station at XX, which records the number of particles crossing that slice of the tube.

a In 16 seconds, with a current of 10^{-2} ampere, what electric charge passes XX?

b If each particle has a charge of 1.6×10^{-19} coulomb (the same as the charge on an electron), how many particles pass XX in 16 seconds?

c Suppose there are 6×10^{26} charged particles in each cubic metre of liquid. How many charged particles are there in each one metre length of the tube, if the area of cross-section is 10^{-4} m^2?

d From the answer to **b**, the number of particles crossing XX in 16 seconds, and the answer to **c**, find the length of liquid in the tube behind XX from which all the particles cross XX in 16 seconds. (Of course, this length is 'filled up' again with more particles from behind.) You should have an answer much less than one metre. If not, think again.

e The length in the answer to **d** is also the distance a particle travels in 16 *seconds at the unknown velocity* v, *since it is* that velocity which carries it past XX. What is the velocity, v? Is this result surprisingly large or small? Is there any evidence that helps you to have confidence in it?

19 **a–e** Now go through *questions* **a** *to* **e** *in question* 18 but using I for current, t for the time of flow, q for the charge on each particle, n for the number of particles in each cubic metre, A for the cross-sectional area of the tube, and v for the velocity. You should get $v = \dfrac{I}{Anq}$. Why is there no time, t, in this answer?
f For a given current in a given sized tube, what is the effect on v of decreasing the density of charged particles, n? What is the effect of decreasing the charge on each particle, q? Is the charge likely to be less than 1.6×10^{-19} coulomb? What reasons might be given to support a value of around 10^{26} particles per cubic metre for n? Can you think of a liquid (pure? *solution?*) in which n might be substantially less than this?

20 Try this question only after doing questions 18 and 19. It is about the velocity of travel of electrons in a metal and, as with the liquid in the earlier problems, makes some risky assumptions.

In question 19, you showed that the velocity v of the drift of carriers with charge q, when there are n carriers per cubic metre, if a current I flows through a conductor of cross-section A, is:

$$v = \frac{I}{Anq} = \frac{I}{A} \times \frac{1}{nq}.$$

(I/A is often called the 'current density'.)
a If a length of wire has a resistance R, and there is a p.d. V across it, then

$$I = V/R.$$

Write an equation for I/A in terms of V, R, and A.

b If the length of the wire is L, and the resistivity of the materials is ρ, then the resistance is

$$R = \frac{\rho L}{A}.$$

Write a new expression for I/A without R in it.
(*Check* – A should have vanished.)

c In a wire of copper, resistivity 1.7×10^{-8} ohm metre, when there is a potential difference of, say, 10 volts across 10 metres of wire (1 volt per metre), what is the current density in amperes per square metre?

Check: this seems big, doesn't it? What is the current through a wire of cross-section 1 mm^2 at this current density?

Do you think that a piece of copper is often arranged in a circuit with 1 volt per metre across it?

d As was said above, the carrier velocity v is, on average

$$v = \frac{I}{A} \times \frac{1}{nq}.$$

You now have a value for I/A. Assuming that the carriers in copper are electrons, use $q = 1.6 \times 10^{-19}$ coulomb, to find the value of the constant in

$$v = \frac{\text{constant}}{n}$$

when the wire has 1 volt per metre across it.

e Suppose that there is just one conduction electron for each copper atom (a very risky guess). Then n is the same as the number of atoms in a cubic metre of copper.

You may have a value for this from your previous work on X-ray diffraction, or have worked it out when using the Advanced Chemistry programme, *Amount of substance*.

Alternatively, you can calculate the number of atoms in one cubic metre of copper from these data:

1 1 cubic metre of copper has a mass of 9.0×10^3 kg.

2 63.5 kg of copper contain 6.0×10^{26} copper atoms.

Find n, assuming that one electron per atom takes part in conduction.

f Now find the average drift velocity v of the electrons in metres per second, combining the answers to **d** and **e**.

21 Figure 11 shows a junction of two pieces of copper wire which form part of a simple series circuit around which a current is flowing. Discuss the accuracy of the following statements.

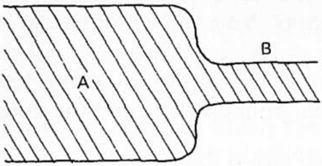


Figure 11

a Charge must be piling up at the junction.
b The conduction electrons in B are moving more slowly than those in A.
c The conduction electrons in B are moving faster than those in A.
d There are more electrons per cubic metre doing the conduction in A than in B.

22 *Hard*
This is a hard question, and may not seem to have anything to do with physics or electricity. Yet it uses one of the important ways of thinking about electricity, and is about one of the urgent problems that afflict modern cities. If you can tackle it, you probably understand electric currents quite well, and you will have seen how one kind of argument can be used to handle a variety of problems.
a Go back to questions 18 and 19. Think now of a busy road carrying people to work into London in the morning. Suppose that there are n vehicles on each kilometre of road, with q people in each vehicle. The road carries I people per hour, in vehicles travelling with velocity v, measured in kilometres per hour. Use an argument parallel to that used in question 19 to show that $I = nqv$
b Find the capacity of a road, that is, the number, I, of people per hour, that it can carry for:
cars carrying 2 people each
buses carrying 80 people each
trains (the road is now a railway) carrying 10^3 people each.

You will have to estimate the speed and the number of vehicles per kilometre. The latter might be related to the stopping distance of a car at the speed you choose (perhaps 50 km per hour). It would be worth finding o the capacity is more or less in a nose to tail crawl at 10 per hour than at 50 km per hour. You may want to allo\ .ᴗı more than one lane of cars.

For trains, you might guess the number per kilometre from the greatest frequency of rush hour services and the speed of a train.

c All these estimates were for one 'road' only. London has perhaps 10^2 major roads leading into it from the suburbs, and about ten railway termini. (Vary these estimates if you do not agree.) The central area provides jobs for at least 10^6 people* who do not live there, and all these people have to enter (and leave) in about one hour. Can you estimate how near the transport system is to its maximum capacity?

It has been suggested that if cars were banned, an adequate number of buses could carry many more people on the roads. Do you agree? How many buses would be needed, if each bus makes one journey into London in the rush hour?

Consider any other aspects that interest you: for example, what area would be covered by parked cars if everyone travelled by car? How many new roads might then be needed?

Part Two

Currents in circuits

Questions 23 to 27 Circuit problems

23 A light fitting in the ceiling of the living-room has three bulbs which are switched on and off together by the wall switch. Would they be connected in series or parallel? What is the quickest way to decide experimentally? Why is one arrangement preferred to the other?

*Hall, P. (1966) *The world cities.* Weidenfeld & Nicolson.

24 a–e In the figures below, A, B, C, D are four terminals of a box containing resistors connected between the terminals. The resistors are not shown, being inside the box and not visible. All the resistors have constant resistance and there are no diodes, lamps, or other components with non-linear characteristics. The terminals C and D are joined by a wire of low resistance, as shown. The battery has a potential difference of 6 V and has negligible resistance.

How much can you say about the contents of the box as a result of each test shown in figures 12*a* to *e*?

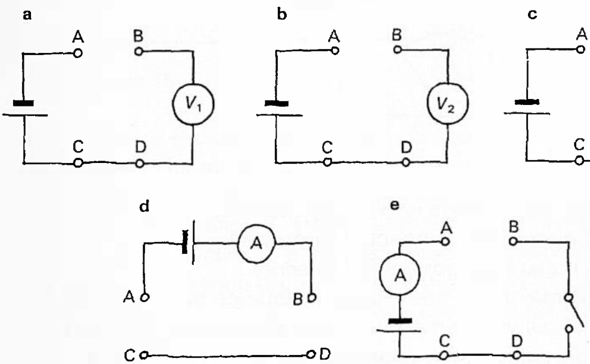


Figure 12

a V_1, *a high resistance voltmeter, reads* 6 V. (Figure 12 *a*.)
b V_2, a voltmeter of resistance 1000 Ω, reads 4.5 V. (Figure 12 *b*.)
c A is a milliameter, and reads 18 mA. (Figure 12 *c*.)
d A again reads 18 mA. (Figure 12 *d*.)
e When the switch is open, A reads zero (figure 12 *e*). When it is closed, A reads 18 mA again.
Taken together, what do all these tests suggest might be the circuit inside the box?

25 You find a box (part of some apparatus) with two ammeters in it. One is marked 0–10 A, the other 0–10 mA, and the box has just two terminals and no other connections to anything. When the terminals are joined to a 12 volt accumulator, both meters read nearly full scale. Consider the following statements.

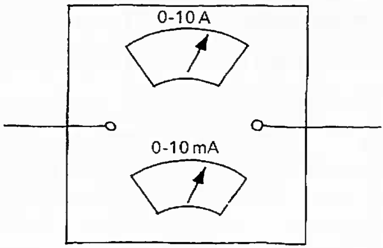


Figure 13

a One of the two meters is wrongly marked.
b The two meters are connected in parallel.
c The two meters are connected in series.
d The 0–10 mA meter has a large resistance in series with it.
Say as much as you can about these statements, or about how they are related. For example, you might say that **a** *must* be true; that **c** *could* be true, or that *if* **d** is true then **b** *must* also be true.

26 When using a 'dimmer' for a stage light, it was found that if the variable resistance was connected as shown in figure 14, the lamp was still glowing when the full resistance was used.
a To get a full range from dark to bright, the circuit of figure 15 was proposed. Would it work as intended?
b It was found that the dimmer in figure 15 was hot even when the lamp was at its brightest, and clearly energy was being wasted. Two schools of thought developed: one said 'Now make the dimmer resistance much less', and the other said 'Now make the dimmer resistance very big.' Outline the consequences of following the advice of each group.

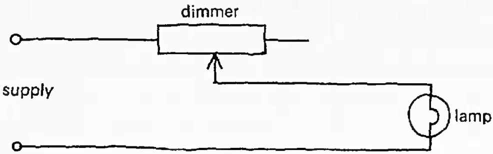


Figure 14

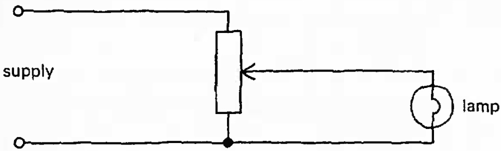


Figure 15

27 When a resistor is placed across the terminals of an 'ohm-meter' its resistance can be read from the meter. Design an 'ohm-meter' to be made out of a spare milli-ammeter which reads 0–1 mA. It should be protected against damage if connected to a very low resistance. What might be the largest resistance it could usefully measure? Make a sketch showing what the resistance markings on the dial might look like.

Questions 28 to 36 Potential difference and energy

28 **a** Guess how much energy is stored in a 1.5 volt U2 cell.
b Guess how many joules are needed to set a train in motion.
c Estimate the least time in which a train of mass 500 tonnes could attain a speed of 30 metres per second on level track, taking 100 amperes from a 20 000 volt supply.
Kinetic energy $= \frac{1}{2} mv^2$. 1 tonne = 1000 kg.

29 A typical lamp for a room is labelled 240 V, 100 W. How much current does it take? If a class room had two sets of four such lamps, how would they be wired together? Let there be a separate switch for each set of four lamps. What is the total current flowing? What current flows if one of the lamps 'burns out'?

30 **a** A farmer requires a d.c. electricity supply and a cable is laid, containing two wires, to his farm 4 km from the supply station. The wire has a resistance of 10^{-4} ohm per metre. Assume that the generator at the supply station has a resistance less than 0.01 ohm. The farmer uses a 100 watt lamp on his 240 volt supply, but finds that when his wife switches on her cooker at full load (say 32 amperes) his lamp dims. Calculate by how much the voltage at his lamp has dropped. (You can ignore the current flowing through the lamp.)

b He decides to use a 12 volt car battery (B) to 'top-up' his voltage. He considers how he might connect it, producing the sketches shown in figure 16.

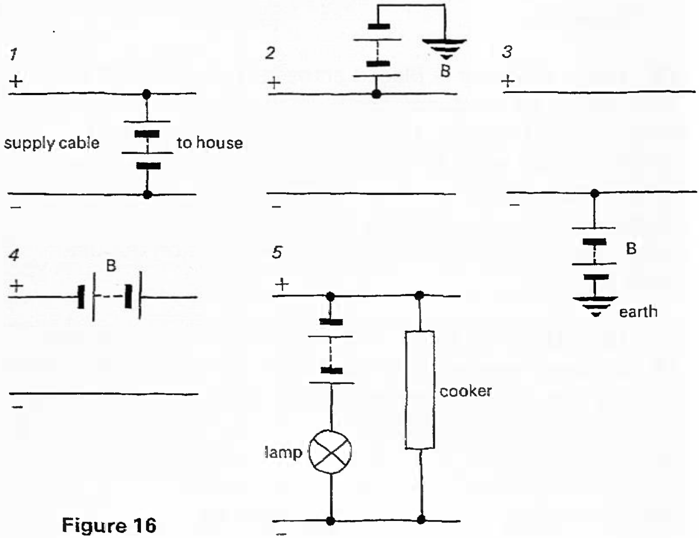


Figure 16

Comment on each of the designs, if the generator delivers direct current.

The farmer has hopes of *4* but finds that the brightness he gains in his lamp is soon gone. The battery is labelled 100 ampere-hours. What has happened? He is pleased (but not his wife) with *5* though not so pleased when his wife switches off her cooker (why?).

c Then he finds that another customer nearer the supply station has been connected to his cables and when that household switches on a large load the farm voltage drops. He finds another neighbour, on a separate cable, who is similarly handicapped. They write to the electricity authority which points out that the farmer already has a very expensive cable (if it were of pure copper each wire in his cable would need to be 20 mm thick). Nevertheless a cable is laid joining his supply to his dissatisfied neighbour's, so making something like a ring of cables. Discuss whether this arrangement would have any advantage.
d Inquire of electrical technicians how 'ring mains' are laid in houses, shops, and offices where a great many power points are required.
Note: the cost of cables for this farmer would be wholly uneconomic. As you may know, more reasonable costs are achieved by using higher voltages for transmission of power than are used by the consumer. You may already know or be able to guess why this is done, and how the necessary changes of voltage are made.

31 *For discussion*
An e.h.t unit intended to supply 3 kV has a safety resistor of 50 M Ω connected in series with the output terminal. How does this make it safe? What safety resistor would you need to make a mains plug just as safe to touch? Would it be a good idea to connect such resistors permanently into mains plugs?

32 The p.d. across the output terminals of a source of electrical energy connected to a variable resistor R was measured for different values of current as R was varied. The following results were obtained:

p.d./V	10	9	8	7	6	5	4	3	2	1
current/A	0	1	2	3	4	5	6	7	8	9

What is the internal resistance of the source? Plot a graph of the resistance in the external circuit (R) against the output power as ordinate. What general conclusion do you draw from the graph?

33 *For discussion*

What is a fuse for? What is the earth for on a three-pin plug? A mains socket (240 V) is thought to be faulty because its earth lead has a high resistance to earth. The socket is used for a 2 kW electric kettle. The electrician finds that he will have to pull up a lot of floorboards to get at the socket wiring so he measures the resistance to earth and states that it doesn't need immediate attention because the resistance is 'low enough to stop you getting killed if anything went wrong with the kettle'. How could he have made the measurement? Could he have been right in his safety judgment? If he could, how low would the resistance have to be?

34 An electric train runs at its maximum power of 2.5 MW. What current does it use if it is supplied at

a 2500 V?

b 25 000 V?

c If the supply current in each case runs through supply cables, by what factor would the power wasted in heating the cable be greater for **a** than for **b**?

d For the same wastage in the two cases, how much longer might the cable be in case **b** than in case **a**, assuming the same area of cross-section of cable in each case?

35 A student is experimenting with a resistor which has a sliding contact, using the circuit shown in figure 17 *a*. With a high resistance voltmeter, the p.d. indicated by the voltmeter is found to be directly proportional to the distance L of the contact from the end of the resistor.

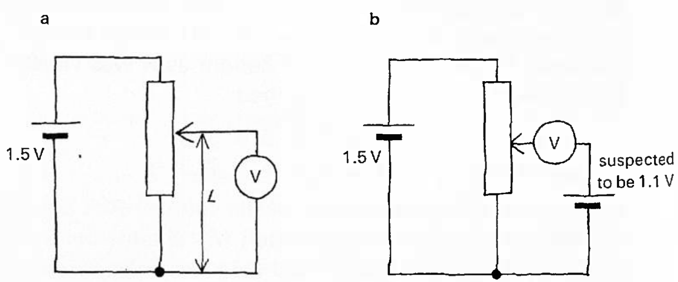


Figure 17

a What can be said about the construction of the resistor?
b Will the result above always be obtained, whatever the voltmeter's resistance?
c Having set the sliding contact so that the voltmeter in the circuit of figure 17*a* reads 1.1 V, a second cell whose voltage is believed to be 1.1 V is inserted as in figure 17*b*. So far as the student can see, the voltmeter reads zero and he or she claims that this means that the new cell does have a voltage of 1.1 V. Is this right? Why?
d The voltmeter is of the kind in which a sensitive micro-ammeter is connected in series with a large resistance. The student removes this resistor, leaving the microammeter in circuit. The meter does not now read zero, but indicates that a very small current is flowing. Suggest one or more reasons why this could happen.
e Another student sets up the circuit of figure 17*b*, to repeat the zero voltmeter reading observation described in **c**. Despite care in setting the contact position, the voltmeter reads about 2.6 V, not zero. What could have gone wrong?

36 This question expects you to use common sense, and a knowledge of the size you can reasonably expect quantities of energy to be.
Suppose you found a small square box, about 0.1 m each way, which felt fairly heavy. It had two terminals, and when you connected a single torch battery to them for a few seconds, the box got very hot, and melted. Having destroyed it, you can't tell what was in it! What can fairly be said about its original contents?
a Nothing.
b It contained a very efficient means of extracting energy from a battery.
c It contained some substantial store of energy.
d It contained a 'heating element' (like that in an electric fire).
e It *must* have been connected to some external source of energy in some undetected way.

Questions 37 to 40 Meters

37 A meter has a resistance of 1000 ohms and a full scale deflection of 100 microamperes. How can the meter be adapted to read a full scale deflection of

a 10 milliamperes?

b 1 volt?

38 Alan is using a voltmeter across a 100 Ω resistor with an ammeter and a 12 V battery, as shown in figure 18*a*. Bob says, 'But the ammeter will record the current through the voltmeter as well as through the resistor.'

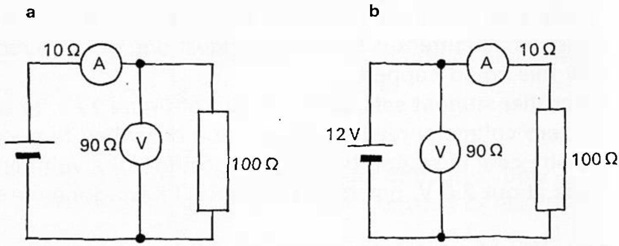


Figure 18

He rearranges the circuit as figure 18*b*. Alan says, 'But now the voltmeter is not measuring the p.d. across the resistor only.' Colin says, 'I expect one way is better than the other.' Which way is better? Under what circumstances might the other way be better? The ammeter has a resistance of 10 Ω, and the voltmeter a resistance of 90 Ω.

39 This question asks you to make some scientific guesses. Don't worry about being badly wrong: guessing is a difficult but worthwhile art. You might like to make a 'blind' guess first, and then to see if you can think of any way of making a rough estimate to check your first guess. Try to guess:

a The electric current in a torch bulb.

b The electric current in a 'mains' lamp.

c The electric current entering your home at 8 p.m. in winter.

d The electric current supplied at 8 p.m. in winter to the town you live in.
e The *largest* current you could pass through a pencil lead using the apparatus in your laboratory.

In your laboratory you may have seen some of the following kinds of ammeter. Check off the ones you have seen, and try to decide about each whether it would be suitable for checking one or more of the guesses **a** to **e** above.

Meters

a 'multimeter', for example, an AVO meter
a miniature 'multimeter' or 'testmeter'
an ammeter of range 0–1 A
an ammeter of range 0–5 A
a meter of range 0–10 mA, provided with adapters ('shunts') for 0–100 mA, 0–1 A, 0–10 A
a meter of range 0–100 μA, provided with adapters ('shunts') for 0–1 mA, 0–10 mA, 0–100 mA, 0–1 A, 0–10 A
a moving iron meter, with a scale from 0–5 A
a centre zero galvanometer, range about 3–0–3 mA
a light beam galvanometer, with full scale deflection for a few microamperes

40 *Hard*

The electrical resistance of metals increases with temperature. This effect has been used to measure temperatures, and also as the basis of a heated filament air flow meter (used in air or gas ducts).

See how far you can go in designing either instrument, or in suggesting investigations you would need to do in order to make a design. Books of data should provide some valuable information.

Electric charge

Questions 41 to 49 Charge and capacitance

41 Suppose a car battery supplies a current of 2 amperes for 10 hours, the change of current with time being shown in figure 19.

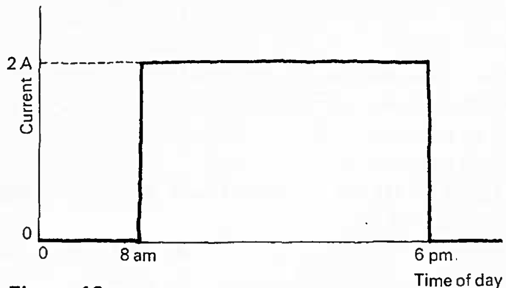


Figure 19

a Describe the change of current with time.
b What quantity of electric charge flowed past each place in the circuit?
c Indicate on a copy of figure 19 how the charge flowing can be represented on the graph.
d Sketch a modified graph of current against time to show what might happen if the battery is completely exhausted after 10 hours, the initial current still being 2 amperes. How is the charge flowing now represented on your new graph?

42 An 'electrolytic capacitor' is made of aluminium plates in ammonium borate. A small current flowing between the plates will produce a film of aluminium oxide on one plate (the anode), and this film has a very high resistance. If the thickness of the film is proportional to the charge that has passed, sketch roughly how you would expect the current to change with time, if a constant voltage is connected to the plates, starting with no film.

Will the current ever fall to zero?

If too large a voltage is connected across the capacitor, and some current flows, the temperature may rise. At higher temperatures the oxide film may disperse more rapidly and there may be more current still. What would you expect to happen?

43 In figure 20, C is a capacitor, and A is a direct current moving coil milliammeter that gives a 'fling' which increases as the charge flowing through it increases, but not in proportion to the charge. If the charge flow is the same, the fling is always the same, and the meter is equally sensitive for current pulses in either direction.

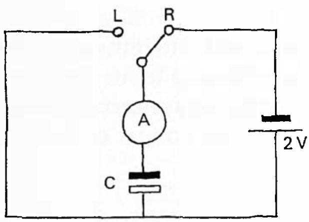


Figure 20

When the capacitor and meter are switched over from R to L, the meter pointer deflects 2 divisions to the left.

What can you say about the direction (left or right) and the size of the fling (2 divisions, more than 2, less than 2) if, starting with the switch connected to L, the following changes are made *in sequence*:

a Switch to R?
b Battery voltage raised suddenly to 4 V?
c Switch to L?
d Switch to R?

44 You may have experimented with a circuit like figure 21 with a capacitor C and two milliammeters.

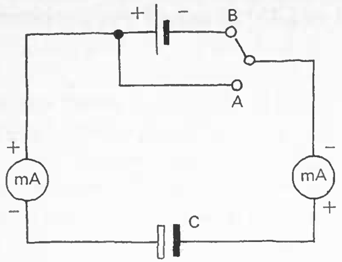


Figure 21

a The milliammeters are identical, and when the switch is moved from A to B, the pointer of one of them moves *momentarily* 5 divisions to the right, and returns to zero. Which way and by how much will the pointer of the other move? Choose from:

1 Not at all.
2 5 divisions to the right.
3 5 divisions to the left.
4 More than 5 divisions to the right.

b Noting the battery polarity, insert arrows on a copy of the diagram showing the (conventional) direction of the current flow when the switch is moved from A to B.

c What evidence is there in the meter readings that no charge is conducted through the insulation of the capacitor?

d When the switch is moved back from B to A, in what direction would the pointers of the meters move? Choose from:

1 Both move to the right.
2 One moves to the right, one to the left.
3 Neither move.
4 Both move to the left.

e In the light of the answers to these questions, what electrical changes occur at the plate of C which is connected to the positive side of the battery, when the switch is moved from A to B? What happens at the other plate? What happens when the switch is moved back again? (Your answer should use words like 'charge', 'positive', 'negative', 'flows', 'stored', 'equal'.)

45 A constant current of 1 mA flows for 100 s onto one plate of an uncharged capacitor connected to a battery in a circuit. At the end of this time, the p.d. across the capacitor is found to be 10 V.

a What current flows onto the other plate of the capacitor?
b How many coulombs are needed on one plate to give a p.d. of 1 V?
c What is the capacitance of the capacitor?

46 A capacitor is charged to 10 volts and then connected to a variable resistor. Describe how you would have to vary the resistor to obtain a discharging graph like the one on the right of figure 22. If you did succeed what would be the value of the discharging current, if the capacitor ended up uncharged?

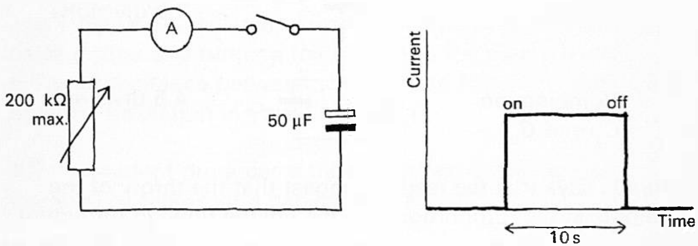


Figure 22

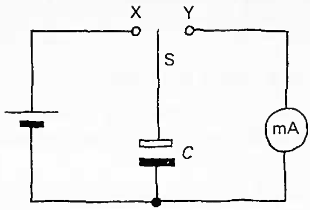
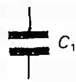
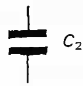
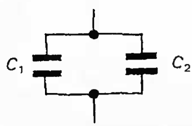


Figure 23

47 Alf finds that when he moves the switch S from X to Y in the circuit in figure 23, using for the capacitor C the following different arrangements, he obtains throws on the meters as below:

		Throw
Capacitor C_1		1.5 divisions
Capacitor C_2		3.0 divisions
Combination C_1 and C_2		4.5 divisions

Brenda says that the results suggest that the throw of the meter is in fact proportional to the charge flowing through it.
Colin says that that would depend on whether the charges on C_1 and C_2 added up in the third arrangement.
Dorothy thinks that the meter is one she used a week before and that she had shown experimentally by a different method that its throw was in fact proportional to the charge.
Alf then claims that, if Dorothy is right, 'charge is conserved'.
Brenda wants to know if they can now work out how much bigger C_2 is than C_1.
Dorothy claims that the experiment also shows, given her earlier experimental result, that $C = C_1 + C_2$ in a parallel arrangement.

Take each statement in turn, and comment on it. Make any calculations the speakers propose, if it is possible to do so.

48 An isolated sphere of radius 0.9 m has a capacitance of 100 pF between it and the distant earth or walls of a room. (1 pF = 10^{-12} F.)

Two plates, each 0.1 m square, separated by 1 mm of air, have a capacitance of about 100 pF; when separated by 1 mm thickness of paper they have a capacitance of about 500 pF.

A polythene-insulated coaxial cable has a capacitance of about 75 pF per metre. The capacitance between two telephone wires stretched between telephone poles is about 6 pF per metre.

Make rough guesses or estimates of:
a The capacitance of a man falling freely through the air.
b Your capacitance when standing on an earthed floor with insulating soles 10 mm thick on your shoes.
c The capacitance of a coaxial down lead from a television aerial on the roof to a television set in the house.
d The capacitance between the mains lead of an oscilloscope and 1 metre of insulated wire connected to the Y input of the oscilloscope and running fairly close to the mains lead.
e The capacitance between yourself and this wire when you hold the insulation in your fingers.

49 A student produces a model, shown in figure 24, intended to represent a capacitor in a circuit.

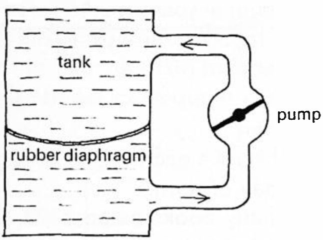


Figure 24

A pump P pushes water into the top of a tank, which is divided into two compartments by a leak-proof rubber diaphragm. The whole model is filled with water. When the pump is running, the diaphragm bulges as shown.

a Another student says that the device doesn't store water, but that a capacitor does store electricity, so it is a poor model. Comment.
b Does the model store energy?
c How would you modify such a model to represent an increase of capacitance?
d For a capacitor, charge is proportional to potential difference. What quantities would you measure to investigate whether an analogous relationship holds for the model, if you had one?

Questions 50 to 57 Decay of charge, exponential change

50 This question may help you to think about rates of change and graphs representing changes over periods of time.

In some schools, exercise books are issued from a central store. Suppose that books are delivered to the school at the start of a term and the store-keeper makes a weekly chart of the number of books in the store, recording the stock at the start of each week. For example, if he issues half the books in the first week of term, and the other half in the week after half-term, his record would be as in figure 25.

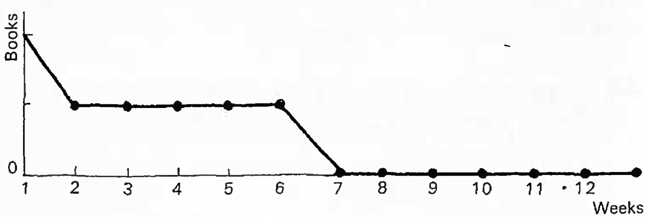


Figure 25

Sketch the shape of his stock-chart if:
a He issues the same number of books each week, giving out the last of his stock on the last day of term.
b Pupils always try to draw as many books as possible, and the store-keeper issues them rather freely when he has a large stock, but rations them more and more as his stocks dwindle.
c (*Harder*) Conditions are as in **b**, but he starts the term with no books and has a small constant weekly delivery. He always rations the issue so as to give out a constant fraction of his current stock.

51 (Treat this and question 52 as a pair.)
A cylindrical bucket has a hole in the bottom and when it is full, water leaks out at a rate of 100 cubic centimetres per second ($cm^3\ s^{-1}$). Table 3 shows subsequent rates.

Time elapsed/s	Rate of water leakage/$cm^3\ s^{-1}$
10	78
20	61
30	47
40	37
50	29
60	17
70	13
80	10

Table 3

After 80 seconds there are 540 cubic centimetres of water left in the bucket. Make an approximate calculation of how much water was in the bucket when it was full. Explain why this answer is only approximate. Is it too big or too small? What could you do to make it more accurate?

52 Try this after question 51.
The 400 μF capacitor in figure 26 is charged to 10 V and then connected to a 100 μA meter in series with a 100 kΩ resistor (the meter plus resistor is in effect a voltmeter with a full scale deflection of 10 volts). When the switch is first closed the current is 100 μA (100 microcoulombs per second).
Table 4 shows subsequent currents.

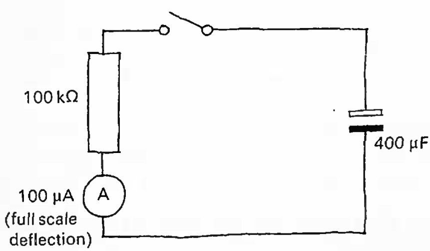


Figure 26

Time elapsed / s	Current / μA
10	78
20	61
30	47
40	37
50	29
60	17
70	13
80	10

Table 4

80 seconds after closing the switch the charge remaining on the capacitor is 540 microcoulombs.

a Make an approximate calculation of the original charge on the capacitor. How does this compare with the result obtained by using $Q = CV$? If it is different explain why.

b Do you think that an ordinary moving coil meter would give the readings quoted above?

c What do you think the values of currents and the original charge would be if the capacitor were charged originally to 20 V?

53 When a 100 μF capacitor is charged through R_1 as shown in figure 27 the graph of current against time looks like figure 28. Assume that the ammeter's resistance is small.

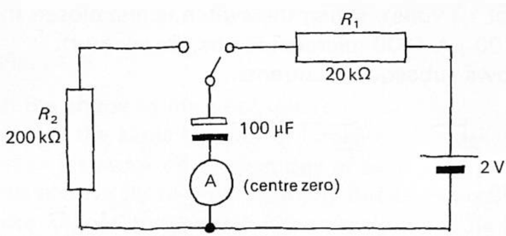


Figure 27

a Sketch the graph of current against time when the switch is now connected to R_2.

b Now sketch the graphs you would expect if the process were repeated with $R_1 = R_2 = 40\ \mathrm{k\Omega}$. Remember that the total charge, which is represented by the area under the graph, must be the same as before, but that the currents will be smaller.

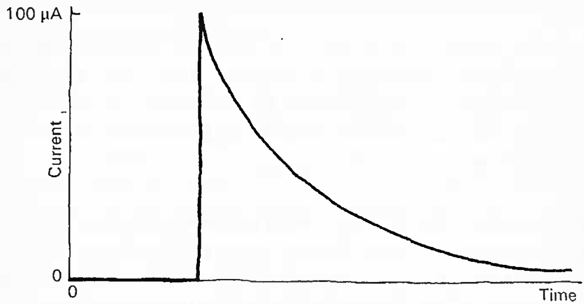


Figure 28

54 The number of cars in private ownership in Britain has risen over the years as in table 5.

Year	1947	1948	1949	1950	1951	1952	1953	1954
Millions of cars	1.94	1.96	2.13	2.26	2.38	2.51	2.76	3.10
Year	1955	1956	1957	1958	1959	1960	1961	1962
Millions of cars	3.52	3.89	4.19	4.55	4.97	5.53	5.98	6.56
Year	1963	1964	1965	1966	1967	1968	1969	
Millions of cars	7.37	8.25	8.92	9.51	10.30	10.82	11.24	

Table 5

From Central Statistical Office (1970) Annual Abstract of Statistics, *reproduced with permission of the Controller, H.M.S.O.*

a Plot a graph of the number of cars against time.

b Use a slide rule to find the *ratio* of the numbers of cars in each year to the number in the year before. For example, the ratio for 1949–1948 is $\frac{2.13}{1.96}$, that is, 1.09.

What do you notice about these ratios?

c In the series 10^2, 10^3, 10^4, 10^5, 10^6 each number is larger than the previous one by a constant factor (10). The powers 2, 3, 4, 5, 6 increase in equal steps and are the *logarithms* (to base 10) of successive numbers in the series. So, if a series of numbers increase in a constant ratio, their logarithms will increase in equal steps.

Now plot a graph of lg (number of cars) against time. Is the number of cars increasing in constant ratio over all these years? Predict the number of cars in the year in which you are doing this question or, better, suggest limits between which this number is likely to be.

55 Suppose that if there were no emigration or immigration, the population of Great Britain would stay steady. Suppose now that immigration is totally stopped, but in each year 10 per cent of the population of the country at the start of that year emigrate in that year. Draw a graph of the variation of the population over the next decade. Start at, say, 50 million people.

56 A research experiment requires an average current of 10 000 amperes to be supplied in a burst lasting 10^{-3} second through a coil of resistance 0.2 ohm. What can you say about the value of a capacitor which would store enough charge for this purpose, and deliver the charge fast enough to give the required current? To what p.d. would it need to be charged?

57 Invent a circuit, based on a capacitor, relay, and variable resistor, suitable for use as a photographic enlarger timer. For making exposures it is required to switch the enlarger lamp on for times within the range 5 to 15 seconds.

Part Four

Stored energy

Questions 58 to 64 Storage of energy, electrical and mechanical
The two kinds of question are mixed together because of the close parallel between the two cases.

58 Aircraft are catapulted off the decks of aircraft carriers so that they are moving fast enough to fly when they leave the deck and catapult.
a Guess the mass and minimum flying speed of an aircraft, and estimate the energy that must be delivered to it. (Kinetic energy $= \frac{1}{2}mv^2$.)
b Guess the catapulting distance and estimate the steady force that the catapult must apply to the aircraft.
c Experiments have been tried in which a form of electric motor (a linear motor) has been used for the catapult. Estimate the *least* current that would have to be supplied to the motor if it worked at 500 volts. (To do this, you will have to guess the time taken to catapult the aircraft.) What else would you need to know, or guess, to estimate more than the *least* current needed?

59 On Christmas day, a number of the order of 10^6 families cook a turkey or some other bird in electric ovens.
a If the power used averages 3 kW, and is in use for about two hours (the cooking time may be longer, but the oven thermostats turn the power off some of the time), what is the total energy used?
b At a supply voltage of about 200 volts, what is the quantity of charge that flows?

c If the energy were all supplied from dams by hydroelectric generators, if the water were stored in the dams at an average depth of 10 metres, and if the generators converted into electrical energy 50 per cent of the energy of the stored water that flows through them, what mass of water would flow in order to cook the nation's Christmas dinner? ($g = 10\ \mathrm{N\ kg^{-1}}$; you may suppose that the water level in the reservoirs does not drop appreciably.)
d If the supply voltage were raised to 400 volts, would this alter the energy demand; the charge flowing; the flow of water? If so, by how much?

60 Treat this and question 61 as a pair, to be done together.

Some babies play in a 'bouncer'. This is a harness attached to a rubber cord hung from a door frame, and the baby is suspended so that his (or her) feet just brush the floor. They do actually seem to enjoy it, although it sounds, and looks, like an elaborate form of torture!
a Suppose a baby has a mass of 10 kg. What is its weight in newtons?
b This weight may stretch the elastic by 20 cm (0.2 metre). If the force exerted by the elastic were proportional to the amount it is stretched, what force would it exert when the baby has been attached to the unstretched elastic and then lowered by 2 cm (0.02 m)?
c What is the *average* force exerted by the elastic as the baby is gently lowered the full 20 cm?
d What is the energy stored in the elastic as the baby is lowered? (Use the average force, and the distance.)
e If the *greatest* force exerted is F and the *greatest* extension is x, what is the energy stored if the force is proportional to the extension?
f In fact, however, for rubber the proportionality assumption made above is wrong. The graph of force and extension will be as in figure 29. If the force at 20 cm is still 100 newtons, is the energy stored more, or less than that given by the answer to **e**? ($g = 10\ \mathrm{N\ kg^{-1}}$ approximately.)

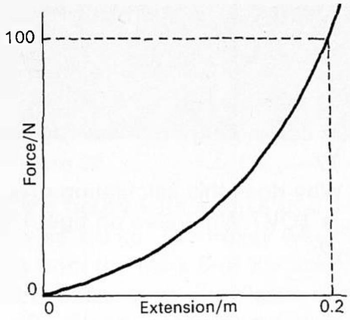


Figure 29

61 Electric charge is stored on a capacitor, and, as indicated in figure 30, at 20 V the charge stored is 0.2 C.

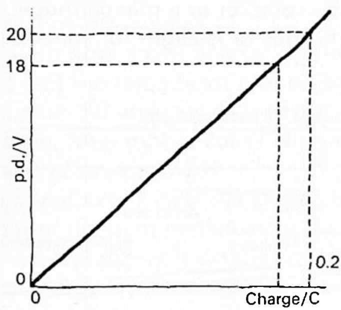


Figure 30

a What is the capacitance?
b If the p.d. across the capacitor fell to 18 V, how much charge would have flowed off the capacitor?
c During this small discharge, the p.d. was first a little above 19 V, then a little below. What energy was transformed? Shade, on a copy of figure 30, an area that represents this energy.

d If the p.d. now falls to 16 V, the same charge will flow. Will the energy transformed be the same? What will it be? (Take an average p.d. again.)
e The energy transformed as the capacitor discharges completely can be found by completing the following series: total energy = 0.02 (19+17+ . . .) J.
What is the total energy? Why does this calculation give the same answer as the formula $\frac{1}{2}QV$? What area on figure 30 represents this total energy?
($C = Q/V$.)

62 *a Calculate the energy that can be stored in a* 10 000 μF capacitor capable of being charged to a p.d. of 30 V.
b Describe one or more ways of storing or transforming about this amount of energy which would make its magnitude more real to someone – for example, energy stored in a weight held above the floor, in a catapult, or in a rifle cartridge, or transformed when a lamp flashes or is alight for some period of time.

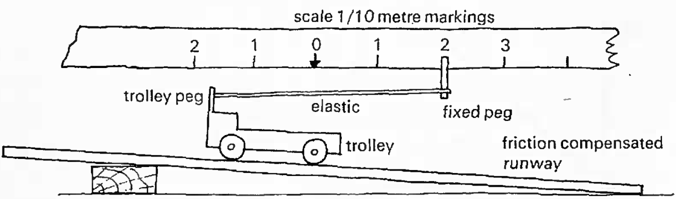


Figure 31

63 Figure 31 shows the apparatus with which the stroboscopic photograph (figure 32) was made. The photograph shows the distance scale marked in 1/10 m intervals and below it a series of 'glimpses', at 1/10 s intervals, of the peg attached to the trolley. An elastic cord was held at one end on a fixed peg (whose shadow obscures the righthand mark 2 on the scale) and at the other end by the peg on the trolley. The elastic was *just* taut when the trolley peg was below the *zero* mark on the scale. Then the trolley was pulled back so that its peg was below the lefthand mark 5: that is, half a metre extension of the elastic. At this point the elastic

Figure 32

pulled the trolley with a force of 0.44 N. The mass of the trolley was 1.0 kg. The trolley was then released from rest, starting from the mark 5 of the scale. As the trolley peg passed the zero mark, the elastic became slack and dropped off the fixed peg, so that there were now no forces on the trolley.

a From mark 5 to mark 0 the trolley accelerates. *Would you* expect *uniform* acceleration?

b *Measure the velocity of the trolley after the elastic has* stopped pulling and finds its kinetic energy.
(Kinetic energy $= \frac{1}{2} mv^2$.)

c Find out how much energy would have been stored in the elastic had the force been proportional to the extension.

d Compare the answers to **b** and **c**. Is the supposition made in **c** likely, for a rubber cord? How might the comparison of **b** and **c** be explained?

e (*Optional extra*) Find the kinetic energy of the trolley at a number of different distances to the left of the zero mark; that is, for several different extensions of the rubber. (Find the kinetic energy from the velocity close to that distance.) Now find the potential energy at each point. For this, you can use the fact that the total energy is constant, and is equal to the kinetic energy after the elastic goes slack, since there is then no potential energy. At all points, the total energy is the sum of potential and kinetic energy. Draw a graph of potential energy against extension of the elastic.

f (*Hard*) Has the curve of potential energy against extension roughly the shape you might expect?

64 The following extracts are taken from an article in a popular magazine *Good Words,* written in 1862 by Professors W. Thomson and P. G. Tait. It was one of the earliest statements of the principle of the conservation of energy which used the phrases kinetic energy and potential energy in the way we all now accept. For many years kinetic energy had been called *vis viva* ('living force') and confusion between 'force' and 'energy' was even more widespread than it is today.

A

Every one knows by experience what Force is. Our ideas are generally founded on the sensation of the effort required, say, to press or to move some mass of matter. In general, Force is defined as *that which produces, or tends to produce, motion.* Now if no motion be produced, the force which may have been exerted is absolutely lost. Hence the inconvenience and error of the phrase, 'Conservation of Force', which is very commonly applied to our present subject. Among the host of errors which are due to confounding Force with Energy, one of the most extraordinary was some time ago enunciated in a popular magazine in some form as this, 'The sum-total of the Forces in the Universe is Zero' – a statement meaningless if it be applied to Force in its literal sense, and untrue if it refers to Energy. This is one example of the errors we have undertaken to combat...

B

When an eight-day clock has been wound up, it is thereby enabled to go for a week in spite of friction and the resistance which the air at every instant offers to the pendulum. It has got what in scientific language we call a supply of *Energy.* In this case the energy simply consists in the fact of a mass of lead being suspended some four feet or so above the bottom of the clock-case. The mere fact of its being in that position gives it a power of 'doing work' which it would not possess if lying on the ground. This is called *Potential Energy.* It will evidently be just so much the greater as the weight is greater, and as the height through which it can fall is greater. Its amount is, therefore, proportional to the product of the weight and the height it has to fall, because such a product is doubled, as the energy is, by doubling either factor. Thus a weight of one pound with an available descent of forty feet, has the same amount of potential energy as ten pounds at four feet, eight pounds at five feet, or forty pounds at one foot.

C

There are two ways of raising a weight to a height: by a continuous application of force, as by a windlass, or by an almost instantaneous impulse, such as a blow from a cricket bat, or the action of gunpowder. A 64 lb shot, fired vertically from a gun loaded with an ordinary service charge of powder, would, if unresisted by the air, rise to about 35 000 feet, and if seized and secured at the highest point of its course, would possess there, in virtue of its position, a potential energy of 2 240 000 foot-pounds. When it left the gun it had none of this, but *it was moving at the rate of fifteen hundred feet per second.* It had *kinetic* or (as it has sometimes been called) actual energy. We prefer the first term, which indicates motion as the form in which the energy is displayed. Kinetic energy depends on motion; and observation shows that its amount in each case is calculable from the mass which moves and the velocity with which it moves. And this being understood, it is easy, by considering a very simple case, to find how it so depends. For, if a stone be thrown up with a velocity of 32 feet per second, it will rise to a height of nearly 16 feet; if thrown with *double* velocity, or 64 feet per second, it will rise *four* times as high, or to about $63\frac{1}{2}$ feet; if the velocity be *trebled*, it rises *nine* times as high, or to 143 feet, and so on. Hence, as we must measure the energy of a moving body by the height to which it will rise if its motion is directed vertically upwards, we find that we have to measure it by the *square* of the velocity. The recent tremendous performances of the 12-ton Armstrong gun form an admirable illustration of the same point, showing, as they do, that to penetrate a thick plate of iron mere *weight* of shot is comparatively unavailing – it must have great velocity; and, in fact, with double the velocity we get at once four times the penetrating or destructive power. By such facts as these, we are led to measure kinetic energy by the square of the velocity with which a body moves.

D

We may then express the relation between the forms of energy, in the case of a projectile unresisted by the air, by saying, *the sum of the potential and kinetic energies does not vary* during its flight. As it rises it gains potential energy, but its motion is slower, and thus kinetic energy is lost; – as it descends it continually loses potential energy, but gains velocity, and, therefore, kinetic energy. But what happens when it reaches the ground and comes to rest? Here it would appear to lose both its potential and kinetic energies. The first, indeed, is all gone just as the mass reaches the ground. To a superficial observer, the second might seem to be expended in bruising and displacing the bodies on which it impinges. But there is something more profound than this, as we shall presently see.

Paragraph A

a What confusion are Thomson and Tait attacking?
b Why do they say that if 'Force' means *'that which produces, or tends to produce motion'*, the statement 'the sum-total of the Forces in the Universe is Zero' is *meaningless*?
c They also imply that the statement, 'The sum-total of the energy in the Universe is zero' would be *untrue.* What would they consider to be a true variation of this statement?

Paragraph B

a How do Thomson and Tait explain the meaning they give to the phrase 'It has got . . . a supply of *Energy*'?
b Suggest two other forms of potential energy that could be used to illustrate this paragraph.

Paragraphs C *and* D

a What reason do Thomson and Tait give for supposing that a moving shot has energy?
b Thomson and Tait carefully calculate kinetic energy in such a way that the sum of kinetic energy and potential energy will automatically be constant. Therefore the law saying that the sum of kinetic energy and potential energy is constant is not a law of physics; it is just an expression of the way these things are calculated. What do you think?

c *Suppose paragraph C went on:*
'Some have supposed that the true measure of kinetic energy is the product of mass and velocity (*mv*) which is also called Momentum. This is false, because . . .'
Try to write some reasons which might be offered for thinking that *mv* is *not* equal to the kinetic energy. (There is no need to try to write in Thomson and Tait's style unless you find it fun to do so.)
d At the end of paragraph D, the energy of the projectile seems to vanish, but Thomson and Tait hint that it is still there in a 'profound' sense. Where is this energy?
e Thomson and Tait continue their article by describing a bowl of water, which is stirred round and round. When left alone, the motion stops and the energy 'vanishes'. They then suggest an experiment to show that the energy is 'really still there'. What experiment would you expect them to suggest?

Part Five

Electrons and energy levels

Questions 65 to 70 Electrons

$e = 1.6\times10^{-19}$ coulomb
$m = 9.1\times10^{-31}$ kilogramme

65 Find a book which gives a diagram and an explanation of the working of a cathode ray tube. It will no doubt mention electrons, but *if you knew nothing* about electrons, what might you guess about them just from the design of the tube? (Look, for example, at where the positive and negative connections go.)

66 A current of 1 μA passes through a thermionic diode. How many electrons hit the anode in
a one second?
b one millionth of a second?
c one million millionth of a second?
d Suggest a way of testing that such a current is carried by particles with a finite charge.

67 How fast is an electron going if it has an energy of
a one electronvolt?
b 100 electronvolts?
(*Kinetic energy* $= \frac{1}{2}mv^2$.)

68 Estimate the energy emitted from the screen of a television set. (Compare it with the brightness of a lamp of known power – preferably a fluorescent lamp.) If the electrons in the tube are accelerated by a p.d. of 20 kV, estimate the minimum current required to maintain the picture. How many electrons per second per square millimetre of the tube face does this give?

69 The results shown in table 6 were obtained with a Millikan apparatus, using oil drops. For each of several drops, the experimenter measured the potential difference across the plates (which were 4.42 mm apart) at which each charged drop was just held poised against the gravitational pull of the Earth. The weight of each drop was found by calculating it from the observed steady speed of fall in the air between the plates.

a Suppose an object with charge q lies between the plates and the plates have a potential difference V across them. How much energy would be transformed if the charge q moved from one plate to the other?

b Suppose the plates are a distance d apart, and a steady force F is exerted on the charge. How much energy would be transformed if an object were moved under force F from one plate to the other?

c If the pull F of the charged plates on the charge q balances the weight W of the drop, the drop will be held at rest. Express q in terms of W, V, and d.

d Find the charge on each drop in the results in table 6.

e Try to identify a basic charge e such that each charge q is some whole number multiple n of e. ($q = ne$.)

f Given that other experimenters have shown that q is always accurately a whole number multiple of $e = 1.6 \times 10^{-19}$ C, what do you think about the accuracy with which this experimenter was determining the balancing voltages and drop weights?

V p.d. to balance drop/V	W Weight of drop/N	q Charge on drop/C	n Multiple
470	5.05×10^{-14}		
820	5.90×10^{-14}		
230	3.35×10^{-14}		
770	2.85×10^{-14}		
1030	3.65×10^{-14}		
395	7.00×10^{-14}		

Table 6

70 In an experiment to show the force exerted by a beam of electrons (PSSC film, 'Momentum of electrons'), the beam was fired at a suspended vane and was switched on and off as the vane swung to and fro, so as to build up the swing of the vane, rather as one builds up the motion of a child on a swing by a series of short pushes.
The increase of the angle of swing of the vane for each burst of electrons was measured, giving a quantity proportional to the force exerted by the beam. This was done for two different beam currents at the same accelerating voltage, and for a different voltage, as shown in table 7.

	Proportional to force exerted by beam (arbitrary units)	**Electron gun accelerating voltage/V**	**Electron beam current/mA**
1	1.5	2500	200
2	0.86	2500	100
3	0.67	1250	120

Table 7

Questions **a**, **b**, and **c** concern results **1** and **2**.
a When the beam current was reduced from 200 mA to 100 mA, the p.d. staying at 2500 V, what happened to the number of electrons hitting the vane each second while the beam was on?
b How does the velocity of electrons in result **2** compare with that in result **1**?
c What should have happened to the force exerted by the beam when the current was halved?

Questions **d**, **e**, **f**, and **g** concern results **2** and **3**, in which the potential difference was reduced.
d By what factor has the energy of an electron been reduced when the potential difference is halved?
e By what factor has the velocity of an electron been reduced?
f Multiply the force 0.67 at 1250 V and 120 mA by 100/120 to find the force there would have been for a current of 100 mA, as in the second result, at 1250 V.
g Use the above answers to explain why the force calculated in **f** should be $\sqrt{2}$ times smaller than the force 0.86 in result **2**.

Questions 71 to 77 Dynamics (momentum)

71 *For discussion*
A distinguished Cambridge physicist, interested in the way some fish propel themselves by water jets, made a bet with some doubting colleagues. He proposed to propel a punt (a long flat-bottomed boat) by dipping and filling a bucket at the front end, walking to the back end, and pouring (not throwing) the water back into the river. His colleagues bet him that this would not move the punt forward, so they decided to settle the bet by an actual trial. Who do you think won the bet, and why? (*Hint:* think about changes of momentum.)

Questions 72 and 73 take you step by step through arguments about conservation of momentum.

72 Two rail trucks, each of mass m, travel towards each other, each going at velocity v_1, on a smooth, level track.
a How much momentum has each truck?
b How much momentum has the pair of trucks? (*Not* $2mv_1$.)
c How much kinetic energy has each truck?
d How much kinetic energy has the pair of trucks?
e The trucks collide, and are at rest for a moment before they spring apart each with velocity v_2. How much momentum has the system of two trucks when they are momentarily at rest?

f How much energy has the system of two trucks and the near surroundings at the moment the trucks are at rest? Why the phrase, 'and the near surroundings . . .'?
g Why must the velocities (v_2) of both trucks after collision be the same, if the track is smooth?
h Why cannot the velocities v_2 be larger than v_1 unless there are some special circumstances not mentioned above . . .? Can you think what the special circumstances would be?
i If the trucks (on another occasion) stuck together, what would their common velocity have to be if they started off in the same way?
j In this second try, would their combined momentum alter on collision?
k Would their kinetic energy now alter? What would happen to their *total* energy? Explain.
l *One* truck now hits a buffer fixed to the track and stops. Has the truck less momentum after hitting the buffer than before? What has happened to this momentum? (Think of the truck running into a massive train.) Has the truck less kinetic energy than before the impact? What about the total energy of truck and surroundings?
m Write a few sentences pointing out the difference between kinetic energy and momentum. (Imagine that a friend of your own age in another school wants a short statement from you because he is having an argument with his class and teacher.)

73 A vehicle A of mass 0.1 kg moves to the right along an air track at a steady velocity of 3.0 m s^{-1}. Ahead of it, also moving to the right, but at 1.5 m s^{-1} (figure 33) is a vehicle B of mass 0.05 kg.

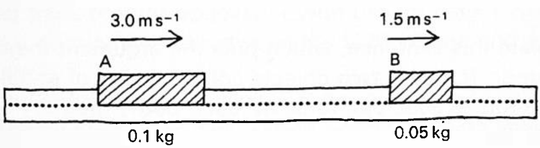


Figure 33

a What is the momentum of vehicle A?
b What is the momentum of vehicle B?
c What is the total momentum of A and B?
d What would the answer to **c** be if B were moving to the left?

Vehicle A now overtakes B and sticks to it, and they move off together to the right at a velocity observed to be 2.5 $m\ s^{-1}$.
e What is the new momentum of vehicle A?
By how much has the momentum of A changed? (Is it an increase or a decrease?)
f What is the new momentum of B?
By how much has the momentum of B changed? (Is it an increase or a decrease?)
g What is the new total momentum of A and B?
h Look at the answers to **e** and **f**. What can you say about the changes of momentum of the two vehicles? (Two things.)
i Suppose the collision took 0.1 second. What is the average rate of change of momentum of A? What average force on A would cause such a rate of change of momentum? In which direction (to left or right) would it have to act?
j Write down (without further calculation) the average force needed to change the momentum of B by the observed amount in 0.1 second. In which direction would the force act?

Figure 34

k On a copy of figure 34 draw arrows, labelled F_A and F_B, showing the directions of the forces on A and B as they collide.
l Complete this sentence, which puts the argument the other way round: 'If, when two objects collide, a pair of equal and opposite forces acts, one force on each body, then . . .' (Discuss the changes in momentum.)

74 *For discussion*
Question 73 was about the relation between changes of momentum and Newton's Third Law of Motion. Question 74 is about difficulties you may have in thinking about the Third Law.

a Find out what the Third Law says, from a textbook. If the statement mentions 'action' and 'reaction', say what you think these words mean. Try re-wording the law using a phrase like 'a pair of equal and opposite forces'.

b A freely falling weight is acted on by a force W, the gravitational pull of the Earth. According to Newton's law there should be another force, also equal to W, in the opposite direction. If there is, on what body does it act?

c (*Hard*) Now criticize this statement:
'A falling body is continually gaining momentum, so violating the law of conservation of momentum.'

d (*Hard*) What about this statement?
'A train starts from rest – momentum zero – and speeds up, gaining momentum. So momentum is *not* conserved, there being more of it when the train is moving than when it is at rest.'

e (*Hard*) If you like, try this argument with a donkey on your friends. 'Gee up!' said the driver. 'No' said the donkey, giving as his reason: 'If I pull the cart forward, it will pull backwards with exactly the same force and we shan't get anywhere.'
What can the driver answer, apart from 'A little knowledge is a dangerous thing'?

75 **a** A football hits another the same size which was lying on the ground. It hits it exactly in the middle. If the collision is very nearly elastic, what happens? (Try a similar collision on an air track or with trolleys, or with billiard balls.) How is the kinetic energy shared between the balls before and after the impact?

b An elephant on roller skates slides along and hits a stationary ping-pong ball, which bounces off its head elastically. Where is most of the energy before the collision? Where is most of the energy after the collision?

c A very light electron hits a gas atom which is at rest and is, say, 10 000 times more massive than the electron. If the electron rebounds elastically and the collision is 'head on', what, approximately, is the ratio of the velocities of the electron and the gas atom after collision? What, approximately, is the ratio of their kinetic energies? Has the electron 'lost' energy appreciably?

76 A space-ship has a total mass of 10^5 kg and is propelled by a jet of protons which have been accelerated by a potential difference of 10^7 V. The current carried by the jet is 1 A. What is the acceleration of the space-ship and how much hydrogen will it need to increase its speed by 1 kilometre per second? How much charge would have been carried away?

There is something gravely wrong with this as a practical proposal, as it stands. Suggest what is wrong, and offer a cure. (Proton charge = 1.6×10^{-19} C;
mass of proton = 1.7×10^{-27} kg.)

77 Discuss the feasibility of an electron gun as a device for propelling space-ships (in regions well away from planets or stars).

Questions 78 to 80 Ionization and energy level experiments

78 The p.d. between two large parallel conducting plates (figure 35) is 1000 V, and they are 10 mm apart. The gap contains a gas whose molecules can be ionized if they are struck by an electron of energy at least 20 electronvolts, but not by electrons with less energy.

Suppose there are so many gas molecules that an electron travels on average 0.01 mm between collisions.

a How much energy can an electron gain in travelling this distance?

b If there are always a few free electrons in the space, how far must the electrons travel between collisions if the gas is just to begin conducting rather better?

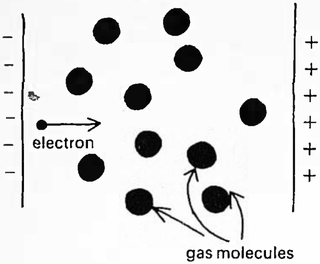


Figure 35

c (*Harder*) To allow the electrons space to travel and gain energy, the gas pressure must be reduced. Figure 36 shows the current through the gas rising just as ionization starts.
If the pressure is reduced even more, what would you expect to happen? (How many molecules can be hit?) Complete the low pressure end of the graph.

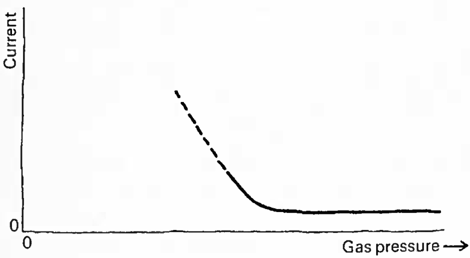


Figure 36

79 In the section 'The experimental evidence for the existence of energy levels in atoms', there are selections from the papers of three investigators. This question is about the first experiment, in the paper by McMillen.
Look carefully at the diagram of the apparatus (reproduced in figure 37) and read McMillen's account of it (pages 96 to 99).

a The electron gun A sends a stream of electrons into the space B. The paper mentions trouble with slow electrons. Why does the energy of the electrons have to be controlled precisely?

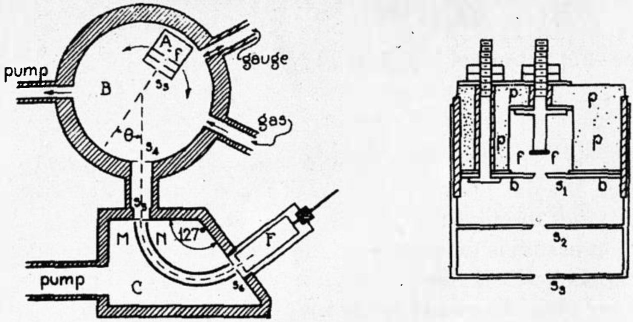


Fig. 1. Diagram of apparatus.

Figure 37
From McMillen, J. H. (1930) *'Angle and energy distribution of electrons scattered by helium, argon and hydrogen',* Physical Review, **36**, 1034.

b If there were no gas in the space B, would any electrons reach the lower space C through slits s_4 and s_5? What gas *is* in B?

c An electron might 'bounce' *elastically* off a gas atom and pass through slits s_4 and s_5 into the space between curved plates M and N in C. If the gun were accelerating electrons with 50 volts p.d., what energy (electronvolts) would such an electron have after collision?

d This electron might make an *inelastic* collision with a gas atom, lose 20 electronvolts energy to the gas atom, and arrive in C without further collisions. How much energy would it have, as it came into the space C?

e The *curved* plates, M and N, are there so that a p.d. between them will pull electrons of a certain energy round and into the collecting electrode F. Why is the upper plate made *positive*?

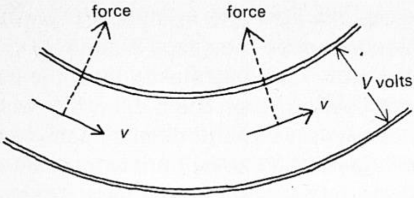


Figure 38

f The force on an electron at any point along the centre line between the curved plates is the same, proportional to the p.d. V across the plates and directed along the radius of the curve at that point (figure 38). Can you show that, as is said in the paper, the p.d. across the plates is proportional to the energy of electrons that just travel round the centre line between the plates?

(force towards centre $= \dfrac{mv^2}{r}$; kinetic energy $= \frac{1}{2}mv^2$.)

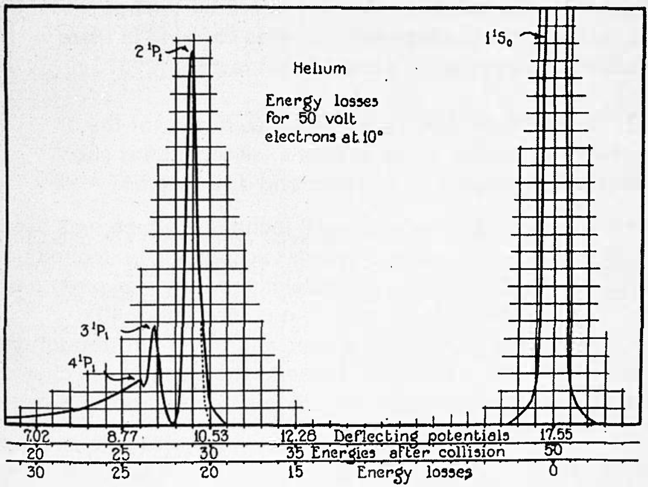


Fig. 2. Energy losses in helium for 50 volt electrons simultaneously deflected at 10°.

Figure 39
From McMillen, J. H. (1930).

g Why is the space between the curved plates in C pumped out to a very high vacuum, while the space B is not?
h The peaks on the graph in figure 39 (taken from the paper) show the large current flowing when the p.d. on the 'velocity selector' curved plates was set so as to detect electrons of each of a series of energies. The lowest horizontal scale shows the *energy loss* of electrons passing into the velocity selector or 'analysing chamber'.
The peak at the right is of electrons with 50 electronvolts energy, having lost no energy. What kind of collisions have these made in B?
i There are no electrons detected which have lost energies between 0 and 20 electronvolts. What kind of collision do you think an electron which has an energy of 15 electronvolts would make with a helium atom?
j Suppose it were said that the experiment suggests that, 'Helium atoms have a first energy level about 21 electronvolts above their lowest energy state, and no energy levels between these, but some energy levels at values of around 23 and 24 electronvolts.' What is meant by 'energy level'? Do you regard the statement above as correct? Is there evidence for each point made? What is it?

80 The section 'The experimental evidence for the existence of energy levels in atoms' also contains short extracts from papers by G. Hertz and J. C. Morris.

Hertz pioneered the experimental technique which was used by Morris in experiments of greater accuracy. The technique is quite simple. Electrons are accelerated by a measured p.d. into a gauze chamber containing gas (see figure 40).
Some may collide with gas atoms, and travel out through the sides of the gauze chamber. Close to the sides of the chamber is a collecting plate, and a current is detected from this plate if electrons reach it.

Now suppose electrons colliding with gas atoms happen to lose nearly all their energy. They can still travel slowly from the gauze chamber to the collecting plate if these have no p.d. between them, and a current is detected. But suppose a small p.d. is switched on between the plate and the gauze, the plate being the more negative. Now electrons may not have enough energy to reach the plate, and the plate current will show a large drop. Large *changes* of plate current when the small detecting p.d. is switched on are the signal that electrons are losing just about all their energy on collision with atoms in the chamber.

The following questions consider a numerical example of the process described above.

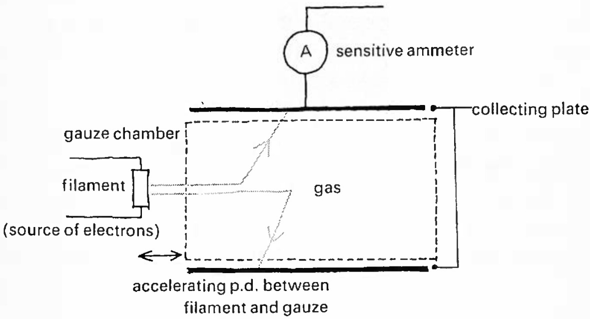


Figure 40

a Suppose the gas atoms have an energy level at 4.0 electronvolts and no lower level except the lowest state of all. If they are bombarded with electrons of energy 3.9 electron-volts, can any of these electrons lose energy on collision? What energy will they have after collision? (Suppose that the gas atoms are very massive.)
b Suppose a reverse voltage of 0.1 volt is switched between the gauze chamber and the collecting plate. Will the bombarding electrons have enough energy to cross the space to the plate? Will there be a change in the plate current when the detecting p.d. is switched on?

c The bombarding electrons now have energy 4.05 electron-volts. Can any lose energy on collision with gas atoms? What is the least energy they can have after collision?
d The detecting p.d. of 0.1 volt is again switched on. Will the electrons with least energy now be able to cross the gap to the plate? Will there be a change in the plate current when the detecting p.d. is switched on?
e Now the bombarding electrons are given energy 4.15 electronvolts. Go through the argument again. Will the plate current change when the detecting p.d. is switched on?
f Sketch the graph changes in plate current when the detecting p.d. is switched on or off, as the accelerating p.d. is varied through 4.0 volts. How would you recognize the presence of another energy loss by the bombarding electrons?

Answers

1 Your list might mention connecting ammeters in series with the resistor under test but connecting voltmeters across it; trying a high current range of an ammeter before a low current range (or a less sensitive meter before a more sensitive one); noting a need to check the resistance of the voltmeter when the resistor proves to have a high value; noting a need to beware of the ammeter resistance when the resistor proves to have a low value. A 10 V supply across a 10 Ω resistor could dissipate 10 W in the resistor and overheat it, so the supply p.d. would have to be considered carefully.

2 You could mention suitable shapes into which to form the paste, depending on whether it proved to conduct well or poorly, as shown by rough initial tests. The resistivity would be worth measuring. There are many other things you might think of: changes as the paste sets, changes with age, changes with temperature, or changes with surface moisture being some of them. You should indicate what sort of apparatus you would use, what ranges of p.d. and current you might try, and whether any changes might be expected to be large or small.

3 It is valuable to be able to make rough guesses, and they can be made in many ways. You might think that the resistance would be mostly in the surface moisture on the body, and estimate the surface's resistance from a knowledge of the current passed by a solution. You could set a lower limit on the resistance by noting that a torch bulb doesn't light when in series with a human body and a dry cell, though the neon lamp in a mains testing screwdriver may do so.

You could set an upper limit by noting that the charges (about 10^{-8} C) on charged balls, electroscopes, and so on (at about 10^3 V) are always discharged through the body in a time too short to observe easily.

4 The resistance of *a* is larger than the resistance of *b* and both seem to be linear components, obeying Ohm's Law. *c* might be a diode, and it changes its resistance when the p.d. is reversed. *d* could be a filament lamp, for its resistance increases as the current increases. Initially, *d* conducts better than any of the others. You could also compare the forward and reverse resistances of *c* with the resistances of *a* and *b*.

5 a Only graph *b* obeys Ohm's Law as stated. Graph *a* is linear, but there is a current when there is zero p.d. applied (perhaps the component included a source of p.d.). *c* shows a constant current, not a constant rate of change of current with change of p.d. Graph *d* is non-linear, though it might be said to obey Ohm's Law for voltages in one direction only.
b Yes. A graph of current against voltage is a straight line through the origin. Alternatively, equal increases in current go with equal increases in voltage. The resistance, at 2.0 mA and at all other currents given, is $14.5 \times 10^3\ \Omega$.
c The answers here are partly matters of opinion. Certainly Ohm's Law is not applicable to all objects that conduct, but it does compactly describe the behaviour of some. Suggestion **3** avoids trouble by defining it away; sometimes physicists do this, but in this particular case they usually speak of 'ohmic' or 'linear' materials. **4** is wrong, for Ohm's Law requires the current-voltage graph to pass through the origin and a small section of a curve, though nearly straight, will not project back to the origin. Whether Ohm's Law is important and general enough to count as a law is a matter of opinion. It does not rank with those 'Laws of Physics' to which we know no exception (give an example).

6 a 2 A.
b 4 A.
c 6 A.
d 2 Ω.

7 a V/r_1.
b V/r_2.
c $V/r_1 + V/r_2$.
d V/R.
e Because $V/r_1 + V/r_2$ is the current through r_1 and r_2, while V/R is the current through R.
f $1/R = 1/r_1 + 1/r_2$.
g No.

8 1.6 A.

9 For the same length and resistance, the aluminium power line needs to have a cross-sectional area 1.6 times greater than the copper line. The volume of aluminium is 1.6 times greater than the volume of copper; its mass is smaller by a factor 3.2/1.6, so its cost would be half as much. Because the line is lighter, the pylons and insulators that support it can be built more cheaply, unless the extra thickness leads to problems of larger forces on the line in high winds. You may be able to think of other advantages and disadvantages.

10 a Their resistivities rise in constant ratio.
b The logarithm to base ten of the resistivity.
c More than 10^{20} km, over ten million light years; further from us than the nearest galaxy.

11 Notice that the question says *might* apply, not *does* apply.
a X will if any do; you might argue for Y on the grounds that even a tiny current could represent a flow of electrons.
b Z.
c Y or Z because resistivity falls with rise in temperature.
d X because resistivity rises with temperature.
e Y, identifying X with metals and Z with insulators.
f Z.
g Y, excluding graphite.
h Z.
i X.

12 Your answer should have included the effect of surface moisture. You may have thought of other reasons.

13 Include among your reasons: resistivity 10^{12} Ω m or more; resistivity not to fall much when hot; not to melt, soften, or be decomposed when hot. The material needs to end up in a thin sheet but it could possibly be poured into place to set later, as long as this does not conflict with the requirements above. The trouble is that good electrical insulators usually don't conduct heat well, which is why the insulating layer must be thin.

14 Current passing leads to warming up, reducing the resistance, which leads to more current passing. A resistor in series can help, and you should be able to explain why.

15 V_1 is about 20 V.
V_2 is not in the range shown, for the current does not rise with temperature at fixed voltage in the range covered by the graphs.

16 This question is about extracting information by intelligent reading and thinking. Faraday's new fact was a fact about lead chloride, though he writes as if he saw it in a more general way. His 'law' cannot have been meant too seriously, but he is seeing whether there is a range of materials which start to conduct when they melt.

17 a 500; 10000.
b West, 1.6 A.

18 a 16×10^{-2} C.
b 10^{18} particles.
c 6×10^{22} particles per metre.
d $1 / (6 \times 10^4)$ metre.
e Just over 10^{-6} metre per second.

19 a It.
b It/q.
c An.
d It/Anq.
e $v = 1/Anq$ (the time t cancels).
f Reducing n raises v; fewer particles have to go faster. Reducing q raises v; each carries less charge, so they must go faster to convey the same total.
No particle has ever been found with a charge less than that on an electron or proton (though at the time of writing some people are looking for "quarks', particles expected to have charge $\frac{1}{3}$ or $\frac{2}{3}$ of the electron charge).
A molar solution is strong, but can often be made, and contains 6×10^{23} solute molecules in one litre, and so 6×10^{26} molecules in one cubic metre. If every molecule provides an ion, there will be 6×10^{26} ions in each cubic metre. Water molecules are not by any means all dissociated into ions in very pure water while, say, paraffin would contain almost no ions.

20 a $I/A = V/AR$.
b $I/A = V/\rho L$.
c 5.9×10^{7} A m^{-2}; current in 1 mm^2 wire is 59 A.
d $v = 3.7 \times 10^{26}/n$.
e 8.5×10^{28} atoms, or electrons, per cubic metre.
f About 4 millimetres per second.
(Answers above are given to two significant figures only.)

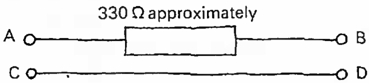
21 a It does not have to pile up if the charges in B move . . . (continue).
b No.
c Yes.
d Not if both are copper.

22 See answers to questions 18 and 19. The rest of the question asks for sensible guesses. You will probably show that rough estimates cannot tell whether there is spare capacity, for it is likely that any difference between use and capacity is small.

For any given mode of transport, the number of roads needed and the area occupied at work increase directly in proportion to the commuting population. But the roads have to enter the perimeter of the working area, which increases only as the square root of the area, and so as the square root of the population. There must come some size of commuting population which is too big to travel into its work area!

23 Either would do. The parallel arrangement is more usual. To test, remove one lamp.

24 **a** A is connected electrically to B, B is not connected to D (unless by a very high resistance). A may or may not be connected to C (or to D).
b The effective resistance between A and B has 1.5 V across it when a current of (4.5/100) A passes, and is thus just over 330 Ω.
c The effective resistance between A and B is just over 330 Ω, in agreement with **a** and **b**.
d If there were resistors connected between A and C or between B and D, the meter would read more than 18 mA (but **a** suggested that B and D were not connected).
e If A and C were connected, the meter would give a reading when the switch was open. So they are not. The 18 mA reading when the switch is closed confirms earlier suggestions that the circuit is:



25 There are many possible answers. If the meters are in series, one is wrongly marked. They could be in parallel if both are correctly marked. If they are in parallel, the more sensitive meter probably has a resistor in series with it. And so on.

26 a Yes.
b This we leave to you. The debate once really happened!

27 Clearly you need a battery and a resistance to protect the meter. The zero resistance mark will be at the high current end of the scale, and equal resistance marks won't be equally spaced. You should be able to see how the spacing will vary, and also give fuller design details, including a reason why the largest resistance the meter will measure is much less than one megohm.

28 a You may have guessed from an average current delivered by a cell and its (rough) lifetime; from a knowledge of energies in typical reactions and the size of a cell; or in some other way.
b You need to find the mass and speed of a train, and to use $\frac{1}{2}mv^2$ for the kinetic energy. You might allow quite a lot extra for inefficiency.
c Energy more than 2×10^8 J with no losses allowed for at all. A current of 100 A at a p.d. of 20 000 V cannot deliver such energy in under 100 seconds.

29 0.42 A approximately. The probable wiring is as in figure 41.

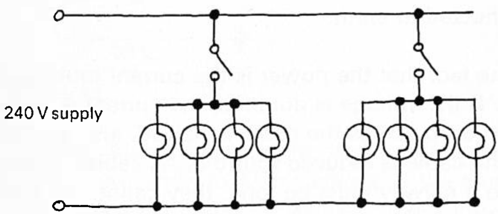


Figure 41

Total current, 8×0.42 A. If one lamp burns out, 7×0.42 A.

30 **a** The resistance of the cable is 0.4 Ω, so the generator resistance is negligible. At 32 A, the p.d. across the cable is 12.8 V.
b Circuit *1* is a good way to ruin a battery. Circuits *2* and *3* don't help him, though whether the battery is affected depends on whether one cable is earthed at the generator. Circuit *4* would add 12 V to the supply voltage, but if the cooker is in use, the charge in the battery only lasts about three hours. Circuit *5* avoids this because the cooker current does not pass through the battery, but when the cooker is off the lamp is over-run and won't have so long a life.
c,d The advantage of a ring is that current can flow either way around it, so that the cable need not be so thick.

31 The current is limited to a value which cannot harm you even if it passes through your body. You can calculate the resistor needed to limit a 240 V supply to such a current, but a current of this size wouldn't be much use for anything that is usually connected to a mains socket.

32 1 Ω. You should find, and perhaps be able to prove, that the power delivered has a maximum value when R is 1 Ω, when it is equal to the internal resistance.

33 The essential point is that the fuse must blow if the live wire is connected to earth.

34 Use the fact that the power is the current multiplied by the voltage. If the voltage is doubled, the current is halved, the potential drop across the cable is halved, and the power wasted in the cable is reduced fourfold. As cables to supply electricity to a railway must be long, they cannot be allowed to be very thick, or they would be very expensive.
a 1000 A.
b 100 A.
c 100 times.
d 100 times

35 **a** It is linearly wound; resistance proportional to length along it.
b No. A low resistance voltmeter could read lower (explain why).
c Approximately (explain why).
d The cell voltage is not exactly equal to that across the lower part of the potentiometer, either or both not being quite 1.1 V.
e The cell has been connected the 'wrong' way round.

36 It is not possible that a single cell could deliver enough energy to melt the contents of a box of this size, but such a box could contain enough material to melt it if the current from the cell triggered off a reaction.
The answers follow from this fact about orders of magnitude, and **c** is a sensible suggestion.

37 **a, b** See figure 42.

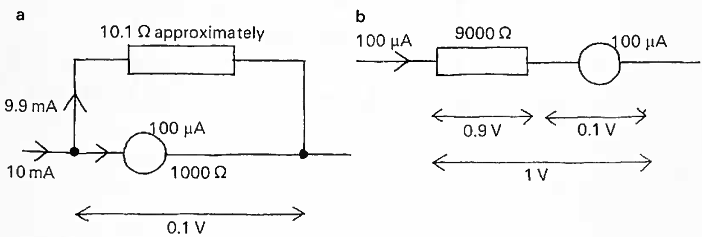


Figure 42

38 Bob and Alan are both right, the best way being that which gives least error. In Alan's circuit, *a*, the ammeter will read about twice the current it would show if the voltmeter were removed. In Bob's circuit *b* the voltage across the resistor is only about 10 per cent less than the voltmeter reading. So *b* is best here.

39 This is not the kind of question we can answer for you. It is well worth while getting to know the meters in your laboratory. It is also worth while to improve your ability in guessing rough values: scientists need to do it very often.

40 Here is a design problem. You should judge your answer not by whether it is 'right' or not, but by whether you have put forward sensible ideas linked together in a sensible way.

41 **a** A sharp rise at 8 a.m.; steady at 2 A for 10 hours; sharp drop at 6 p.m.
b 72 000 C.
c See figure 43 *a*.
d See figure 43 *b*.

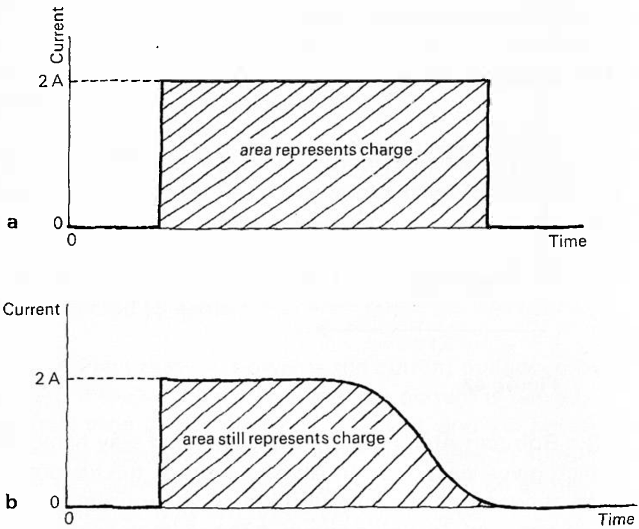


Figure 43

42 The current will go on decreasing, but need never fall to zero.

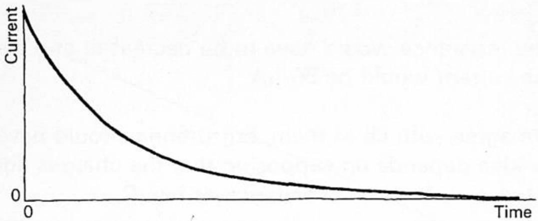


Figure 44

More current leads to a higher temperature, which leads to more current . . . There may be a 'run-away'.

43 **a** 2 divisions, to right.
b 2 divisions, to right.
c More than 2 divisions, to left.
d More than 2 divisions, to right.

44 **a** 2.
b See figure 45.

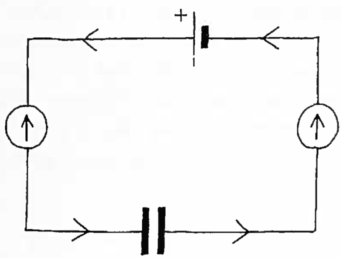


Figure 45

c The meter readings always fall to zero in the end.
d 4.
e Describe how the plates acquire charge, one positive, one negative. The charge on one plate is the size of the charge that flows all round the circuit, the charges on the plates being equal but opposite.

45 a 1 mA.
b 0.01 C.
c 0.01 F.

46 The resistance would have to be decreased at a steady rate. The current would be 50 μA.

47 We agree with all of them, but Brenda should have said that her idea depends on supposing that the charges add up. C_2 has twice as large a capacitance as has C_1.

48 These are more estimating or guessing questions. For example, **a** could be 100 pF, comparing the falling man with the sphere. For **b** the capacitance between shoes and floor usually outweighs that of the rest of the body. **c** requires a guess of the height of a house. **d** you might estimate from the telephone wire data and the coaxial cable data, and **e** you might obtain from the coaxial cable data or the parallel plate data.

49 **a** When the diaphragm bulges, there is as much more water on one side as there is less on the other. When a capacitor is charged, there is as much extra positive charge on one plate as there is missing on the other. If the pump were removed and a pipe substituted, the extra water would flow round the circuit. If a capacitor is connected to a wire, the extra charge on one plate flows round to the other. No water enters or leaves the system as a whole. No charge is created or destroyed in a capacitor circuit. The analogy is rather good.
b Yes (say how).
c Make the diaphragm easier to stretch.
d Pressure differences across tank, corresponding to p.d., and amount of extra water in one side (and equal amount less in the other side) corresponding to charge.

50 a See figure 46 *a*.
b See figure 46 *b*.
c See figure 46 *c*.

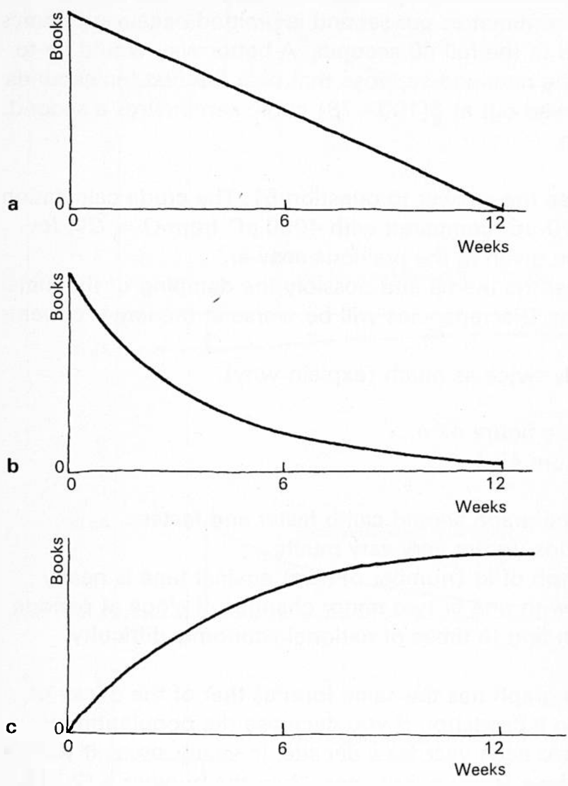


Figure 46

51 There are several possible answers. $10(100+78+61+\ldots+13)+540 = 4470$ cubic centimetres is too big, for the water is assumed to flow out for ten-second intervals as fast as it was flowing at the start of such an interval. The rate 10 cubic centimetres per second is omitted because it comes at the end of the full 80 seconds. A better way would be to average the rate, and suppose that over the *first ten seconds* water flowed out at $\frac{1}{2}(100+78)$ cubic centimetres a second, and so on.

52 a See the answer to question 51. The crude calculation gives 4470 μC, compared with 4000 μC from $Q = CV$, for the reason given in the previous answer.
b Consider the inertia and possibly the damping of the meter movement. Discrepancies will be worse at the larger currents (why?).
c Roughly twice as much (explain why).

53 a See figure 47 *a*.
b See figure 47 *b*.

54 a The graph should climb faster and faster.
b The ratios do not vary very much.
c The graph of lg (number of cars) against time is nearly straight, with one or two minor changes of slope at periods corresponding to times of national economic difficulty.

55 The graph has the same form as that of the decay of charge on a capacitor. If you decrease the population by 10 per cent each year for a decade, in yearly steps, it will be reduced by a factor a little more than the number e (2.718 . . .) in a decade. (If the population falls smoothly all the time at a similarly changing rate, it will be reduced by exactly a factor e in this period.)

56 The charge is 10 C. The product CR must not be more than about 10^{-3} s, so C must be less than 5×10^{-3} F. Thus the p.d. needed exceeds 2000 V.

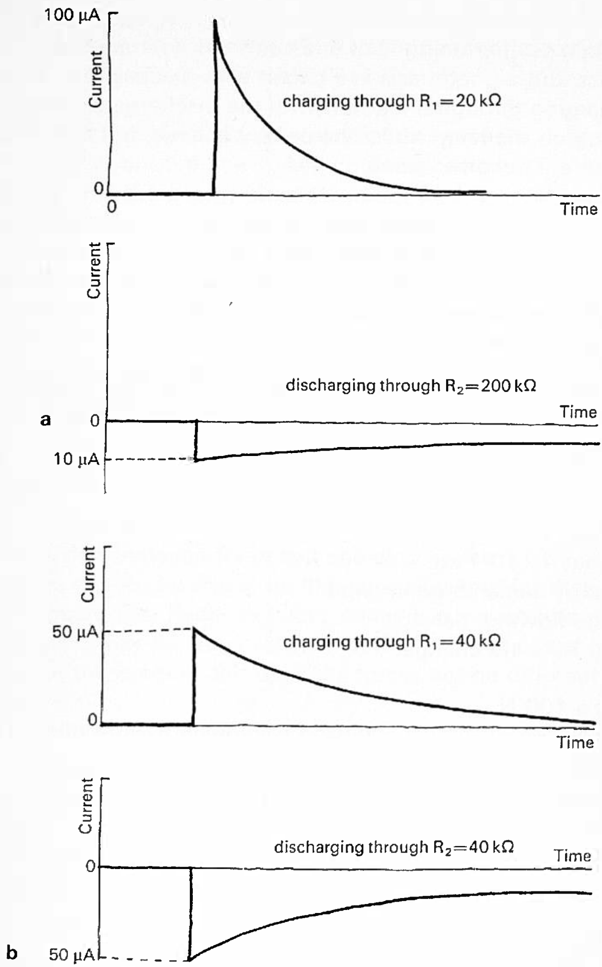

100 µA
Current
charging through R₁=20 kΩ
0
0
Time
Current
discharging through R₂=200 kΩ
Time
a
0
10 µA
Current
50 µA
charging through R₁=40 kΩ
0
Time
Current
discharging through R₂=40 kΩ
Time
0
b
50 µA

Figure 47

57 Many circuits are possible, and you may see further possibilities after doing Unit 6, *Electronics and reactive circuits*. But a good basis is a circuit with a capacitor discharging through a resistor, with the discharge circuit holding on the relay whilst the current is large, but not when the current becomes small.

58 You have to supply your own guesses of the appropriate quantities. The steady force needed can be found by equating the work (force multiplied by distance) to the kinetic energy. The current I, flowing for time t, at a p.d. V, can be found from: energy transformed electrically $= IVt$.

Because the electrical catapult is bound to be inefficient, the value of I found by equating this to the kinetic energy is only a lower limit.

59 **a** 216×10^{11} J, say 2×10^{13} J.
b About 10^{11} C.
c About 4×10^{11} kg.
d Energy demand: no change.
Charge flowing: halved.
Water flow: no change.

60 **a** 100 N.
b 10 N.
c 50 N.
d 10 J.
e $\frac{1}{2}Fx$.
f Less.

61 **a** 0.01 F.
b 0.02 C.
c 19×0.02 J.
d 17×0.02 J.
e 2 J.
You should be able to see that the area below the graph, $\frac{1}{2}QV$, gives the same as $0.02(19+17+ \ldots 3+1)$.

62 a 4.5 J.
b Of many possible answers, one might be lifting a loaded teatray (mass 5 kg) off a table (lift it 0.1 m).

63 a No. The tension in the elastic is continually decreasing.
b Velocity about 0.4 m s^{-1}, kinetic energy about 0.08 J.
c Using $\frac{1}{2}Fx$, the energy stored is about 0.11 J.
d The calculation of energy stored gives a larger value than the actual kinetic energy found, partly because some energy is dissipated in friction and partly because, for elastic, the force is not proportional to the extension (see question 60).
e, f If the force F were proportional to extension x, so that $F = kx$, then the energy $\frac{1}{2}Fx$ would be $\frac{1}{2}kx^2$. The graph of potential energy against extension would be a parabola.

64 The answers to the questions are to be found in the passage. The following brief notes outline answers.

Paragraph A
a Confusion between force and energy.
b Forces cannot be added up like bags of sugar, for they are vector quantities. Because forces come in equal and opposite pairs, there may be some sense in saying that their total is zero, but these equal and opposite forces act on different bodies.
c The sum total of energy is constant.

Paragraph B
a A weight has been raised, and can now fall, transforming energy.
b There are many examples: energy stored in a wound up spring or in a deep reservoir, for instance.

Paragraphs C *and* D
a They say that it has energy because it can rise to some height above the ground without further help.
b Probably a fair view, though the calculation of $\frac{1}{2}mv^2$ for kinetic energy depends on Newton's laws, which themselves can be subject to some experimental tests. There is still room for disagreement among physicists as to whether the conservation of energy is more than book-keeping. See Rogers, *Physics for the inquiring mind,* Chapter 26.

c Momentum is a vector quantity, energy is scalar; momentum is related to force multiplied by time, energy to force multiplied by distance.
d The energy is now spread among the molecules in the ground near the impact and among those in the shot, both of which objects are warmer than they were.
e Putting a very sensitive thermometer in the water.

65 Some things you might guess, on the evidence of the tube construction, would be:

that electrons are charged
the sign of the charge
that they have mass (deflection in curved paths)
that they are emitted from some heated materials.

You could not tell that their charge comes in lumps of the same size, or indeed that a beam of electrons consists of particles rather than a smooth stream of material. There is a vacuum in the tube, so presumably electrons would be deflected by collisions with gas molecules. You also know, from the design, that electrons can make some substances glow when they strike them.

66 **a** Approximately 6×10^{12} electrons.
b Approximately 6×10^{6} electrons.
c Approximately 6 electrons.
d If one could observe over a short enough time, perhaps one could count individual electrons as they arrive. This would need a detection method, perhaps a fluorescent screen. More practically, small currents in a diode should show random fluctuations (one would not expect to get 6 electrons in each interval in **c** every time, though that would be the average). In fact, such fluctuations can be observed without great difficulty by placing a resistor in series with the diode and observing the fluctuating p.d. across it as the current through it fluctuates. An oscilloscope, rather than a meter, must be used because it is essential to 'watch' fluctuations over short periods of time.

67 a 6×10^5 m s^{-1} approximately.
b 60×10^5 m s^{-1} approximately.
(Note that for larger potential differences, the velocity will soon approach the velocity of light, and that the kinetic energy will no longer be given by $\frac{1}{2}mv^2$, but by a new equation from relativity.)

68 The current is the ratio of power to potential difference (energy per coulomb). Notice that the number of electrons per square millimetre of screen is large; were it small, it might be possible to see random fluctuations in the brightness as the number of electrons arriving in a short time fluctuated (see question 66). One of us guessed: power 10 W, current 5×10^{-4} A, equal to 3×10^{15} electrons per second, area 10^5 mm^2, 3×10^{10} electrons per second per square millimetre.

69 a qV.
b Fd.
c $qV = Fd$. If $F = W$, then $q = \frac{Wd}{V}$.
d See table 8.

V **p.d. to balance drop/V**	q **Charge on drop /Coulomb**	n **Multiple**
470	4.75×10^{-19}	3
820	3.18×10^{-19}	2
230	6.44×10^{-19}	4
770	1.64×10^{-19}	1
1030	1.57×10^{-19}	1
395	7.83×10^{-19}	5

Table 8

e Basic charge e about 1.6×10^{-19} C.
f The accuracy could be assessed by seeing how close to whole numbers are the ratios of the charges q to the average of the values of e found by taking each multiple to be an exact whole number.

70 **a** It was halved.
b It is the same.
c It should have been halved. The measured force is not exactly halved, but the discrepancy can be accounted for by the uncertainties in the results. The forces are very small and hard to measure accurately.
d It has been halved.
e A factor $\sqrt{2}$.
f Nearly 0.56.
g $0.86/0.56 = 1.5$ approximately, while $\sqrt{2} = 1.4$ approximately. At the same current, but with half the p.d., the same number of electrons arrive each second, but with a velocity, and so a momentum, reduced by a factor $\sqrt{2}$. Thus the force should be reduced by a factor $\sqrt{2}$.

71 The purpose of this question is primarily to stimulate discussion, so that ideas can be sorted out. It can be an important part of learning to make mistakes and get into confusions, for one finds out how to use ideas partly by finding out how not to use them.

The key to a solution is to note that the momentum of the physicist walking with a full bucket is not the same as his momentum when walking at the same speed with an empty bucket.

72 **a** mv_1 (or $+mv_1$, $-mv_1$).
b Zero.
c $\frac{1}{2}mv_1^2$.
d mv_1^2. (Energies do simply add up, being scalar quantities.)
e Zero (same as **b**).
f mv_1^2. (Some energy stored in the compressed material of the colliding trolleys; some spread out among molecules of the trucks and the nearby matter, all of which is a little warmer.)
g If the track is smooth, the total momentum of the two trucks must stay constant (at zero), so the velocities of trucks of equal mass must be equal and opposite after collision, unless both are zero. If the track is not smooth, some momentum can be transferred to the track.

h The kinetic energy would seem to be larger after the collision than before. (Perhaps the collision could have triggered off an explosive charge between the trucks.)
i Zero (see **g**).
j No.
k Yes; the combined kinetic energy becomes zero. But the total energy is constant, energy being spread out among the molecules of warmed up material in the trucks and nearby matter.
l Yes. The truck, the buffer, and the Earth to which the buffer is attached, are now moving very slowly forwards (actually the Earth is rotating a very little faster, but at the same rate as before the truck was set in motion in the first place). Again, kinetic energy of the truck is smaller, and the energy is spread out among the molecules of the truck, buffer, and surroundings.
m You might mention:
1 A pair of moving bodies can have zero momentum, but not zero kinetic energy.
2 Momentum is a vector; energy a scalar (see **b** and **d**). Both are conserved, but momentum and energy can seem to vanish unless the motions or energies of all the matter involved are counted in.
3 The conservation of momentum sets certain limits on what can happen as a result of a collision, but exactly what happens depends on whether some of the kinetic energy of the bodies is changed into another form of energy, and on how much is transformed.

73 **a** $+0.3$ kg m s^{-1}. (+ sign refers to momentum directed to the right.)
b $+0.075$ kg m s^{-1}.
c $+0.375$ kg m s^{-1}.
d $+0.225$ kg m s^{-1}.
e $+0.25$ kg m s^{-1}. The momentum of A has decreased by 0.05 kg m s^{-1}.
f $+0.125$ kg m s^{-1}. The momentum of B has increased by 0.05 kg m s^{-1}.
g $+0.375$ kg m s^{-1}.
h They are equal, and they are opposite in sign.

i 0.5 kg m s^{-2}. 0.5 N, directed to the left.
j 0.5 N, directed to the right.
k See figure 48.

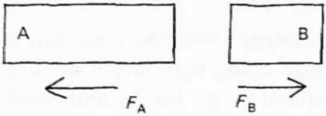


Figure 48

l You might write '. . . then, as the forces act for the same time, they produce equal and opposite changes of momentum in the two objects, force being the rate of change of momentum.' You could go on to explain why this result holds even if the forces vary during the collision, as they usually will do.

74 These questions are intended to put before you some of the commoner confusions and errors concerning momentum conservation and Newton's Third Law.

Some books are helpful here, others are not. Try:
Arons, *Development of concepts of physics,* Chapters 6 and 17.
Feather, *Mass, length and time,* Chapter 8.
PSSC, *College physics,* Chapters 13 and 16.
PSSC, *Physics,* Chapters 19 and 22.
Rogers, *Physics for the inquiring mind,* Chapters 7 and 8.

75 **a** Ignoring the rolling of the footballs (if you don't the problem is very hard), the first stops moving and the second travels on as fast as the first came up to it.
b Before the collision, the elephant conveys all the kinetic energy. After the collision, the elephant still conveys most of the kinetic energy.
c Velocity ratio approximately 1 to 10 000.
Energy ratio approximately 1 to 10 000 (mass ratio approximately 10 000 to 1; ratio of v^2 approximately 1 to $10\,000^2$).
The electron loses very little of its kinetic energy.

76 The jet ejects about 6×10^{18} protons each second, each with momentum *mv* of about 7.4×10^{-20} kg m s^{-1}, so that the beam conveys momentum at a rate of about 0.44 kg m s^{-2}.

The acceleration of the space-ship, mass 10^5 kg, is 0.44×10^{-5} m s^{-2}. An increase of velocity of 100 m s^{-1} will take about 2.3×10^8 seconds, so ejecting nearly 1.4×10^{27} protons, equivalent to a mass of about 2.4 kg of hydrogen.

The space-ship would have lost a charge of about 2.2×10^8 C if only protons were ejected, and the build-up of such a charge would make it increasingly hard to eject further protons. A beam of electrons could, however, be ejected at the same time, keeping the charges in balance.

77 See question 76. Points to consider are:

means of accelerating electrons
how to convey enough momentum in the electron beam
whether the small mass of electrons is an advantage or a disadvantage
problems arising out of the charge carried off by the electrons
rough estimate of force, and so of acceleration, available by this means.

78 **a** 1.6×10^{-19} J, or 1 electronvolt.
b 0.2 mm.
c See figure 49.

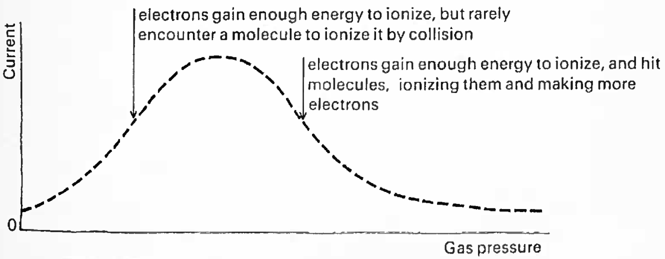


Figure 49

79 **a** The experiment aims to measure losses of energy accurately, so the electrons must all begin with the same energy, as far as possible.

b No. There is helium gas in B.

c Very nearly 50 electronvolts.

d 30 electronvolts.

e Because electrons are negatively charged, and the upper plate is on the inside of the curve, into which the path of the electrons must be pulled.

f The electrical force is proportional to V; the force needed is mv^2/r, and is thus proportional to the kinetic energy $\frac{1}{2}mv^2$. So the p.d. V is proportional to the kinetic energy.

g Electrons must *not* make collisions in C, but they *must* make collisions in B.

h Elastic collisions.

i Elastic collision.

j Briefly, no electrons lose energy in amounts between zero and 21 electronvolts.

It seems likely that a helium atom cannot increase its energy from the lowest possible energy by less than this amount. Electrons do also lose energy by amounts around 23 and 24 electronvolts, suggesting that the helium atom can also lie at energy levels having these energies above the lowest possible energy.

80 a No. Very nearly 3.9 electronvolts.
b Yes. No change.
c Yes. 0.05 electronvolts.
d No. The current will fall substantially.
e The electrons can have energy 0.15 electronvolts, enough to cross a gap with 0.1 V across it. So the current need not fall when the detecting p.d. is switched on.
f See figure 50.

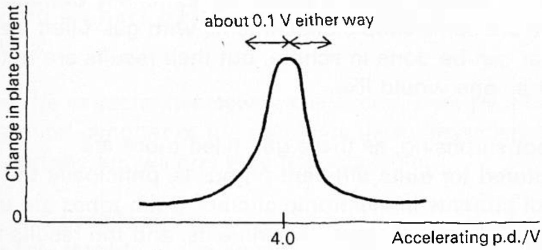


Figure 50

The presence of another energy loss at another accelerating voltage is indicated by the presence of another peak in the graph of change of plate current, as the detecting p.d. is switched on, against voltage.

The experimental evidence for the existence of energy levels in atoms

Introduction

Experiments which give clear and convincing evidence for the existence of energy levels in atoms are extremely difficult to do. There are some simple experiments with gas-filled electron tubes that can be done in school, but their results are not as clear cut as one would like.

This is not surprising, as these gas-filled tubes are manufactured for quite different purposes, principally the control of currents in electronic circuits. Such tubes are used in ionization or energy level experiments, and the results they give depend, among other things, on the gas pressure and also on the spacing between the electrodes.

The tubes selected for school experiments have been chosen just because the results they give happen to agree with those of more refined experiments. It is quite easy to find other tubes which, because of their design, seem to give quite different results. More accurate and refined experiments are difficult because of this problem of design, and building or buying tubes especially designed for the experiments is time-consuming or expensive. So the following extracts are intended to give you a picture of what is involved in doing careful energy level experiments, by reporting the work of some of those who did them.

There are other reasons for using extracts from scientific papers as part of the course. They may help you to see more clearly what day to day research in experimental physics is like.

Physicists have to learn to obtain information from their reading of papers; indeed much of a working physicist's time is spent reading other people's work. Because of this, and also because, as time goes by, most students have to learn more and more from books and papers and less and less from their own personal experiences in the laboratory, it seems worth while including some such work in a sixth form course. But these papers are written by professionals for professionals and terms are used which a student may not know. So we have added some notes explaining what is meant.

Before the extracts themselves, the scene is set by a brief background account of the problems these physicists had in mind and the knowledge they had available.

The problem

In the first decade of the twentieth century and the final years of the nineteenth century, evidence accumulated which suggested that atoms were made up of collections of charged particles, possibly moving about, and yet held together in some way. The kinetic theory of gases was by then firmly established and the problem was to discover how these complex atoms could possibly collide elastically as the theory required. Think of *any* complicated object you like: if you hit it the bits will inevitably move about and gain energy. Yet when we examine the energy stored in a monatomic gas, as it is heated, the energy is all accounted for by the motion-in-flight of the atoms. There is no trace of any energy going 'inside' the atoms.

It would be unwise to think of atoms as little solar systems but it might help to try to imagine our solar system colliding with another similar one. There can be no doubt that both would be radically affected. The gravitational pull of one star on the planets of the other would certainly alter all their orbits. Such an event would have important, probably disastrous, consequences for life on Earth. Luckily there has been no such collision – at least within the time for which there has been life on Earth. Yet, if we accept the conclusions of the kinetic theory – and there is considerable experimental evidence which forces us to do so – atoms can collide many millions of times every second, rebounding from each other. Yet they are unaffected by these encounters. All the properties of each atom seem to stay exactly the same! At least there is no evidence of spontaneous change in physical or chemical properties of a gas however long one waits. Helium gas, for example, might perhaps become reactive instead of remaining inert. But it does not, even though the atoms hammer each other about so frequently.

Bohr's theory

The first reasonably good theory of atomic structure was suggested by Niels Bohr in 1912, but he had to resort to an arbitrary rule to get over the difficulty. His rule was, essentially, to imagine that atoms could only accept energy in 'lumps' of definite size. Thus a collision involving a smaller amount of energy would have no effect. Bohr knew of Planck's idea that light energy might be radiated in lumps, or quanta, so his suggestion was not entirely a shot in the dark. Bohr was unable to offer any explanation in support of his rule and this was left to Schrödinger, who in 1926 produced a fuller theory based on the wave behaviour of electrons.

In effect, Bohr was getting out of trouble by saying 'Atoms do not seem to respond to low energy influences so let us suppose that they *cannot* do so and make this rule of the theory.' But such a rule, arbitrary and unexplained, although better than nothing, can never be wholly satisfying.

Bohr was, however, able to predict the energies at which simple atoms like hydrogen could exist, and later this was extended to some other atoms.

Figure 51
Niels Bohr (1885–1962), a Danish physicist who was awarded the Nobel Prize in 1922 for work on atomic structure. In 1943 he escaped from German-occupied Denmark to the U.S.A. where he worked on the atomic bomb project and later opposed the dropping of the A-bomb. In 1957 he was the first recipient of the 'Atoms for peace' award. *Photograph, Lotte Meitner-Graf.*

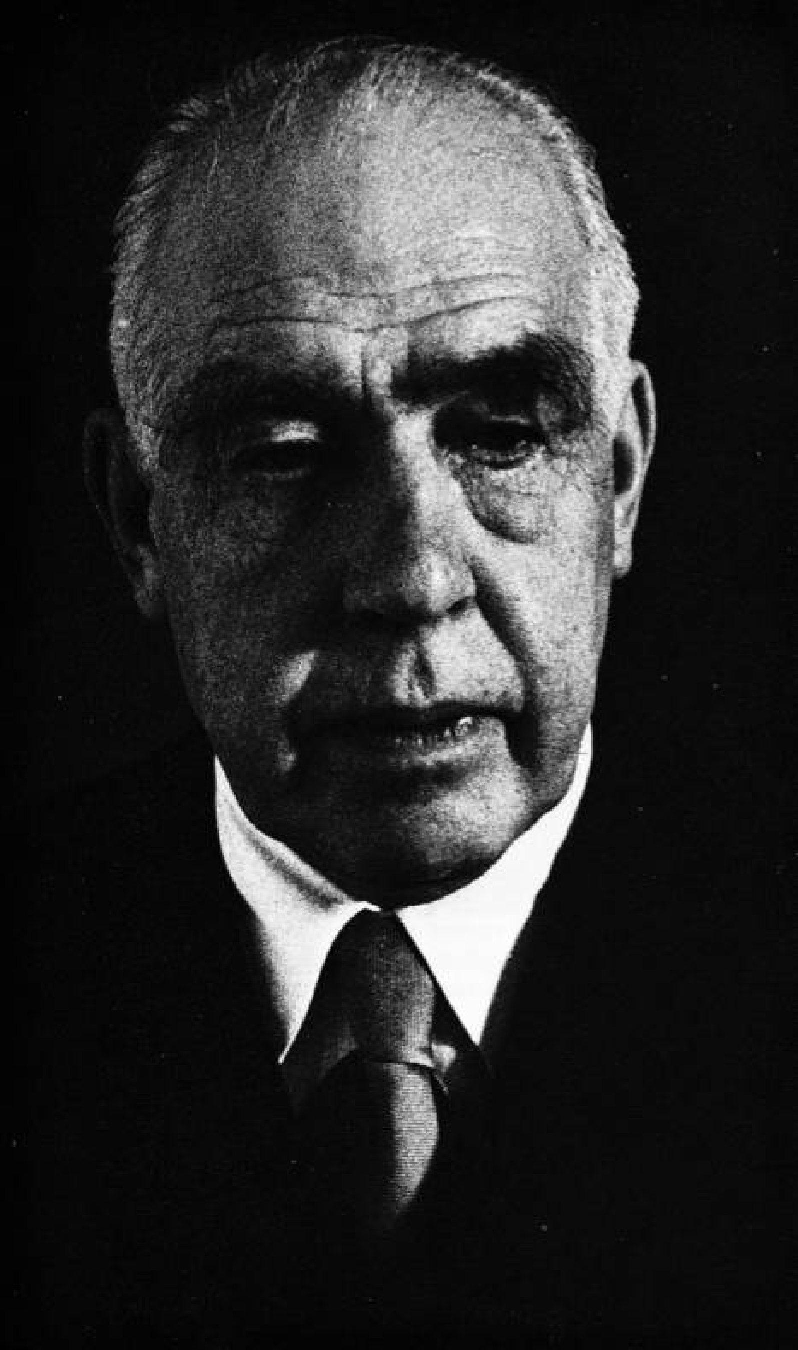


Figure 52
Erwin Schrödinger (1887–1961), born and educated in Vienna, was, with Dirac, awarded the Nobel Prize in 1933. Best known for his work on wave mechanics.
Photograph, Lotte Meitner-Graf.

From 1910 onwards Franck* and Hertz, joined later on by many other workers, looked for experimental evidence that atoms did exist only at definite energy levels. They looked for alterations of the energy of atoms in definite sized lumps as the atoms 'jumped' from one 'rung' of an 'energy ladder' to another 'rung'. Some of the evidence they found is described below with extracts from the published papers. Although easy enough to understand, the experiments are very difficult to do and not surprisingly the earlier ones, while offering hope that the predictions of theory were about right, gave less clear results. The extracts which follow are taken from later experiments, done when techniques had improved and the results were easier to interpret.

*James Franck (b. 1882). Born in Hamburg but became an American citizen after moving to the U.S.A. before the 1939 war. He shared the Nobel Prize in 1925 with Gustav Hertz for work on electron impacts on atoms. In 1939 he joined a team working on atomic energy.

The experiments

J. H. McMillen (b. 1904)

Born at Fort Wayne, Indiana. Worked at various universities and also as a civilian with the U.S. Navy. In 1952 he received a meritorious award of the U.S. Navy. Has worked on electron scattering, shock waves in water, wound ballistics, and high speed fluid dynamics.

The essence of McMillen's experiment (figure 53) is to fire a narrow beam of electrons with definite energy, from an electron gun, into helium gas. A few bounce off the gas atoms at each angle; a pair of slits permits electrons scattered at a certain angle to pass into the other half of the apparatus where their energy is measured. The energy is found by using two curved plates connected to a high voltage, so that the electrons are pulled round into a curved path. Only those electrons going at just the right speed run right round the channel to enter the detector. So the voltage on the plates can be used to select electrons with a definite energy and the detector tells how many there are having this energy. Thus information about the energy acquired by the helium atoms is found from measurements of the energy of the electrons after their collisions with the helium atoms.

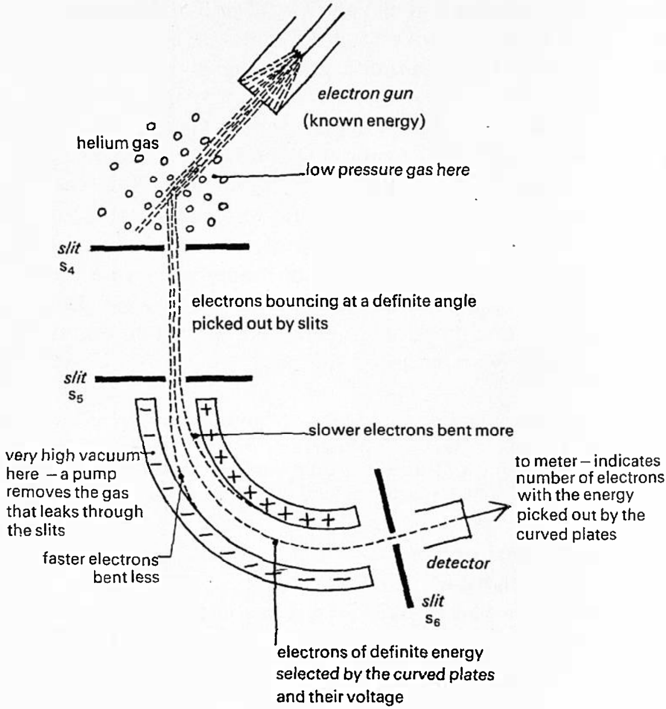


Figure 53
Diagram to show the principle of McMillen's experiment.

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.

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 figure 1 [54]. 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[1] F.

The projector, as shown in figure 1 [54], consisted of an oxide-coated[2] 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[3] 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 $s_1 = 1\text{ mm} \times 15\text{ mm}$, $s_2 = 0.8\text{ mm} \times 14\text{ mm}$, $s_3 = 0.4\text{ mm} \times 14\text{ mm}$.

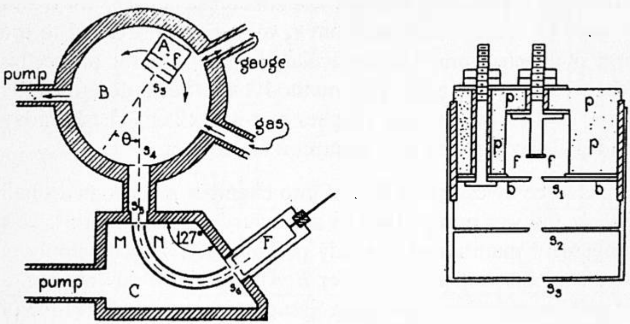


Fig. 1. Diagram of apparatus.

Figure **54**
From McMillen, J. H. (1930).

[1–9]See 'Notes on McMillen's experiment' at the end of this extract.

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. Onto 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 × 14 mm and s_5, 0.3 mm × 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[4].

The gas to be investigated flowed into chamber B through a small capillary and was pumped out by a mercury diffusion pump[5]. 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[6]. 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[7] at liquid air temperature. The hydrogen was obtained by heating a palladium tube[8]. A discharge in the presence of calcium vapour[9] 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. 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.

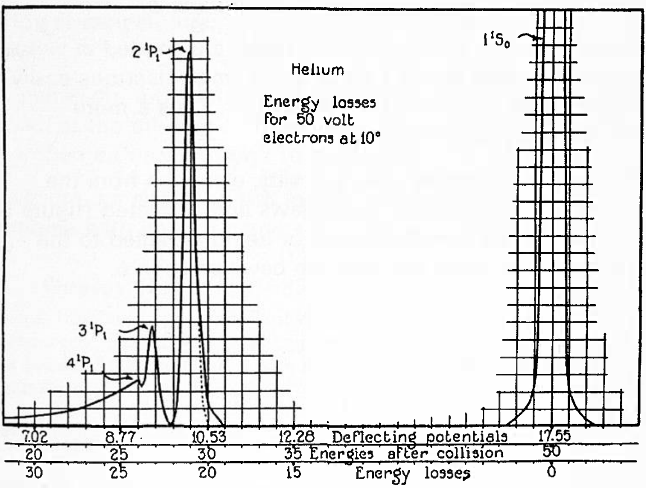


Fig. 2. Energy losses in helium for 50 volt electrons simultaneously deflected at 10°.

Figure 55
From McMillen, J. H. (1930).

In figure 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 the 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.

Notes on McMillen's experiment

[1]*Faraday cylinder:* a metal box with a small hole at which charged particles enter. It is surrounded by another metal box to screen it from electrostatic disturbances.

[2]Electrons emitted from a heated metal are emitted at various speeds. A heated alkaline earth oxide emits electrons easily and copiously, all with very low speeds. Thus a more homogeneous stream is more likely.

[3]While passing through the gun slits, electrons from the filament will be attracted to the jaws and deflected (figure 56). Electrons have a greater chance of being attracted to the jaws in *a* than when the jaws are bevelled as in *b*.

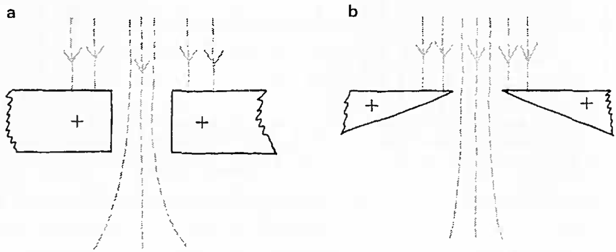


Figure 56

[4]*Compton electrometer:* one of the many sensitive highly developed versions of the simple gold leaf electroscope, intended to measure tiny currents by the motion of a leaf or a fibre. Nowadays a valve electrometer would probably be used, just as in school experiments where small currents or charges have to be measured.

[5]The mercury diffusion pump was invented by Gaede in 1915. A stream of mercury atoms is used to knock lighter atoms out of the region where a low pressure is required. (Compare it with the filter pump used in chemistry laboratories.)

[6]*McLeod gauge:* an improved form of mercury pressure gauge designed particularly for measuring very low pressures.

[7]Charcoal adsorbs gases onto its surface. It is more effective at lower temperatures and for gases with high boiling points.

[8]A palladium tube connected to the apparatus at one end and sealed at the other end. When heated in a hydrocarbon flame hydrogen diffuses through to the inside.

[9]Calcium, an alkaline earth metal, is very reactive. It will combine with impurity atoms but not with argon.

Gustav Hertz (b. 1887)

Born at Hamburg. The nephew of Heinrich Hertz of radio wave fame. Became professor of physics at Leipzig and while at Göttingen in 1925 was awarded the Nobel Prize with Franck. He has also received the Stalin Prize.

Hertz describes his experiment in a paper in *Zeitschrift für Physik* (**18**, 307, 1923) from which figure 57 is taken. See question 80 for a fuller discussion of the technique used by Hertz and by Morris.

Notes on figure 57

The gauze N_1 is positive to the filament D and accelerates electrons into the chamber R which contains gas at low pressure.

Some electrons, scattered from gas molecules, pass through the gauze sides N_2 and reach P, which is connected to a sensitive current meter.

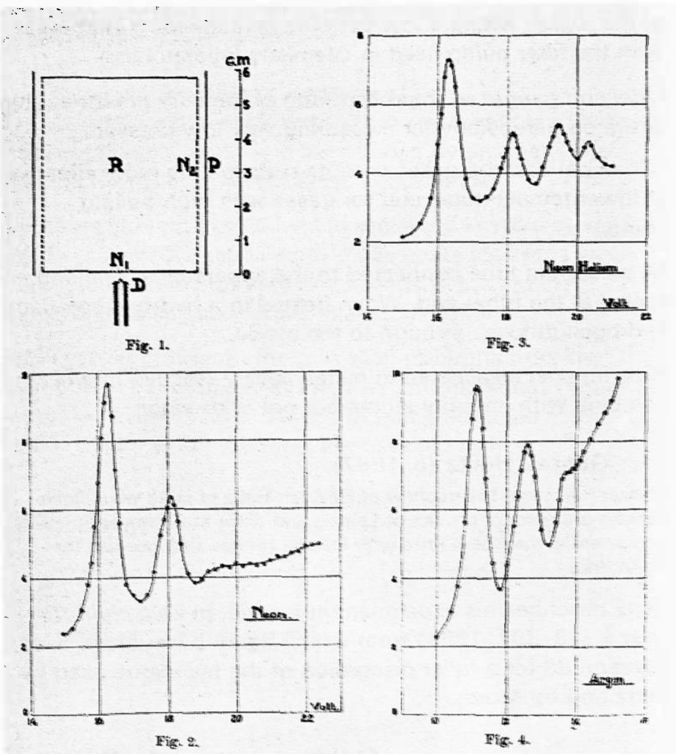


Figure 57

From Hertz, G. (1923) 'Über die Anregungs- und Ionisierungs-spannungen von Neon und Argon und ihren Zusammenhang mit den Spektren dieser Gase, 'Zeitschrift für Physik, **18**, 307.

A small p.d. can be switched on between N_2 and P, making P negative. Then electrons that have lost energy on collision will fail to reach P. The graphs plot the difference in current with this p.d. on and off. Thus a peak represents many electrons colliding and losing energy.

J. C. Morris (b. 1902)

Born in New Orleans where he became professor at Tulane University. From 1962 he was a consultant to the National Aeronautics and Space Administration (NASA). He has worked on ionization of gases, mass spectroscopy, and ionization potentials of hydrocarbon gases.

In one experiment J. C. Morris used Hertz's method to detect the energy levels of atoms in mercury vapour. As in Hertz's paper, a peak represents a large difference in the number of electrons reaching a plate from the scattering chamber, as a reversed potential is switched on and off. So a peak corresponds to many electrons losing energy on collision.

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.

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 shows the interpretation placed on the various potentials. The curves obtained with this method could be reproduced without difficulty.

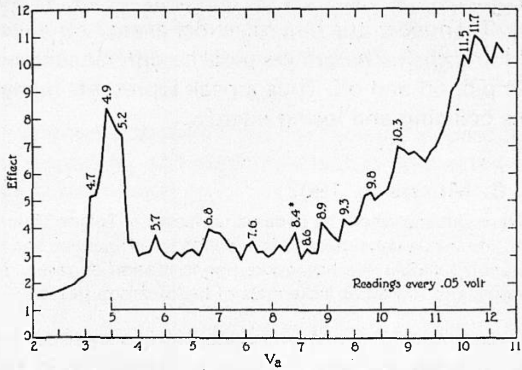


Fig. 5. Critical potentials of Hg vapor by the Hertz method.

Figure 58

From Morris, J. C. (1928) 'Comparison of measurements of critical potentials of mercury vapour', Physical Review, **31**, 447.

Table 1. Results obtained using Hertz method

Pot. observed (volts)	Interpreted from Theory	Calculated from Theory	Remarks
4.7	$1^1 S{-}2^3 P_0$	4.66	Metastable state
4.9	$1^1 S{-}2^3 P_1$	4.86	2537
5.2			5.25 obs. by Messenger
5.4	$1^1 S{-}2^3 P_2$	5.43	Metastable state
5.7	$2^3 P_0$	5.73	Ionization of metastable excited atom
6.8	$1^1 S{-}2^1 P$	6.67	
7.6	$1^1 S{-}2^3 S$	7.69	
8.1			8.0 and 8.5 obs. by Messenger
8.4			8.35 obs. by F. & E. 8.3 obs. by Messenger
8.6	$1^1 S{-}3^3 P_{0,1}$	8.58	
8.9	$1^1 S{-}3^1 P$	8.79	
	$1^1 S{-}3^3 D_{1,2,3}$	8.82	
	$1^1 S{-}3D$	8.80	
	$1^1 S{-}3^3 P_2$	8.80	
9.3	$2(1^1 S{-}2^3 P_0)$	9.32	Successive impact
9.8	$2(1^1 S{-}2^3 P_1)$	9.8	Successive impact
10.3	$1^1 S$	10.39	Ionization
	$6.7+4.9$		
11.5	$6.7+4.7$		

Notes on Morris's experiment

He obtained a graph with many peaks (figure 58).

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 (figure 59).

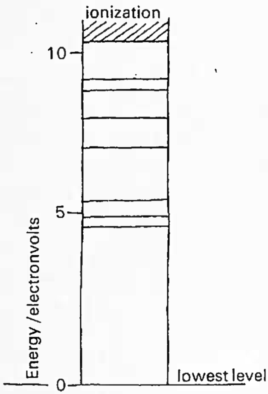


Figure 59

Electrochemical machining

by H. E. Freer
(Department of Engineering, Leicester University)

1 The shaping of metals

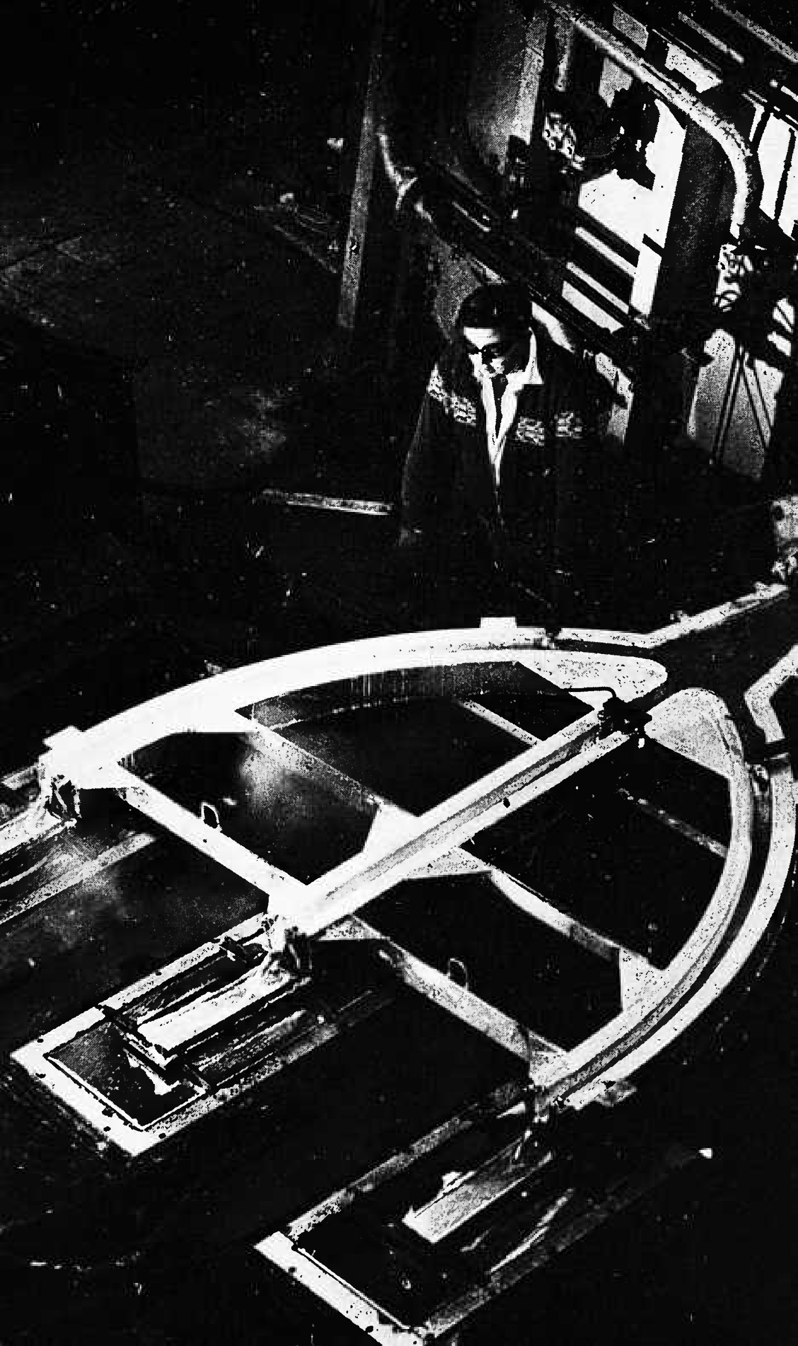
The complex shapes of machinery components have traditionally been produced by casting, forging, or machining. In casting (figure 60), molten metal is poured into moulds suitably designed to allow for shrinkage of the metal as it cools. Although modern techniques of pouring under vacuum conditions have improved the metal properties, castings are still inherently brittle and weak when subjected to shock loads.

Another method of shaping metals is to hammer, that is, forge them (figure 61). This has the advantage that forging can improve the toughness of some metals. Forging either produces rough shapes by hand-manipulated hammers or more precise forms by trapping the metal between two shaped dies.

There are however many metals which cannot be cast or forged well; they lose all their strength or sometimes fracture internally or externally. Also, intricate or accurate shapes are often required and these can only be produced by machining. There are many methods of machining. Drilling, turning, milling, and grinding are the principal ones, but these all rely on material being sheared away by a much harder material which has been shaped into a tool.

Soft materials like aluminium can be cut relatively easily but as the hardness of the material increases the tool begins to wear out more quickly. The production of the moulds for some types of casting and of the dies for forging has long been

Figure 60
Producing aluminium alloy ingots by the continuous casting process at the Rogerstone (Monmouthshire) works of Alcan Booth Industries Limited.
Photograph, Alcan Aluminium (U.K.) Ltd.



tedious and difficult because of the strength of the materials needed to withstand the molten metal and the hot hammering. The temperature and stresses found in rocket engines and gas turbine aero engines have also meant the increasing use of very strong, very hard, difficult-to-machine materials. The wearing out of expensive tools and the greater time needed to shape these materials mean the operation is becoming doubly expensive and there is a need for quicker, cheaper methods.

Newer methods involve either the concentration of thermal energy onto a very small area or the use of chemical action. Flame and plasma torch cutting can only be used for rough cutting; lasers and electron beams can make very fine cuts removing very small quantities of material. Spark erosion does remove appreciable amounts of metal fairly accurately although it often leaves a pitted surface.

Chemical etching also removes small amounts of metal fairly accurately but electrochemical machining uses electrolytic action to remove large amounts of metal, accurately, and with a good surface finish.

2 Theory of electrochemical machining

For many years the effects of an electric current passing through conducting solutions or electrolytes have been used industrially. Many elements, including hydrogen, oxygen, and aluminium are produced commercially from electrolytic cells. In electroplating, the passage of current through a suitable electrolyte will cause plating material from one electrode to be deposited on the other.

Electrochemical machining is the large scale dissolution of electrode material to form a desired shape. The electrolytes used induce reactions such that in the overall process the removed material is taken into solution and removed by the

Figure 61
A propeller blade being forged in the 20 000 kg hammer at the Handsworth, Birmingham works of Alcan Castings and Forgings Ltd. *Photograph, Alcan Aluminium (U.K.) Ltd.*

electrolyte, and hydrogen is liberated at the cathode. For example, the machining of iron in salt solution may be represented overall by

$$Fe+2H_2O \rightarrow Fe(OH)_2+H_2$$

This ferrous hydroxide may then react further to form ferric hydroxide,

$$4Fe(OH)_2+2H_2O+O_2 \rightarrow 4Fe(OH)_3$$

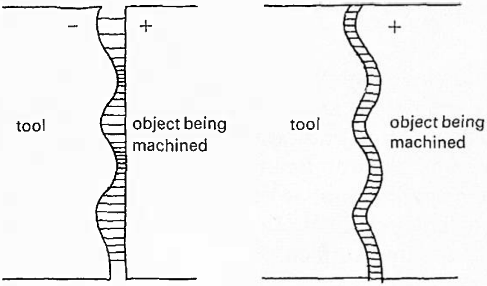


Figure 62
Electrochemical machining.

For every 10 g of iron dissolved, 4000 cm³ of hydrogen and 380 cm³ of wet ferric hydroxide sludge are formed. Suitable precautions must therefore be taken to ensure no concentration of hydrogen occurs and also that the sludge is removed periodically.

Since the current flowing is inversely proportional to the size of the gap between the electrodes, places where the electrodes are close will carry larger currents and will thus machine at higher rates until the shape of the object being machined becomes approximately the mirror image of the tool (figure 62). Typically, the system might be operated with a gap of less than a millimetre and a potential difference across the electrodes of 10–20 V, but satisfactory tests can be carried out over a wide range of values.

3 **Practical electrochemical machining**

The simplest rig to demonstrate electrochemical machining would consist of a d.c. power supply giving 10–15 V, a pump, an electrolyte tank, and a small jig to hold the electrodes and to direct the fluid between them (figure 63).

A more useful rig to investigate some of the process parameters would include means of feeding the anode towards the cathode at the same rate as it is machined away. In this way the interelectrode gap is maintained nearly constant and hence the current flow is kept nearly constant. Unless the electrolyte is only used once, a fine filter should be included in the circuit to prevent any particles bridging the electrodes and causing short circuits.

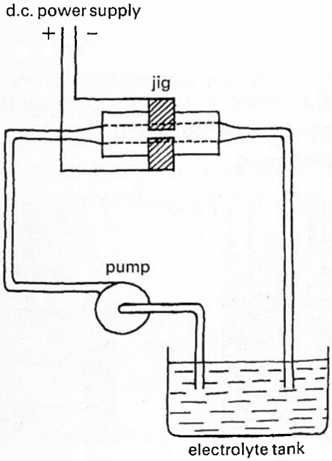


Figure 63
A simple experimental rig to demonstrate electrochemical machining.

Once an electrolyte has been selected the cell voltage and interelectrode gap determine the current and hence the machining rate. Electrolyte flow rate has a second order effect and so the minimum instrumentation should be voltmeter, ammeter, flowmeter, and a means of measuring the electrode movement. With this equipment, the effect of parameters on surface finish and process can be investigated.

A 10–15 per cent aqueous solution of sodium chloride is an effective electrolyte with many materials, but small amounts of sodium fluoride, nitrate, and chlorate, and potassium chloride and nitrate are used industrially as additives to break down passive films which can occur using chloride only. Acid solutions are also used, although they are mostly limited to deep hole drilling operations where their ability to take the dissolved metals into solution prevents any blockage of the narrow working gap.

An industrial machine would operate on the same principle but would probably include automatic monitoring of the electrolyte, several stages of filtration, and conductivity and pH control. It would also include precision control of the tool feed rate.

A typical installation is shown in figure 64, engaged in the production of gas turbine blades. A typical product is shown in figure 65, while figure 66 illustrates the very general use made of the process to remove metal burrs left from conventional machining operations.

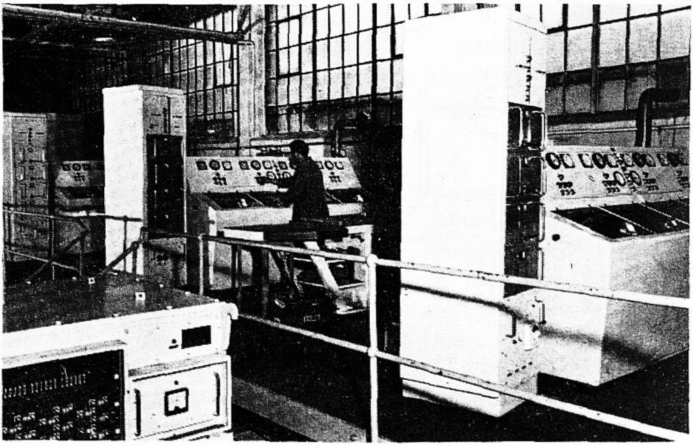


Figure 64
An electrochemical machining installation used by Rolls-Royce to manufacture turbine blades.
Photograph, Rolls-Royce Limited.

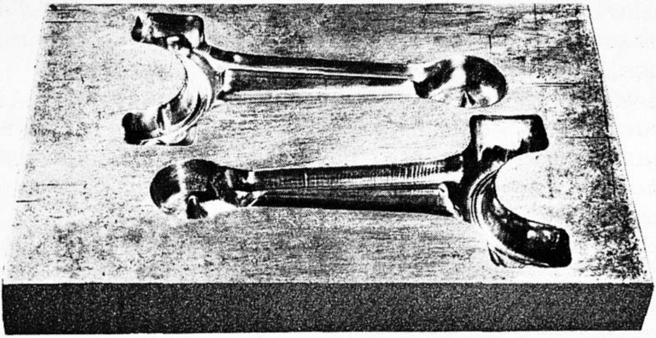


Figure 65
Die for small engine connecting rod produced by electrochemical machining.
Photograph, High Precision Equipment Ltd.

4 Future developments

As technology advances, the demands of lightness, compactness, and high strength will lead to smaller tougher components made in awkward shapes and ever more difficult-to-machine materials. Electrochemical machining can

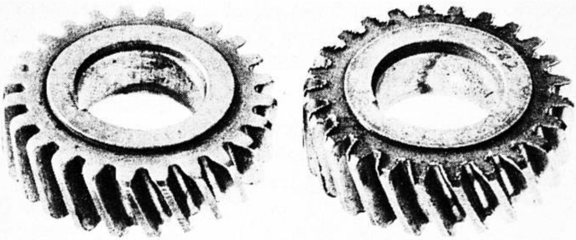


Figure 66
Gearwheel after (and before) de-burring by electrochemical machining.
Photograph, High Precision Equipment Ltd.

satisfy these demands but it is not yet easy to determine which electrolyte will produce the most efficient machining, nor is it possible to design first time a tool which will accurately produce a given shape. Other problems include very high current density machining and low current etching caused by stray currents in regions wetted by the electrolyte but remote from the machining area. All these are the subject of research projects, but much more work is needed.

Electro-deposition, the reverse of electrochemical machining, is potentially attractive to industry for building up awkward shapes. Unfortunately, at deposition rates that are high enough to be economic, gas evolution at the electrode causes porosity and embrittlement of the material. If this could be overcome the whole wasteful operation of dissolving away unwanted material could be replaced by a process using only the material required and wasting nothing.

Books for Unit 2

Textbooks

Arons, A. B. (1965) *Development of concepts of physics.* Addison-Wesley. (Dynamics, Chapters 5, 6, and 17; mathematics, Chapters 8 and 16; energy, Chapter 18; current and p.d., Chapter 25.)

Baez, A. V. (1967) *The new college physics.* Freeman. (Dynamics and energy, Chapter III.)

Bennet, G. A. G. (1968) *Electricity and modern physics.* MKS version. Edward Arnold. (Circuits, resistance, and resistivity, Chapter 2; charge and capacitance, Chapter 11; electrons, Chapter 13.)

Caro, D. E., McDonell, J. A., and Spicer, B. M. (1962) *Modern physics.* Edward Arnold. (Electrons and ions, Chapter 2.)

Holton, G. and Roller, D. H. D. (1958) *Foundations of modern physical science.* Addison-Wesley. (Dynamics, Chapters 4 and 17; evidence, facts, and laws in science, Chapters 13, 14, and 15; energy, Chapter 18.)

PSSC (1968) *College physics.* Raytheon. (Dynamics, Chapters 13 and 16; energy, Chapter 17; currents and p.d., Chapter 27; ionization, Chapter 23; energy levels, Chapter 33.)

PSSC (1965) *Physics.* Second edition. Heath. (Dynamics, Chapters 19 and 22; energy, Chapter 23; currents and p.d., Chapter 29; ionization, Chapter 26; energy levels, Chapter 34.)

Rogers, E. M. (1960) *Physics for the inquiring mind.* Oxford University Press. (Dynamics, Chapters 7 and 8; electric charge, Chapters 32 and 33; electrons, Chapter 36; energy, Chapters 26 and 29.)

Other reading

Feather, N. (1961) *Mass, length and time.* Penguin.
Millikan, R. A. (1963) *The electron.* University of Chicago Press.
Project Physics (1971) Reader, Unit 5 *Models of the atom.*
Holt, Rinehart & Winston, Inc.

Terms, units, laws, formulae, and data

Terms and units

		Unit	
Electric current I	Current is measured with ammeters, which are ultimately standardized by comparison with current balances, in which the magnetic force between wires carrying currents is measured. More of this in Unit 7.	ampere	A
Electric charge Q $Q = It$	The rate of flow of charge is the current, or charge is current multiplied by time of flow. Charge is *conserved.*	coulomb	C
Potential difference V Energy $= QV$ Power $= IV$	The flow of charge in a lamp or a motor can transform energy. The *potential difference* between two places (say two terminals in a circuit) is the ratio of the energy transformed to the charge passing.	volt	V
Resistance R $R = V/I$	The ratio of the potential difference across a conductor to the current through it. It can vary with current, time, temperature, strain, or other factors.	ohm	Ω
Resistivity ρ $R = \rho L/A$	The resistance of a wire depends on its length, L, and its cross-sectional area A but also on what it is made of. The resistivity $\rho = RA/l$ depends only on the material, not on the length or area. Conductivity is the reciprocal of resistivity.	ohm metre	Ω m
Capacitance C $C = Q/V$	The ratio of charge stored on a capacitor to the potential difference across it.	farad	F
Momentum mv	Momentum is a vector quantity. It is of interest because it *is* conserved (see below – *laws*)		kg m s^{-1}

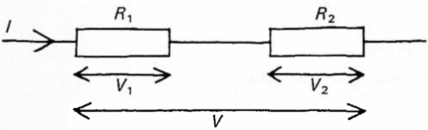
Force F $F = \mathrm{d}(mv)/\mathrm{d}t$ $F = ma$ for constant mass	Also a vector quantity, measured by the rate of change of momentum it produces, or, for fixed mass, by the product of mass m and acceleration a.	newton	N $\mathrm{kg\,m\,s^{-2}}$
Work	A means of calculating the energy *transformed from one form to* another. If a force F moves an object a distance s along the direction of the force, the work done is Fs.	joule	J N m

Laws and formulae

Ohm's Law

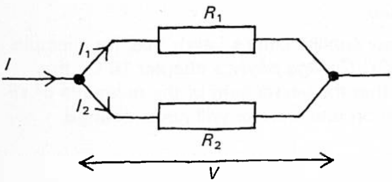
Some conductors and circuit elements, but by no means all, have a resistance V/I which is constant over a wide range of values of current or voltage. They are said to obey Ohm's Law. Because the resistance usually varies with temperature, strain, or other such factors, it is usual to suppose that such factors are held constant in any test of whether V/I is constant.

Resistors in series



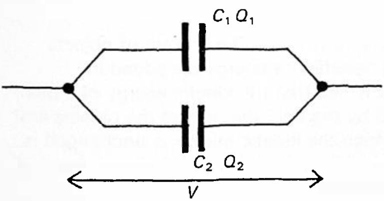
$$V = V_1 + V_2$$
$$R = R_1 + R_2 = V/I$$

Resistors in parallel



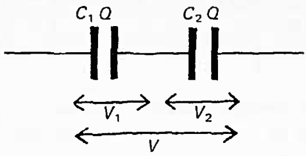
$$I = I_1 + I_2$$
$$1/R = 1/R_1 + 1/R_2 = I/V$$

Capacitors in parallel



$$Q = Q_1 + Q_2$$
$$C = C_1 + C_2 = Q/V$$

Capacitors in series



$$V = V_1 + V_2$$
$$1/C = 1/C_1 + 1/C_2 = V/Q$$

Current conveyed by moving charges

$I = nqvA$ where n charges, each of size q, occupy each cubic metre and travel at velocity v perpendicular to area A.

Decay of charge on a capacitor

The charge on a capacitor discharging through a resistor decreases by a constant factor in equal time intervals. If the decrease in charge is ΔQ over a time interval Δt then $\Delta Q/Q = -\Delta t/RC$. Over an interval of time equal to RC, the *time constant* of the circuit, the charge decreases by a factor known to mathematicians as the number e = 2.718. . . .
Capacitor discharge is an example of *exponential decay.*

Energy of a charged capacitor

Energy $= \frac{1}{2}QV$.

Energy of a stretched spring

Energy $= \frac{1}{2}Fx$ where F is the tension at extension x.

Kinetic energy

Kinetic energy $= \frac{1}{2}mv^2$ where v is the velocity of a mass m.

Conservation of momentum

This is a general, fundamental law (unlike Ohm's Law). See, for example, PSSC *Physics* chapter 22 or PSSC *College physics* chapter 16 for the evidence which leads us to say that the vector sum of the momenta of all of a set of bodies exerting forces on one another will never change.

Conservation of energy

Another general, fundamental law. See PSSC *Physics* chapters 23 to 25, PSSC *College physics* chapters 17, 18, and 20 or Rogers, *Physics for the inquiring mind,* chapters 26 and 29.
The total amount (scalar sum) of energy shared by any set of objects never changes, as long as all the transfers of energy are added in.
But energy has many forms, so it is rare that the kinetic energy of a pair of colliding objects is unchanged by the collision, unless the objects are atomic particles. A collision in which the kinetic energy is unchanged is called *elastic;* one in which the kinetic energy changes, because some of it goes to other forms, is called *inelastic.*

Data and information

Electrons

Electric charge comes in lumps of magnitude 1.6×10^{-19} C. No one knows why this happens to be the value: it is a fundamental constant.

Electrons have charge -1.6×10^{-19} C and mass 9.1×10^{-31} kg.

It is often convenient to have a name for the energy transformed when one electron charge moves through a potential difference of one volt. It is called one electronvolt and is equal to 1.6×10^{-19} J.

Energy levels

When electrons collide with atoms, the atoms accept energy only in lumps. The size of the lumps varies from one sort of atom to another, and any one sort accepts energy in more than one sized lump.

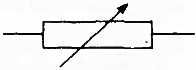
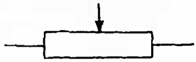
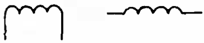
This can be explained by supposing that each atom can exist only at one of a series of energies, or *energy levels,* and that it can change its energy only by jumping from one level to another. An atom in a level above the lowest possible is said to be *excited.*

A definite energy is also needed to *ionize* an atom; that is, to remove an electron from it altogether.

Symbols for circuit diagrams

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		
Transistor (npn)		

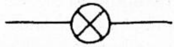
Measuring instruments

voltmeter

ammeter

galvanometer

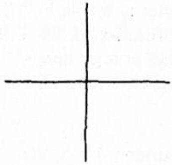
Signal lamp



Lamp for illumination

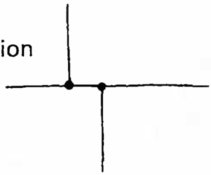
Wires, junctions, terminals

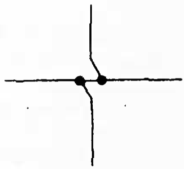
crossing of wires,
no electrical contact



junction

double junction





terminal

Index

Where *significant* information is contained in an illustration or diagram, the page reference is italicized.

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H.E. Freer

This *Students' book* contains a summary of Unit 2, *Electricity, electrons, and energy levels,* and questions on its main work. The Unit is divided into five Parts: 'Things which conduct', 'Currents in circuits', 'Electric charge', 'Stored energy', and 'Electrons and energy levels'. The book also includes answers to the questions, chapters on 'The experimental evidence for the existence of energy levels in atoms', and 'Electrochemical machining', a list of background reading, and notes on relevant units, laws, and other data.

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