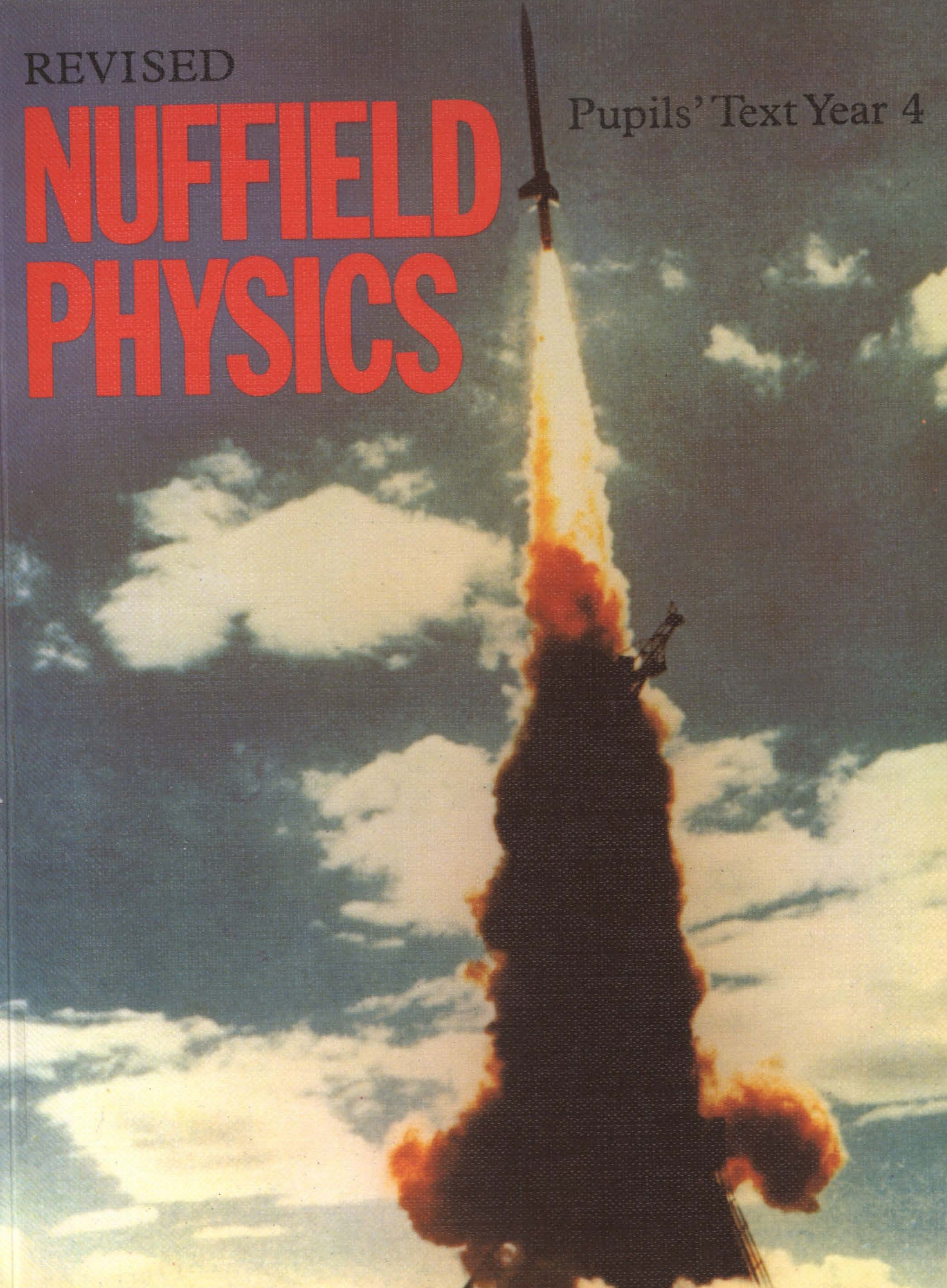
REVISED

NUFFIELD PHYSICS

Pupils' Text Year 4



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Nuffield Physics PUPILS' TEXT YEAR 4

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NUFFIELD PHYSICS PUPILS' TEXT YEAR 4

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Skylark Research Rocket being launched from Woomera, Australia as part of the National space research programme.
British Aircraft Corporation

Contents

Foreword

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

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

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

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

The new volumes draw in many ways on the original *Teachers' Guides* and *Guides to Experiments* and *Questions Books*. Their contribution in providing a firm basis for these further developments is gladly acknowledged here. It is a pleasure to praise the part played by the large number of teachers who have helped in discussion, feedback and persuasion but it is once more to Eric Rogers who, with an extraordinary vitality, has led and completed this work, that we especially record our thanks.

Our thanks go with equal appreciation to Ted Wenham. As well as editing *Teachers' Guide Years 1 and 2* in the new edition and writing the new *Pupils' Text Years 1 and 2*, he has continued to act as a very wise and helpful consultant on all aspects of the programme. His judgement and knowledge have been welcome and essential throughout.

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

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

General Editors' Preface

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

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

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

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

Many teachers have followed some general suggestions:

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

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

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

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

We changed Dr Henry Boulind's excellent Questions for thinking and understanding to simpler wording, but retained their essential enquiry. In response to pleas from teachers, and to the needs of the new school structure, we added Progress Questions to provide a different and easier approach.

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

On behalf of teachers and pupils who will use these books, we owe thanks to many people: to our consultant teachers, without whose advice we could not have envisaged the needs of the project; to Professor R. A. Becher, who was our chief inspiration and guide in the original project, to whom we still turn for wise advice; to Professor K. W. Keohane as our co-ordinator with counsel concerning Physics and teaching and people; to

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

John Maddox, Director of the Foundation, for past interest and care, and now special encouragement.

And we are grateful to Jim Scholefield who has relieved us of administrative burdens connected with the project.

Both teachers and pupils will owe much to the five teachers who constructed the Progress Questions—forged and tempered them: Anthea Arnold, Margaret Fawcett, Reinet Fremlin, Gwen Jones and Hilda Misselbrook.

Producing material for these books has involved consulting, planning, editing, making preliminary sketches, trying experiments and writing chapters. All that has depended on the work of many people associated with the editorial office. In particular, the project owes a special debt to the following for loyal skilful help:

Secretaries: Elizabeth Aldwinckle, who did so much for the development of the Year 3 books and continued, until she left for university studies, to prepare Year 4 with the same skill and understanding. Gillian Brown, Ann Sinclair and Rydal Wade continued the work and extended into some general editorial activities.

Editorial Assistants: Hilary Bunce, Mary-Jean McNeil, Jan Miller and Ron Taylor gave valuable help; Jean Richardson and Truda Temkin brought, and used, special skills.

Art Work: Mr Stanley Wood showed special understanding of our needs; Lorna Jeans acted as constructive critic and courier for art work.

Physics Reader: Bill Trotter acted as physics critic and saved us from many a mistake.

Typesetting: Although outside our editorial group, Keyspools—who did the typesetting—earned our admiration for their intelligent flexibility as well as for their speed and skill.

And, in general, we are grateful to the Staff of the Nuffield Foundation, who made our work easier by many kindnesses.

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

Eric M. Rogers
E. J. Wenham
General Editors

TO THE PUPILS WHO USE THIS BOOK

Welcome to Physics

This book is meant to help you learn some physics. Physics is *doing* experiments and *thinking* about them. If you do the experiments (by yourself or with a partner) you will learn how scientists *find things out.*

If you read the explanations here and try some of the questions you will learn how scientists *think things out.*

So, if you enjoy *doing* experiments and *thinking* about them, you will understand some science and you will have a good chance of keeping that understanding all your life.

Best of all, while you are in the lab pretend you are a professional physicist; 'a scientist for the day'.

These Nuffield Books

Three books came before this but you may not have used all of them. There is one more book after this for you if you wish to continue physics next year.

And there is an A-Level programme with many books and advanced experiments after that.

In this book there are some choices of things that may be left out or put off till later.

Experiments, Demonstrations, Questions

The experiments are here for you to find out some science yourself. They are things for you to do, by yourself or with a partner. Each time there is an experiment, the instructions in this book will suggest what to try.

Those instructions will give you enough help to get the experiment started; but they will not be like a cookery book. They will not tell you everything you should do. You will need to think and plan and try things yourself, as a good scientist.

Demonstrations You will need plenty of time for your own experiments. So your teacher will show you some experiments as demonstrations. Those will save time and give you more time for your own experimenting. Watch those demonstrations carefully. They can tell you a lot.

The questions are here to help you to think about the science you are learning. And they will help you to understand what you are learning. These questions and your own experiments are your chief '*learning aids*'.

So it would be a pity to mistake the idea of the questions and think they want difficult answers with many scientific words. The questions are meant to show you what you can do, not to tease you with things you can't do.

You will be able to answer some of the questions at once. But others may seem difficult at first. If you find a question too puzzling or too hard, try another one.

You will find that some questions have no simple answer. That is intentional: just see what you can do.

And some questions are simply meant to start a discussion: they ask, 'What do you think?'

Some questions will ask about things you have already learnt in science. Others bring in new topics. And some will ask about things which are unfamiliar but which are linked with what you have already heard about. Some questions are just problems to test your ingenuity.

There are too many questions for you to be able to tackle all of them. You will have to pick and choose. You will find some of them more interesting or provoking than others.

Before you start answering questions, see the special pages of 'Help in answering the questions'.

The pages of this book are your worksheets to help you to learn.

HELP IN ANSWERING THE QUESTIONS

Here are imaginary questions—special ones we have made up to tell you about answering our questions. Some questions are clear and easy, like Questions A and B here.

Question A. When you arrange a runway to compensate for friction, you put a book or block of wood under one end. Is that the end where the trolley starts or the other end?

Answer A. *'The starting end'*

Question B. How do you know that your answer to Question A is right?

Answer B. *(i)* You could say: *'I've tried that with my runway and trolley and tape'*.

(ii) You might say, *'It's obvious'*, or *'It's common sense.'* If you say that, aren't you really saying *'I've tried it'*? (Common sense is just the things you have seen and know). Then answer *(i)* would look a little better than *(ii)*.

(Of course you might have missed the first few weeks of school and have never used a runway and have only heard about those experiments. Then, *'I am guessing'* might do; but a better answer—more like a scientist's—would be, *'I don't KNOW, but I've been TOLD that pupils put the book under the starting end'*.

Sometimes a question has an extra part which is more advanced, like Question C. That takes some thinking and needs physics that you know.

Question C. Can you invent a way to find out, using a timer and tape, whether your lab table is exactly level? (It may be sloping too little for you to notice just by looking at it; and in that case you would not know the direction of its slope either.)

Answer C is not given here. Question C is left as a puzzle for the future. You should be able to answer it when you have finished your experiments with trolleys and tape—soon in this Year's work. Wait until then. Answering this question will need some remembering and thinking and guessing. There won't be many as puzzling as that.

Many questions, particularly at the beginning of the year, just need ordinary knowledge. Always look for a common-sense answer first. Don't try to make up a complicated 'scientific' answer with long words instead. Use things you already know, with some of the science you are learning.

Some questions are not so definite. They ask for discussion, or want your opinion about something. Try using imagination as well as things you know. Question D is like that. You might meet it in an exam; but there too you will succeed with ordinary thinking—and extra thinking might bring you some extra reward.

Question D. Suppose you are at the bottom of a hill and must get to the top as quickly as possible, at all costs. Which will get you there quicker, running up the hill or cycling?

Answering Question D. If you meet a question like that you should not think it wants you to find a strange scientific answer, such as some special argument about energy, or a discussion of changes of momentum, which you might not even have met so far. (If the question did expect you to give special scientific reasons it should say so clearly like this: 'Discuss the energy-changes in the two methods and from those calculate the power involved.')

Question D does not say that. It simply wants an ordinary answer from the things you know. Remember that, when you meet questions in science. Think first if an ordinary answer will do.

You should not worry and think you *have* to give extra comments or experimental results. The simple answer that we mentioned here is enough, unless the question asks for more.

But if you think of some extra things you should write them down. They are the result of thinking things out with the help of all the ordinary things you know—that is what scientists try to do.

Answer D. The good answer is the obvious one: '*Cycling is quicker.*'

You might add, '*because I can make the bicycle tyre move faster than I can make my feet move,*' and that should get an extra mark—giving a reason is usually a good idea.

You might be cunning and add a special exception: '*If the hill is very steep, like a road straight up a mountain, I might not be able to pedal my bicycle. In that case, running or walking uphill would be quicker; because if I had the bicycle I should have to walk it with me. I should have to make the bicycle climb as well as myself.*' (That should get a bonus mark or two.)

If you wanted to make an extra good impression, you might do an experiment then say '*I have tried cycling up a hill which is not very steep, and then running up the same distance. 100 metres took about 15 seconds on my bike, and about 40 seconds running.*'

And if you wanted to be specially clever and ingenious you would make experiments with steeper and steeper hills. You might come to the conclusion: '*The steeper the hill, the less the advantage cycling has over running.*'

Question E. (THIS IS NOT A PHYSICS QUESTION. It is just a riddle; but it gives you an example of the way our questions ask for ordinary thinking.)

Think about all the men with beards, in the United Kingdom. Suppose you have counted the number of BLIND MEN with beards and the number of SEEING MEN with beards.

a. Why are there more SEEING MEN with beards than BLIND MEN with beards?

b. Out of every 1000 BLIND MEN there are, say, 500 with beards. Out of every 1000 SEEING MEN there are say, 300 with beards. Why is the fraction (or proportion) of blind men with beards greater than the fraction of seeing men with beards? That is, why do blind men have beards more often than seeing men?

Answer E a. Just common sense: '*There are more of them, more seeing men than blind men.*' (Remember the riddle 'Why do we get more wool from white sheep than from black sheep?' Answer: 'Because there are more white sheep.')

That answer is just ordinary knowledge. If you aim at a simple answer you will get it. It is so simple that you may fear it is only leading you up to a harder question (b). But don't let that fear trick you into thinking that (b) needs a strange, complicated answer.

Think about part **E b**. If ordinary thinking doesn't help you to guess why beards are more welcome to blind men, try turning the story the other way round, and think about CLEAN-SHAVEN men. Ask 'What makes a CLEAN-SHAVEN face less easy for BLIND MEN than for SEEING MEN?' Now can you answer (b)?

Answer E b. *Shaving is rather harder or at least more risky.* (If you add, '*But in a country where every man uses an electric razor, the story might be untrue*', you should hope for a bonus mark.)

CHAPTER 1

MOTION

Experiments for catching up; acceleration; free fall; weightlessness

A NEW EXPERIMENT: MULTIFLASH PICTURES

This is a chapter about measuring motion. It prepares for the next chapter which is about the way forces make things move—cars starting up or coming to a stop, rockets being hurled upward. . . .

Start the year by looking at a new way to find out about moving things. Take a lot of pictures *on the same frame of film*, making sure that these snapshots are taken regularly, say every $\frac{1}{25}$ second from each to the next.

Demonstration 1
Free fall in multiflash photos

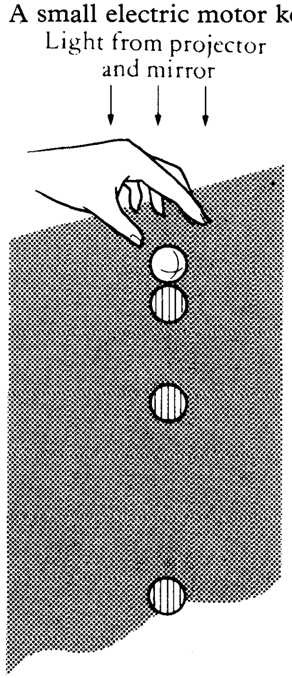
A small electric motor keeps a cardboard disk spinning steadily. The disk has slits cut in it near the edge. So it is a motor-driven strobe disk (remember Experiment 5 in Year 3, with hand stroboscopes).

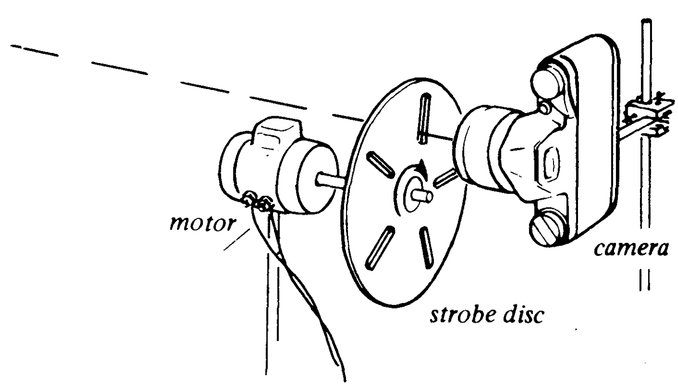
Instead of looking through the slits yourself, let a camera look through them at a falling ball.

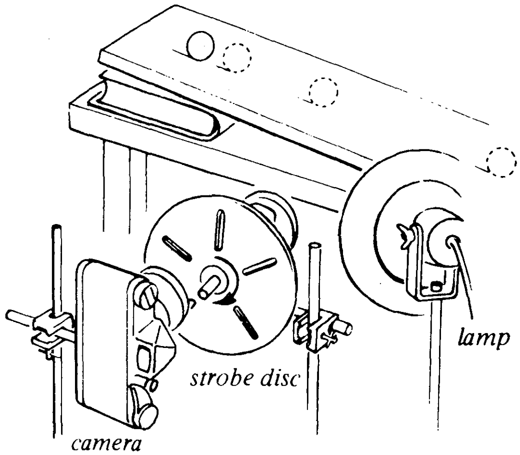
The camera's shutter is kept open, so each slit in turn lets the camera take a snapshot—all on the same piece of film.

Watch the picture being taken and ask for a print of it. Look at it carefully.

What does the picture tell you?







Demonstration 2
Motion down a hill in multiflash photo
(OPTIONAL EXTRA)

You may see a multiflash picture taken of a ball rolling down a hill.

If so, obtain a print of the picture. What does it tell you about the ball's motion?

---

* This is for a blade *magnetised* by a.c., pulled by a permanent magnet.

Demonstration 3
The 'frozen pearls'

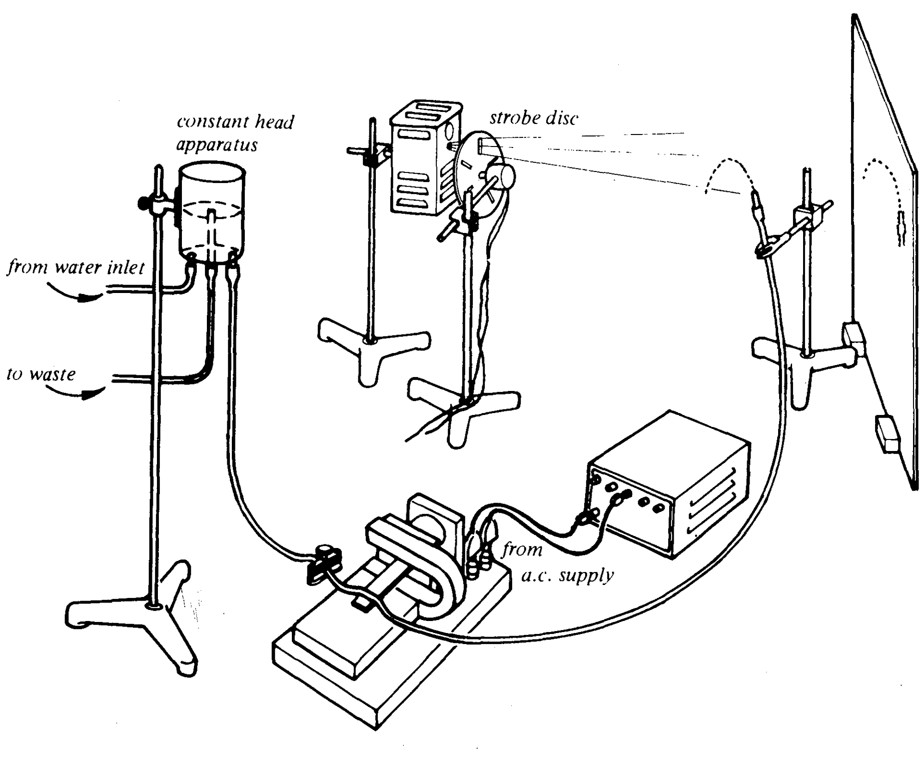
If you have not seen this demonstration of water drops before, watch it now.

A thin stream of water comes squirting out from a nozzle, fed through rubber tubing from a high tank. The tubing is draped over a vibrator which gives it a small jolt 50 times a second. Those jolts make the water come out in a regular series of drops, one every $\frac{1}{50}$ of a second.*

As the drops fly up and over and down in a parabola, they move too fast for you to see them as separate drops—you just see a stream of water. But if you look at the drops in flashing light, as in a multiflash arrangement, you may see the drops 'frozen'. The flashes will have to come at exactly the right rate so that between one flash and the next each drop 'moves on one'.

See the demonstration with the drops shown as shadows on a white wall. Look at the pattern carefully and see how far the drops seem to move on *sideways* from one flash to the next. Can you see a simple story about the 'sideways distances'? What does that tell you about the motion of a projectile?

Also see what happens when the flashes come a little too slowly or a little too fast.

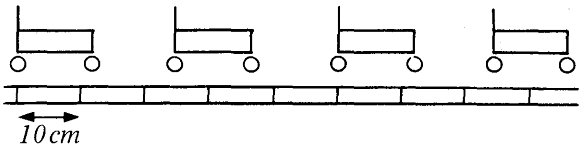


Progress Questions

MULTIFLASH PICTURES

(Do not answer these unless you have seen a demonstration.)

FIG 1a



1a. Fig. 1a is a multiflash photo of a trolley moving to the right along a runway. A picture was taken every $\frac{1}{4}$ second.

(i) How can you tell that this trolley was moving at a steady speed?
(ii) Look at this picture. Say how far the trolley moved in $\frac{1}{4}$ second.
(iii) How far did the trolley move in one whole second?
(iv) Write down the speed of the trolley in cm per second.

b. Fig. 1b is a multiflash picture of the trolley in a second experiment, again with one picture every $\frac{1}{4}$ second.

(i) Is it moving faster or slower than in the first experiment? How can you tell?
(ii) How far does the trolley go in $\frac{1}{4}$ second?
(iii) How far does it go in one second?
(iv) What is the speed in cm/s?

c. Fig. 1c shows the results of a third experiment.

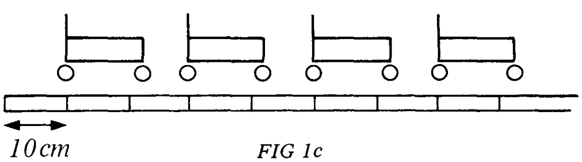


FIG 1c

(i) Is it moving faster or slower than in the first experiment? How can you tell?
(ii) How far does the trolley go in $\frac{1}{4}$ second?
(iii) How far does it go in one second?
(iv) What is its speed in cm/s?

2. Fig. 2 shows two multiflash (or stroboscope) pictures of a moving ball (A and B). A photograph was taken every $\frac{1}{25}$ of a second.

a. In which case, A or B, was the ball moving at *constant* speed?

b. How do you know?

c. In which case was the ball *accelerating*? How do you know?

d. Use a centimetre ruler. Measure the distances between the centres of the balls in line B. The first one is 1 cm, so we can write:

In first gap, distance travelled in $\frac{1}{25}$ s = 1 cm.
In second gap, distance travelled in $\frac{1}{25}$ s = . . ? . .

Continue like that and write down all the measurements in a table like this:

Gap No.	*1*	*2*	*3*	*4*	*5*	*6*	*7*	
Distance (cm in 1/25 sec.)	*1*	*?*						
Increase	*?*	*?*	*?*	*?*	*?*	*?*		

e. Now look at the way the speed *INCREASES* all the time. Fill in the third row of the table.

f. What do you notice about the increases in speed?

g. What can you say about the acceleration?

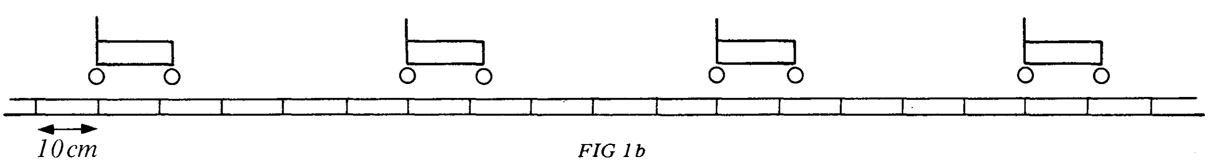


FIG 1b

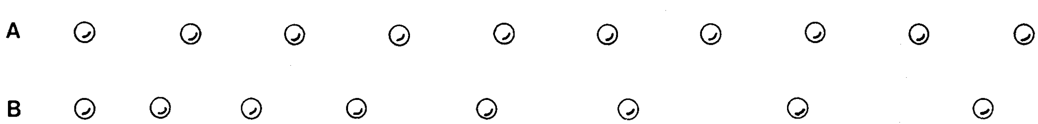


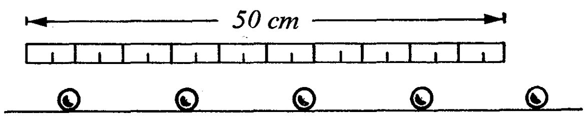
FIG 2

Questions

MULTIFLASH PICTURES

(Do not answer these unless you have seen a demonstration.)

3. The figure represents a multiflash photograph of a ball rolling along a flat surface. The rate of flashing was 1500 per minute.



a. What sort of motion did the ball have?

b. Can you tell which way it was moving?

c. What was its speed?

4. The figure represents a multiflash photograph of a ball falling after being held and released.

a. What can you say about the motion of the falling ball, simply by looking at a picture like sketch I?

b. Why is the picture likely to be rather confused at the beginning, A?

c. Why is the picture likely to be rather blurred at the end, B?

d. Suppose a multiflash picture had been taken of something moving with constant speed, what would it have looked like? (Answer by a sketch.)

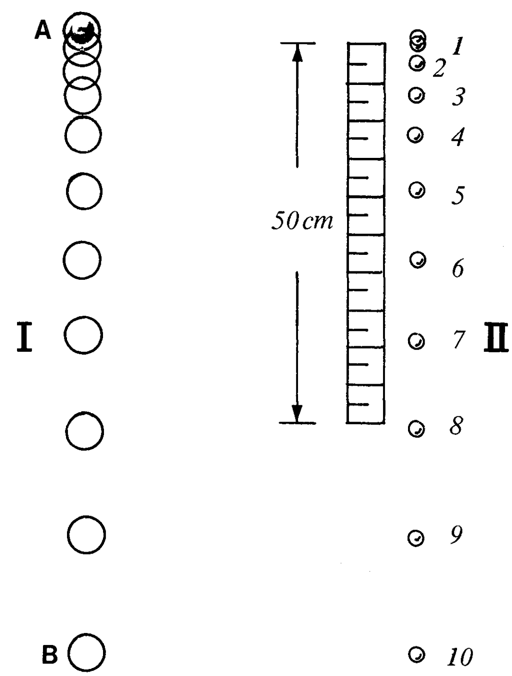
e. These pictures are taken with a white or polished ball and a black background. A boy tried to take a picture with a black ball against a white background. Result—no sign of the ball in the photo at all. How do you explain this?

5a. You will probably guess that sketch II represents a ball falling from position 0 to position 10, but could you really be sure of this from the diagram? Could it be going upwards from 10 to 0?

b. Give a reason for your answer.

c. Assuming the ball is falling from 0 to 10, what can you say about its motion?

Note: Multiflash pictures can tell you the ACCELERATION of the moving object. See Questions 50, 51.



NOTES FOR CATCHING UP AND LOOKING AHEAD

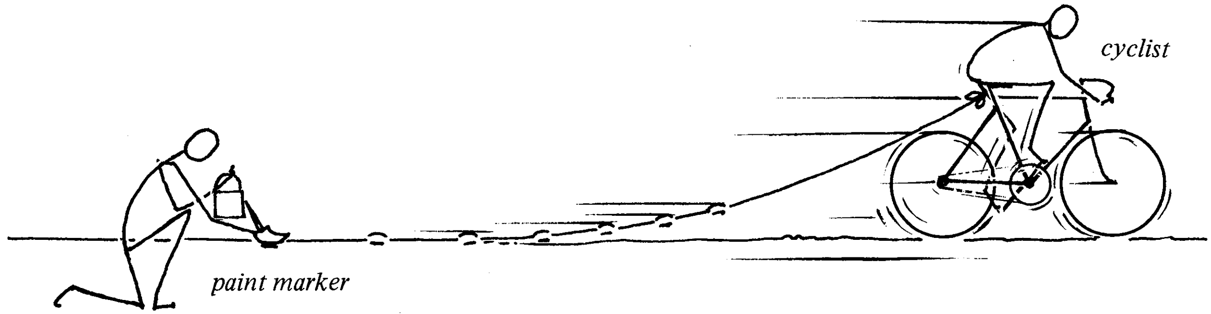
† *TAPE RECORDS AND CHARTS**

A moving trolley drags a tape through the timer; then you mark your tape at an early dot, no. 0, and at dot no. 10, and dot no. 20, etc. You cut your tape at each mark so that you have strips of tape that each took 10 ticks to pass through—each took one 'tentick'.

If you measure the length of one strip in centimetres, that tells you how many centimetres the trolley travelled in one tentick. That is the speed of the trolley in *cm per tentick*.

Suppose you tie a long string to the back of your bicycle and ask someone to stand still nearby and put a splash of paint on the string exactly once every second as you bicycle away dragging the string behind you. The length of string between paint splashes, one every second, will show you how far you bicycled in each second. If you

* The sign † means an experiment or an explanation that will help you to catch up with work that you may have missed earlier. But if you have already done that work you need not repeat it now—there are more important new things ahead.



measure the distance from one splash to the next in metres, this is the distance travelled in one second. So it also tells you your speed, in *metres per second.*

(If your speed is changing as you bicycle along. that measurement will only give an *average* speed for each period of one second.)

How would you measure INCREASES of speed?

† *THE MEANING OF 'PER'*

'*Per*' means '*in each*' or '*for each*'. Examples: 'I earn £10 per week'; 'the price is 12p per orange'; 'eggs cost 90p per dozen'.

The slanting stroke, /, is a short way of writing 'per'.

Try writing those wage and price statements in other words, without using 'per' or the stroke /.

What does '*per cent*' or % mean in other words?

A car's speed of 50 kilometre *per* hour means a speed that would carry the car 50 kilometres *in each* hour—if the car kept up that speed.

† *SPEED*

SPEED is $\frac{\text{DISTANCE TRAVELLED}}{\text{TIME TAKEN}}$. If the distance is measured in metres and the time in seconds, the speed is in metres per second.

You may write that description of speed in symbols $v = \frac{s}{t}$ where v stands for speed or velocity and s for distance travelled. Then the 'formula' $s = vt$ is a useful thing to remember.

Every car has a speedometer that shows speed directly; but someone had to put the marks and numbers on the dial.

For a car, *kilometre per hour* (or mile per hour) are units for speed just as *metre per second* are units for your running speed or *centimetre per tentick* are units for a trolley and tape.

† *ACCELERATION*

When you drive a car faster and faster you say you are accelerating. You say the car, or its motion, has an acceleration. In science, we like to *measure* things connected with motion. So instead of just saying 'faster and faster' we choose a more definite description and say ACCELERATION is the GAIN OF SPEED IN EACH SECOND.

Suppose a car is driving at 10 kilometre per hour as it passes you; and 10 seconds later it is running at 30 kilometre per hour. It has been accelerating. Its GAIN OF SPEED* is [30 km/hour—10 km/hour] or 20 km/hour. Then we say:

Car's ACCELERATION

$$= \frac{\text{gain of speed in 10 seconds}}{\text{the 10 seconds taken to make that gain}}$$

$$= \frac{20 \text{ km/hour}}{10 \text{ seconds}}$$

$$= 2 \text{ km/hour per second}$$

(meaning 2 km/hour gain of speed in each second)

Notice that acceleration has strange-looking units. Time comes in twice over, because the '*hour*' belongs in the *change of speed* and the '*second*' belongs to the *time taken for that change.* You must not cancel them out—they both belong there.

Suppose you are running slowly to catch a train. As you see the train coming into the station, you run faster and faster. When you first see the train, you are running 2 metre/second. But 10

---

* A useful symbol: We can write 'gain of' or 'change of' with a Greek capital D for 'difference'. That is $\triangle$.

$$\text{Then acceleration} = \frac{\triangle\ (\text{SPEED, or VELOCITY})}{\triangle\ (\text{TIME})}$$

$$= \frac{\triangle v}{\triangle t}$$

seconds later you are sprinting at 7 metre/second. Then your acceleration is:

$$\frac{7\text{ metre/s} - 2\text{ metre/s}}{10\text{ seconds}} = \frac{5\text{ metre/s}}{10\text{ seconds}}$$

$$= \tfrac{1}{2}\text{ metre/second in each second}$$

$$\text{or } \tfrac{1}{2}\text{ metre/second}^2$$

The unit for acceleration is called 'metre per second squared' (m/s^2).

† *CONSTANT ACCELERATION*

If the ACCELERATION of a moving object remains the same as the object moves faster and faster, we say it is *constant* acceleration. That means the object makes the same gain of speed in each second.

If you had a tape chart for something with constant acceleration you would see heights of tentick strips jumping up by the same amount from each strip to the next, like the steps of a staircase.

You will meet some examples of constant acceleration in nature. Yet there are many other motions that do not have constant acceleration. (Think of a pendulum swinging to and fro, or a horse increasingly eager as it gets nearer home, or a spaceship falling from Moon to Earth.)

† *VOCABULARY: STRANGE NAMES*

Here are some names of things we measure and calculate. You will soon understand them when you use them.

Forces These are pushes and pulls. You can exert a force with your hands or feet, using muscles. Or you can use a spring or elastic thread or a rubber band. Or you can pull or push on a rod (a rod is really elastic but it is so strong that you can hardly see it stretch or compress).

Measuring forces We say how big a force is by measuring in newtons. Hold one kilogram on your hand and feel the Earth pulling down on it with a force of almost 10 newtons.

Mass Mass tells us how much stuff there is in a thing. We measure mass in kilograms. A kilogram of chocolate (over 2 lbs) would still be a kilogram on the Moon, still as much nourishment—still too much to eat and digest at one go. MASS is a useful idea in physics and you should get to know it well in the course of this year.

Velocity SPEED tells you how far something travels in each second. VELOCITY is a combination of speed and direction. A VELOCITY of 250 ***kilometre per hour due north*** will fly you from London to Scotland in two hours. A VELOCITY of 250 ***kilometre per hour due west*** will carry you from London far out of England in two hours.

Momentum People say that a car which is speeding up is gaining momentum. Then, if its engine fails and the brakes are off, momentum carries the car on some distance, even on a rough road.

In science we can calculate that useful thing momentum as

MASS × SPEED

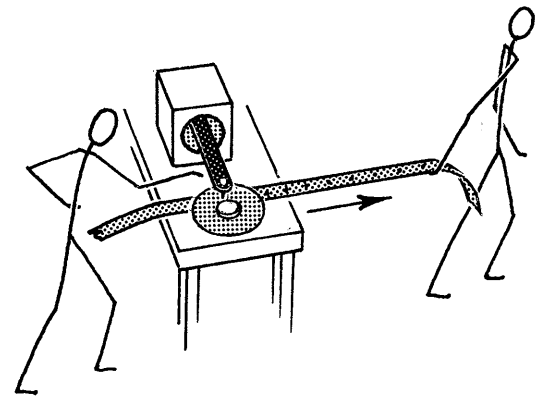
(or, more professionally, MASS × VELOCITY).

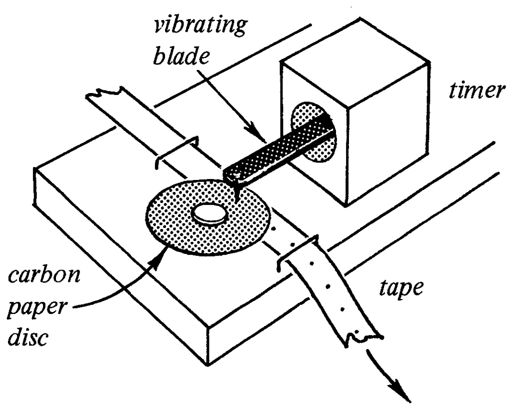
Energy This, as you know, is the important thing we get from food, from oil, from gas, from electric supplies . . ., to run our muscles, our cars, our house heating and lighting. . . . You will learn a lot about energy this year and you may change your mind as you learn more and more; so the best advice about it now is 'wait and learn'. It will become clearer—treat it for now as a giant with a black mask.

g is the acceleration of any object that is falling freely (near the Earth). You have tried letting a large heavy stone and a light one fall side by side. (If not, try that important experiment. Make sure you let both go at the same instant.) Tests show that a falling stone has *constant* acceleration—its acceleration does not change as it falls faster and faster. So there is something that stays the same—something worth naming and measuring. We name it g and measure it just by letting something fall and timing the motion. The experimental result is $g = 9.8$ metre/second squared—almost 10.

Experiments for catching up *If you missed the experiments of Year 3 with a trolley and a ticker-tape timer to measure motion,* catch up quickly by trying one or two experiments with them now. These are marked with the sign†.

If you did those experiments and made a tape chart to look at acceleration, you should skip this section and do Experiments 11, 12, . . . Even if you don't remember last year's experiments fully, you will do best to jump ahead. The new experiments will give you enough revision of the old ones.





† **Using a timer and tape** The timer runs like a fast electric bell, beating out time regularly. Its blade has a small knob that hits carbon paper and makes a dot on the tape at each vibration. When the tape is dragged through the timer the dots are marked on the tape at equal time intervals—not at equal spaces along the tape.

So the timer is like a clock ticking very fast and recording its ticks on the tape.

Examine the timer and make sure you know how it works. If you like, watch its vibrations with a hand stroboscope. Then use the timer to investigate several kinds of motion.

† Experiment 4
Timing your own walk *(OPTIONAL)*

Use the vibrating timer to record your walking trip on tape. The timer hits the tape regularly and makes a mark 50 times a second. We call the time from one hit to the next one *tick*. So the dots on the tape are spaced *one tick of time* apart.

You will find ten ticks make a useful length of time, so we shall call that one '*tentick*'. That is the time from dot no. 0 to dot no. 10 on the tape. (Also from dot no. 10 to dot no. 20 and so on.)

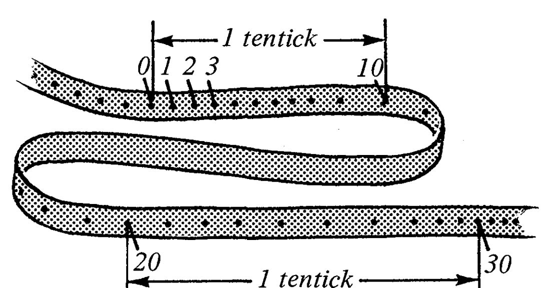
Let your partner operate the timer while you walk away from it, pulling the tape. Also try running.

The dots are made by the vibrating blade at regularly spaced *times*. But they will not be equal *distances* apart along the tape, because you do not walk at absolutely constant speed.

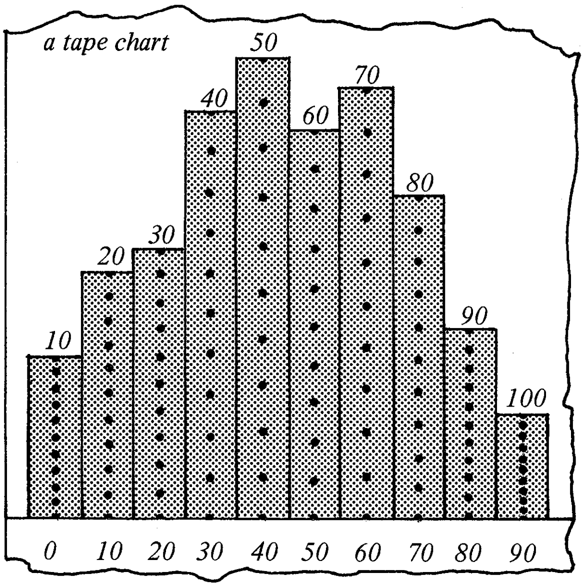
Find out how far you walked in the first 10 ticks. Measure from dot no. 0 to dot no. 10. That is how far you walked in one *tentick*.

Make a tape-chart. Cut off the strip of tape for the first tentick period of your walk and paste that on a sheet of paper.

Cut off the next tentick strip and paste that strip beside the first one, and then the next, and so on, for all your tape. Each strip shows how far you



walked in one tentick of time. Paste all the strips on your chart with their feet on the same line at the bottom; then their heads will show you how your speed changed as you walked.

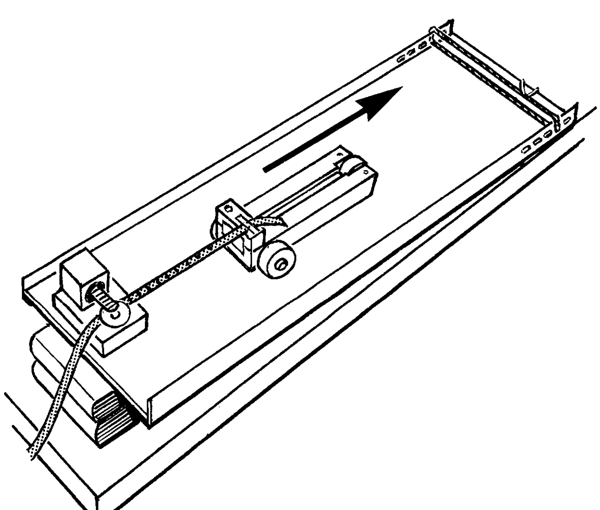


† Experiment 5
Car coasting down a hill *(OPTIONAL)*

Tilt the runway to make a slope of about 1 in 10 by placing blocks of wood or books under one end.

Let the trolley run down the incline, starting from rest and dragging tape through the timer.

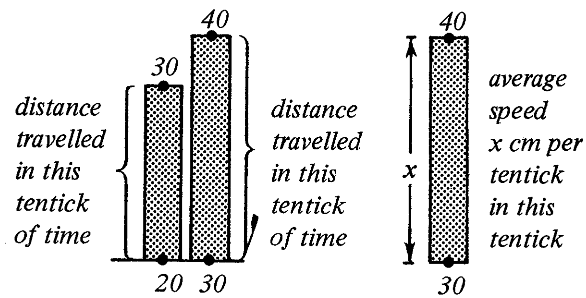
Repeat the run, so that each partner obtains a tape.

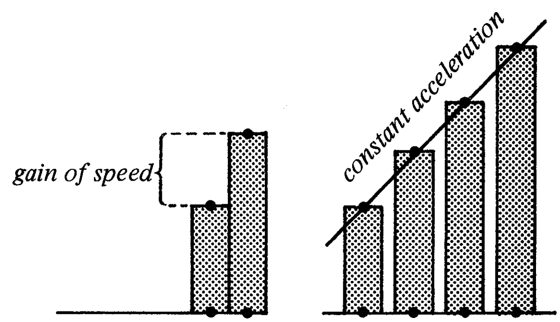


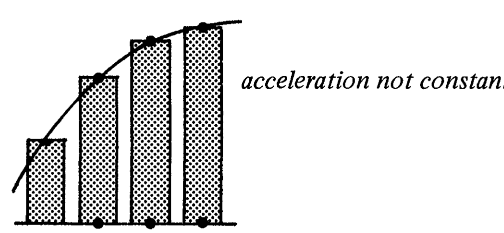
Cut your own tape into tentick strips as in Experiment 4 above. Paste up a tape-chart. Put all the tentick strips side by side with their feet all on a horizontal line, as in Experiment 4.

Look at your chart. *What does it tell you about the motion? Does it show that the trolley ran faster and faster?*

Does the pattern of your tape-chart tell you anything clear and simple about the way the trolley CHANGED *its speed? (Hint: look at the increases of length from each strip to the next.)*







† Experiment 6
What stays the same?

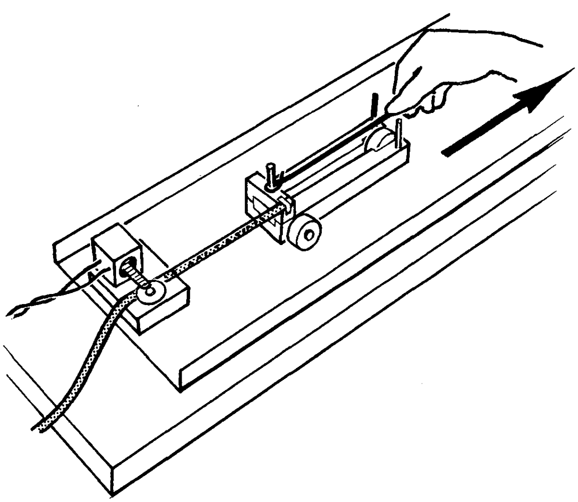
Find out the way a cart moves as you pull it with a steady force along a flat road without friction. We call our cart with three ball-bearing wheels a 'trolley'.

Please be careful of your trolley's wheels. They are easily damaged by traffic accidents—then your experiment will be more difficult and less reliable.

To pull with a steady force, use an elastic cord with a ring at each end. *Stretch the cord the same amount all the time.* Put one ring on the post at the back of the trolley and pull the other ring to stretch the cord till the ring is just level with the front end of the trolley.

(If you prefer, put a pencil through the front ring and hold that level with the front posts on the trolley.)

Let the trolley start from rest. Pull it with steady force. Keep the cord at the same stretch as the trolley runs faster and faster.

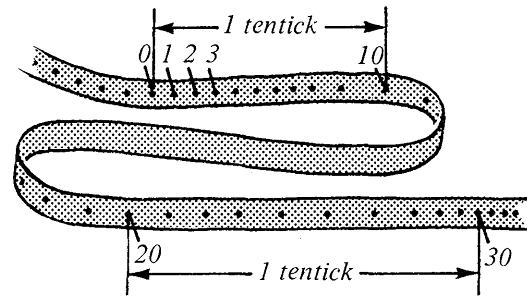


At first this may seem hopelessly rough, but you will soon gain skill. Stand beside the runway; walk if necessary, but do not run. (Or you may let your partner take charge of the timer and tape. For the start he holds the trolley still and gives a signal to you when he releases it.)

Take the tape that records your trip with the trolley. Let your partner have his turn at pulling. Each partner needs to make a tape of his own trip with the trolley.

Your tape and its chart. Cut your own tape into tentick strips.

In trying to see what kind of motion the trolley had, you should use only the part of the tape for which you think you kept the pulling force fairly constant. You may have to leave out the beginning and end parts of the tape. In the 'good' part of your



tape, choose a clear dot near the beginning of the tape and mark that dot 0 (*not* 1). Count ten spaces along and mark dot 10, then dot 20, and so on. Cut your tape at those marks, so that you have a set of tentick strips.

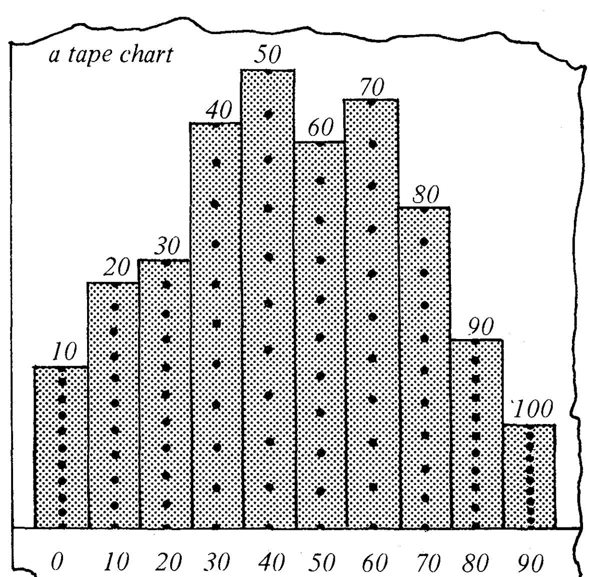
The length of each tape strip is the distance travelled by the trolley in one tentick. So the tape strips show you *distances* travelled in *equal times*.

Obviously it is not the *distances* that are equal; it is the *time* that is the same for all strips—one tentick for each.

Make your own tape-chart by pasting successive tentick strips side by side on a sheet of paper, with their feet all on a straight line.

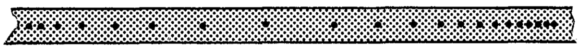
(If your tentick lengths are too long for the page when the trolley is moving fast, use fivetick lengths instead.)

Discuss the meaning of the tape-chart with your teacher.



Progress Questions

TAPES, MOTION AND TENTICKS

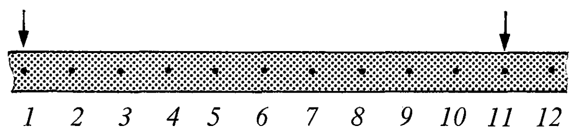


6. Here is a tape which a girl has pulled through a ticker-timer.

a. She started moving very slowly. How can you tell that?

b. Suppose she had pulled it through at a steady speed. What would the tape look like?

c. She didn't move at a steady speed. Describe the way she did move.



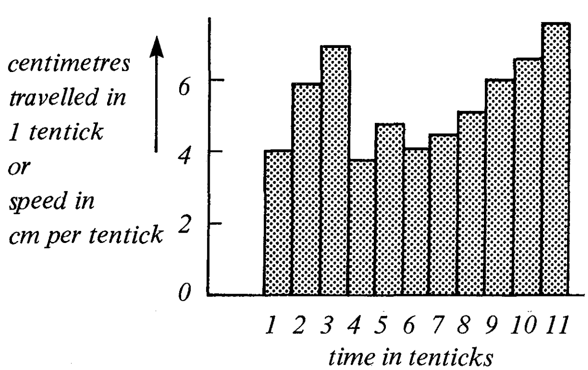
7. The timer marks 50 dots in a second, so the time between dot 1 and dot 51 is 1 second. Copy the sentences below and fill in the blanks as you write:

a. The time between dot 1 and dot 2 is . . ? . . second.

b. The time between dot 1 and dot 11 is . . ? . . second or one tentick.

c. How far was the tape above pulled in one tentick? Measure the sketch in centimetres.

8. After an experiment, a ticker-tape was cut into tentick lengths. They were stuck next to each other to make a chart:



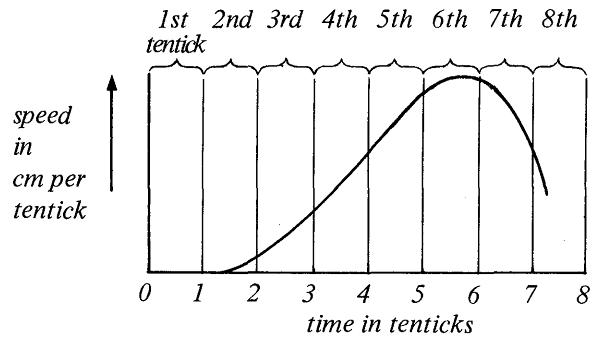
a. During which tentick was the speed greatest? What was that speed?

b. During which tentick was the speed least? What was that speed?

c. Between which two tenticks did the speed increase most? How much did it increase?

d. Between which two tenticks did the speed decrease most? How much did it decrease?

e. How far was the tape pulled during the first three tenticks?



9. Here is a speed: time graph of a girl sprinting across the lab. The lengths of tape strips have been left out of the picture.

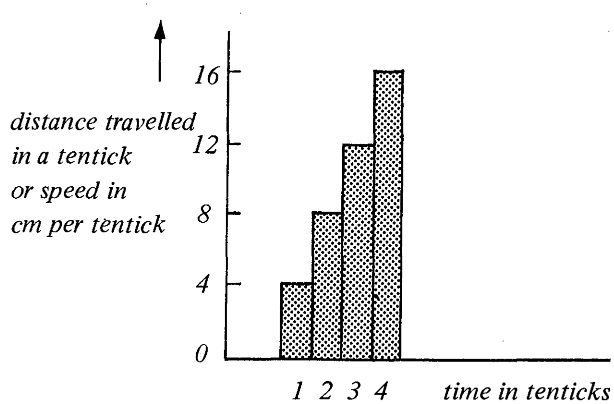
a. Describe the way her speed changed as she moved.

b. During which tentick was she moving fastest?

c. When she started moving was her acceleration constant or changing?

TAPE-CHART AND ACCELERATION

10. A trolley ran down a sloping plank pulling a tape behind it. The tape was cut into tentick strips. Here is a tape-chart of the speed against time.



Copy the sentences below and fill in the blanks:

a. The trolley moved . . ? . . cm during the first tentick. (Look at the picture and find your answer from the numbers on it.)

b. The trolley moved . . ? . . cm during the second tentick.

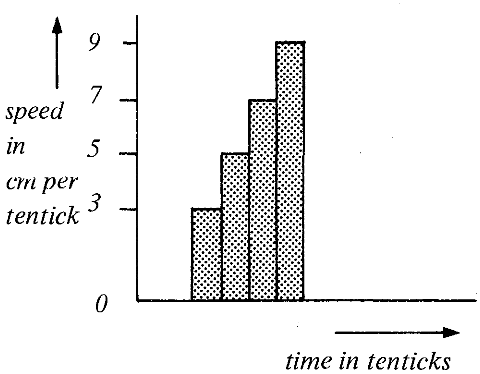
c. So the increase in speed between tentick 1 and tentick 2 was . . ? . . cm/tentick.

d. The increase in speed between tentick 2 and tentick 3 was . . ? . . cm/tentick. This increase of speed happened during one tentick.

e. The increase in speed between tentick 3 and tentick 4 was . . ? . . cm/tentick.

f. The increase in speed in a certain time is called the ACCELERATION. So the acceleration of this trolley was . . ? . . cm/tentick in every tentick, (or . . ? . . cm per tentick in every 5 tenticks).

11. Here is another chart with speeds growing bigger as time goes on along. The chart shows the motion of a trolley moving with constant acceleration.



a. Is the acceleration bigger or smaller than in question 10?

b. What is the increase in speed between
(i) tentick 1 and tentick 2?
(ii) tentick 2 and tentick 3?
(iii) tentick 3 and tentick 4?

c. How much is the acceleration of this trolley (in cm per tentick in one tentick)?

d. How far (in centimetres) did the trolley move during
(i) the first tentick?
(ii) the second tentick?
(iii) the first two tenticks?

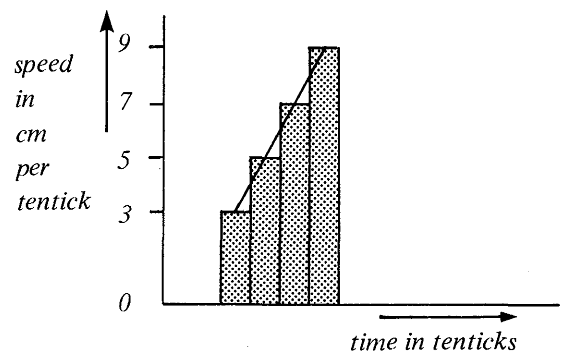
e. How far did the trolley move during the first four tenticks?

12. Look at the patterns the charts made in questions 10 and 11.

a. How can you tell from the patterns that the trolleys each have unchanging acceleration (or are 'accelerating steadily').

b. How can you tell which has the biggest acceleration?

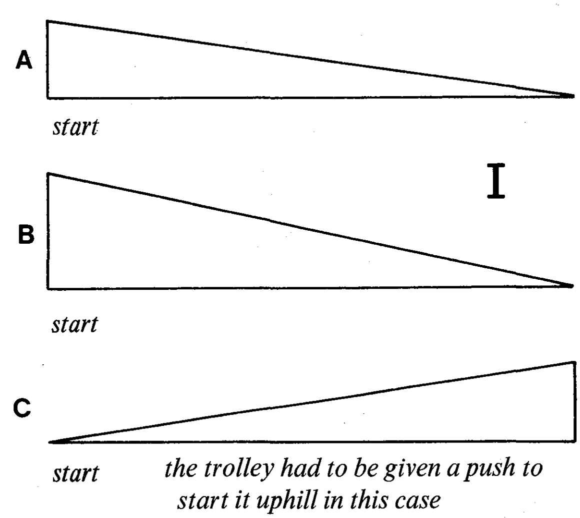
13. Here is the speed:time chart of Question 11. A slanting line is drawn through the tops of the tape lengths. That line may be called a speed:time graph.



a. Suppose you made a tape-chart of something moving with a bigger acceleration. Sketch the new line through the tops. (Show the old line on your sketch too, for comparison.)

b. Suppose you made a tape-chart of something moving with a steady speed. Sketch the line you would get.

14. Three experiments were done with a trolley and tape on a hill.



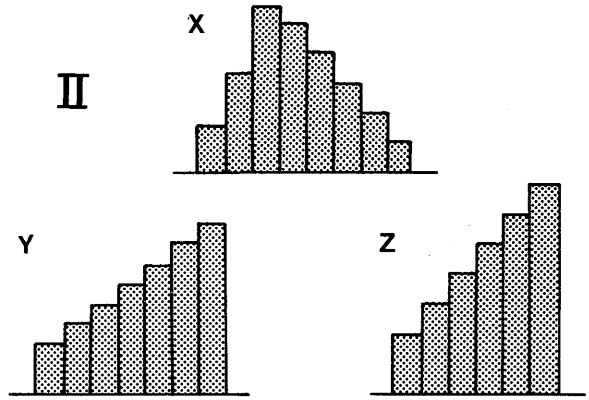
Then the tape was cut into tentick strips. The strips were stuck on a sheet of paper to make a chart.

a. Which of the three charts sketched in II most likely fits A? Which fits B? Which fits C?

b. When you do experiments of your own, the patterns are not usually as regular as these. Suggest possible explanations for this.

c. Suppose you wanted to do the experiments of C. How would you arrange the tape?

II



Questions

VIBRATORS AND TAPE

† **15a.** Two pupils have a stopwatch as well as a vibrator and tape. Their vibrator runs at an unknown rate. They want to find 'How many ticks in 5 seconds?' Tell them how to do this.

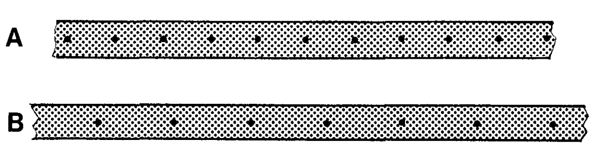
b. They make four 'runs' and count the number of dots in each 5-second run.

The four counts are: 285, 332, 306, 298. How should they calculate their best estimate of the number of ticks (dots) in 5 seconds; and what result should they get?

c. Suggest two or three important reasons why the counts are not all the same.

d. You are told that their vibrator is supposed to be making 60 dots in a second. Do you find the pupils' results agree with this? Write a sentence or two of explanation.

† **16.** In the sketch below A and B are diagrams of torn-off strips of tapes. Both of these represent the same type of motion, though with differing speeds. The vibrator makes 50 dots per second.



a. What type of motion do they represent?

b. What SPEED does strip A show, in centimetres per tick? (Use a ruler.)

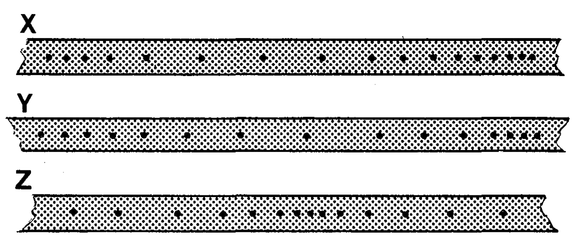
c. What SPEED does strip B show?

† **17.** Which of the tapes X, Y, Z in the sketch shows motion that:

a. Slowed down then speeded up again?

b. Reached the greatest speed?

Give a reason for each answer.



DILUTED FALL

† **18.** A trolley runs down a sloping plank. As it goes, it drags paper tape through a vibrator. Two pupils then cut up the tape into six lengths, the first from 'dot no. 0' to 'dot no. 10', the next from 'dot 10' to 'dot 20', and so on.

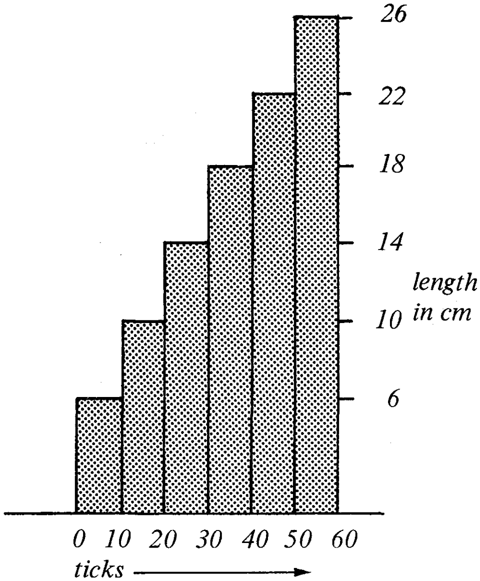
(For 'dot 0' they chose the first of the clearly marked dots, not the actual beginning of the trolley's movement because the dots were too close together to see clearly.)

They then stuck the six lengths of tape beside each other as in the figure opposite, which is drawn $\frac{1}{4}$ actual size.

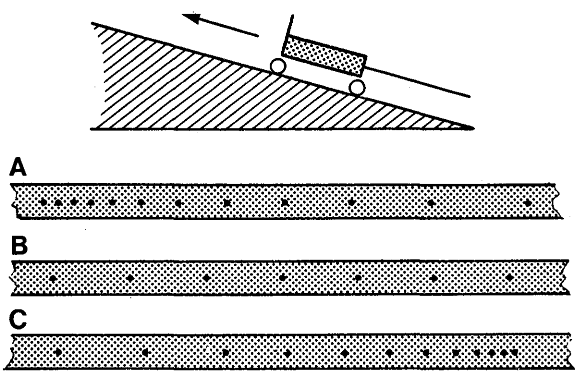
a. What does this tape-chart tell you about the motion of the trolley?

b. Give the reason for your answer to (a).

† From *Pupils' Text 3*.



c. If you can, calculate the acceleration of the trolley
(i) in cm/tentick in every tentick.
(ii) in cm/second in every second. (Remember 50 ticks make one second.)

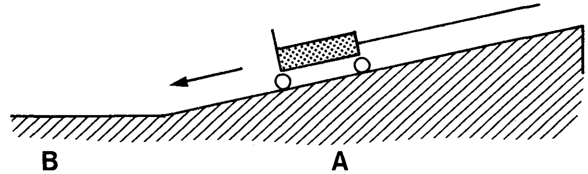


† **19.** A trolley is given a push *up* a hill from right to left so that it travels some way up before stopping. It drags tape through a vibrator. (See the sketch.)

a. Which looks like the tape record you would expect, A, B or C? If none of them look right, draw a fourth tape, D, which *does* look right.

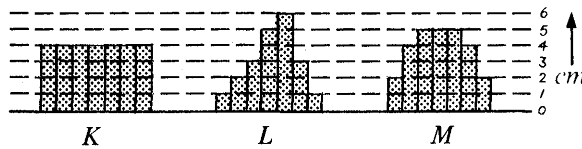
b. Give the reason for your choice (or for your new tape D) in answer (a).

† **20.** A trolley pulling tape through a vibrator runs down a sloping plank and on to a flat horizontal plank. Make a rough sketch of a piece of the tape with dots showing what happens when the trolley



passes from somewhere near point A to somewhere near point B.

21. A person pulls tape through a timer. Diagrams K,L,M show successive tentick strips of ticker-tape cut off and pasted side by side. In each case there are seven pieces. The scale shows their heights in centimetres. The dots at the start and the end were too close to count properly, so the diagrams show only the middle sets of tenticks (70 ticks in each).



a. Describe briefly the kind of motion followed by the person pulling the tape through if the result is (i) like K, (ii) like L, (iii) like M.

b. So far as you can tell from the charts, which tape K, L or M reached the greatest speed? And what was that speed in cm per tentick? (Remember that the length of each strip of tape is distance moved in a time of 10 ticks.)

c. Actually it seems likely that the greatest speed reached was more than the value you calculated in (b), though it lasted for a shorter time than 10 ticks. Why is that a sensible guess?

22. Look again at diagrams K,L,M of Question 21. Suppose a moving object pulled the tape in each case.

a. For the motion shown in K how far did the object move in 70 ticks?

b. How far in 70 ticks for the motion shown in L?

c. How far in 70 ticks for the motion shown in M?

23a. Assume the vibrator tapped out 50 dots in each second. Calculate the *average* speed for the whole time of 70 ticks shown in diagram K, Question 21. To do this, use the answer to (a). Remember that the time is 70 ticks ($=70$ lots of $\frac{1}{50}$ second $= 1.4$ seconds). Calculate by using:

$$\text{average speed} = \frac{\text{total distance moved}}{\text{total time taken}}$$

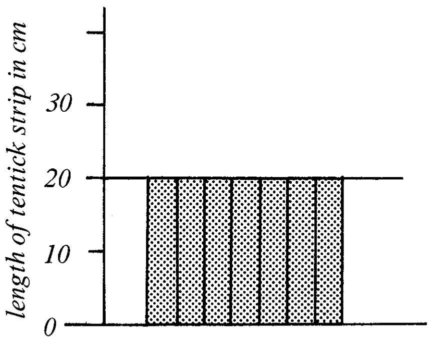
b. In the same way, calculate the average speed for the 70 ticks shown in diagram L.

c. Then do the same for diagram M.

d. The average speed you found in (a) is, of course, the actual speed of tape K throughout the time of 70 ticks. This is not true for tape L. Did tape L ever have the actual speed you found in (b)? If so, how many times did it have that speed?

Note: The question (d) could be asked about tape M, and the answer would be the same.

24.



a. Why does the sketch represent constant speed?

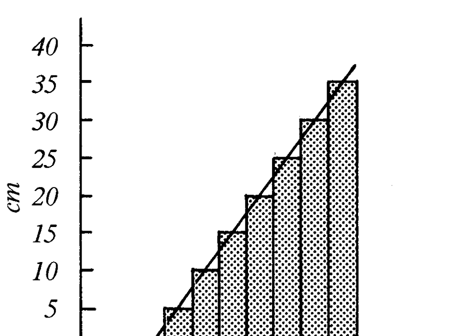
b. What is the value of the constant speed in cm per tentick?

c. If each paper strip above had been for 50 ticks instead of 10, how tall would the strips have been (for the same speed)?

d. If 50 ticks take 1 second, what is the value of the constant speed represented by the diagram, in cm per second?

e. What is the value of this speed in metre per second?

25.



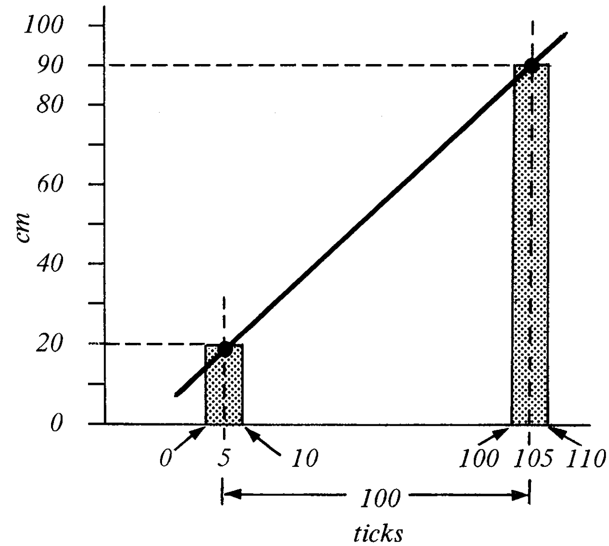
a. What type of motion does this represent?

b. By how much does the speed increase in every tentick interval of time? Give the increase in cm per tentick.

c. How much is this increase of speed in cm per second? (There are 50 ticks in one second.)

d. Answer (c) is the acceleration in *cm per second* in every *tentick*. What is the acceleration when measured in cm/second^2?

26.



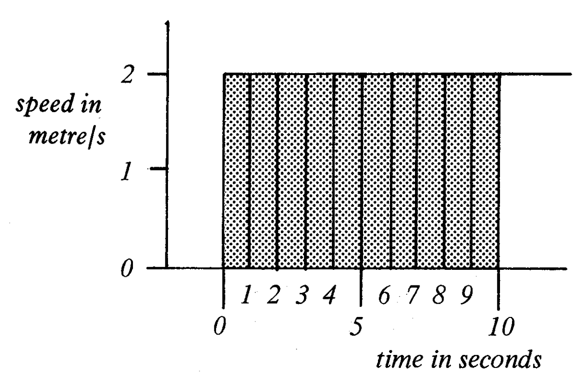
The figure shows two strips of tape. One runs from dot 0 to dot 10, then we count on another 90 dots, and cut off a length of tape that runs from dot 100 to dot 110. So these tapes are '100 dots apart'. And the time for 100 dots is 2 seconds.

a. Find the acceleration in cm/tentick per second.

b. Express the acceleration in cm/second per second.

GRAPHS AND DISTANCE TRAVELLED

27. The sketch shows a graph of the speed of a rabbit running across a field, plotted against time



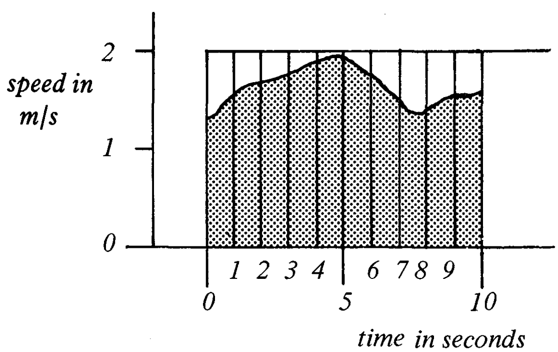
(in seconds). The rabbit's speed is the same all the way across, 2 metre per second.

a. How far did the rabbit travel in 10 seconds? (Use simple arithmetic.)

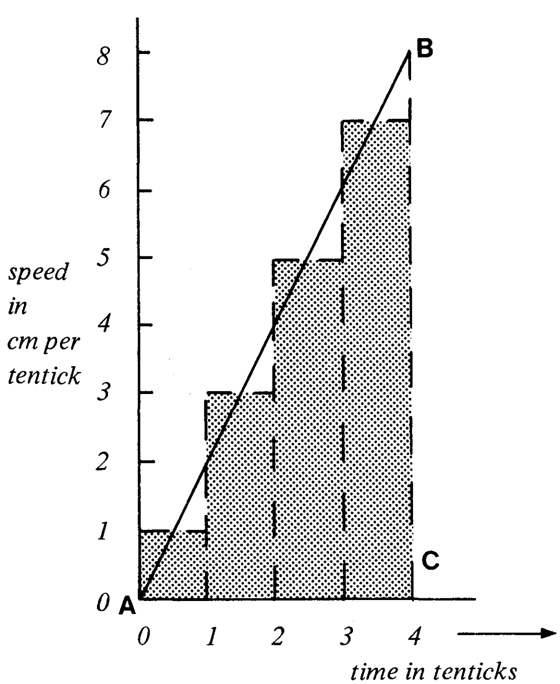
b. Look at the shaded patch under the graph line. Its height is 2 metre per second (on the scale used) and its width is 10 seconds (on the scale used). What is the area of that patch (on the scales used)?

c. What does that area tell you?

d. Suppose the rabbit did not run with constant speed as above, but its graph of speed plotted against time was irregular, as in the sketch below. You could still chop up the shaded area into pillars one second wide (on the scale used) and show that the area would tell you . . ? . .



28. Here is a speed:time graph for a cart running



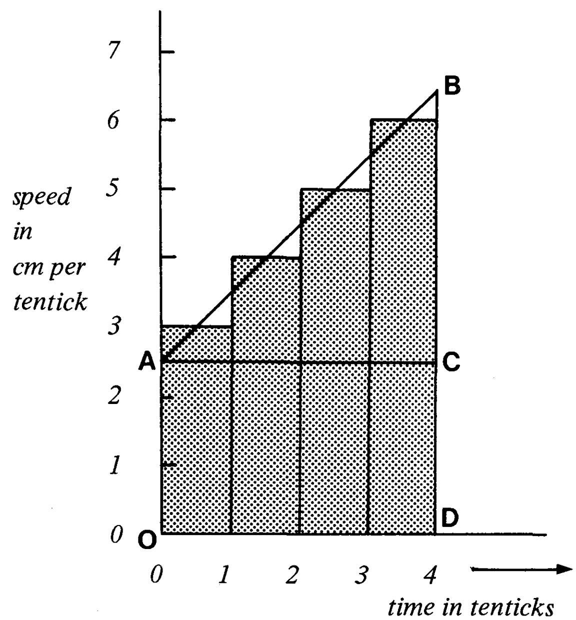
downhill with constant acceleration. The tapes of a tape-chart are shown dotted.

a. How far did the cart travel in the first tentick?

b. How far did the cart travel in four tenticks?

c. Work out the area of triangle ABC. (AREA of a triangle $= \frac{1}{2}$ BASE × HEIGHT)

29.



Here is a speed:time chart of a steadily accelerating object. (The object already had some speed when the first tape shown was taken.)

a. Add up the tape lengths to find out how far the object went in 4 tenticks.

b. Find the area OACD, and the area ABC and add these together.

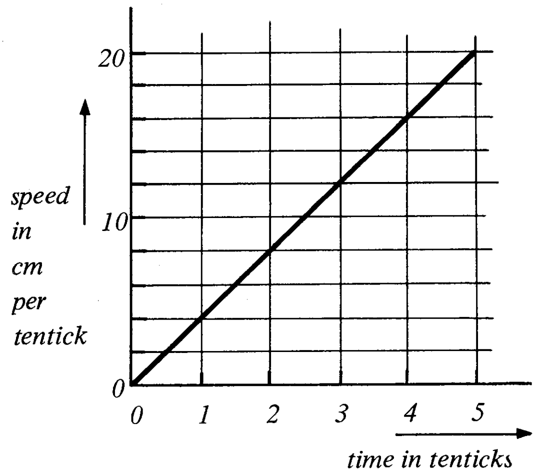
c. What was the speed at the start? What was the speed after 4 tenticks? What was the average speed?

d. Suppose, instead of accelerating, the object travelled *steadily* at the *average* speed. How far would it go in 4 tenticks?

e. Look at your answers to (a) (b) and (d). What do you notice?

30a. In questions 28 and 29 you have used three different methods to find how far something travels when it is accelerating. Look at them carefully then explain in your own words each of the three methods.

b. Use each of the three methods to calculate the distance covered in this case. (You may want to copy the graph and draw in the tapes of the tape-chart.)

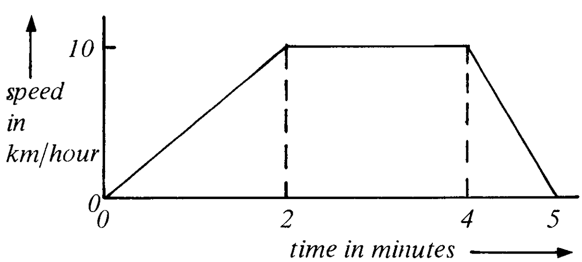


c. See if you can collect your calculating methods into a piece of algebra.

An object starts from rest, and has constant acceleration. At the end, the time is t_{final} and the velocity is v_{final}. What is the distance covered?

Write an equation, calling the distance s.

31.



Here is a speed:time graph of a journey of a milk float.

Copy the sentences and fill in the blanks.

a. The increase in speed during the first 2 minutes is . . ? . . km/hour.

b. So the acceleration during the first 2 minutes is . . ? . . km/hour in a minute.

c. The increase in speed during the next 2 minutes is . . ? . . km/hour.

d. The decrease in speed during the last 1 minute is . . ? . . km/hour.

e. So the deceleration during the 1 minute is . . ? . . km/hour in a minute.

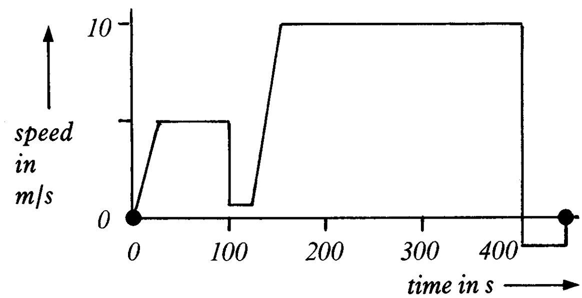
f. The distance travelled in the first 2 minutes is . . ? . . kilometres. (Use one of your methods from Questions 28 and 29.)

g. The distance travelled in the next 2 minutes is . . ? . . kilometres. (The speed is steady.)

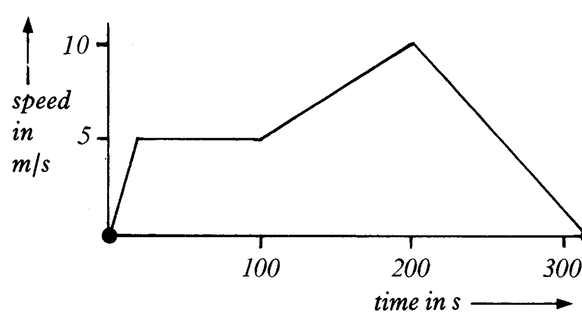
h. The distance travelled in the last 1 minute is . . ? . . kilometres. (Use one of your methods from Questions 28 and 29.)

i. The total distance travelled is . . ? . . kilometres.

32a. The graph shows the motion of a boy who bicycles from home to school. His speed (in metre per second) is plotted upwards, and time (in seconds) is plotted along.

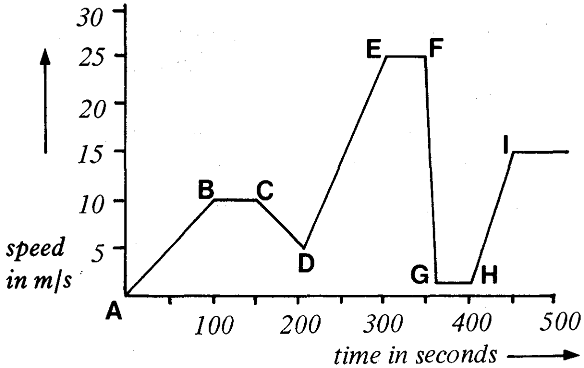


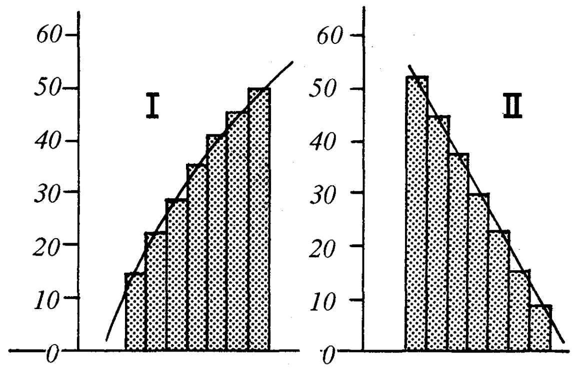
(i) By looking at the graph (without making calculations or measurements) describe his journey, so far as you can tell from the graph.
(ii) From the graph, estimate the distance from home to school.



b. The graph shows the motion of another boy, less impulsive than the first boy, cycling from home to school.

(i) From the graph, describe his journey.
(ii) From the graph find the distance from home to school.





33. The chart shows the motion of a car which travelled from the centre of a town to a nearby village.

a. After looking at the chart describe the journey. (Do not make any measurements or calculations.)

b. From the graph, find the acceleration of the car during each of the following time intervals:
(i) From A to B.
(ii) From B to C.
(iii) From C to D.
(iv) From D to E.

c. Find the distance covered by the car during the time interval represented by D to E by two methods:
(i) By measuring an area on the graph (which you may break up into two parts for measurement).
(ii) By using $s = ut + \frac{1}{2}at^2$.

d. The motion of a real car, driving on a real road, could not have this simple chart. Why not?

34. Above right: two tape-charts. (Two other tape-charts were shown in Questions 24 and 25.) The tape was attached to a moving object which dragged it through the vibrator.

Strips of paper, seven in each case, were cut off from dot 0 to dot 10, 10 to 20, 20 to 30, and so on, up to dot 60 and dot 70. The strips were stuck side by side to make a tape-chart.

a. What kind of motion is represented by the figure of Question 24?

b. What kind of motion is represented by the figure of Question 25?

c. What kind of motion is represented by figure I here?

d. What kind of motion is represented by figure II here?

e. How far did the object in the figure of Question 24 move between dots 0 and 70?

f. How far did the object in the figure of Question 25 move between dots 0 and 70?

g. How far did the object in figure I move between dots 0 and 70?

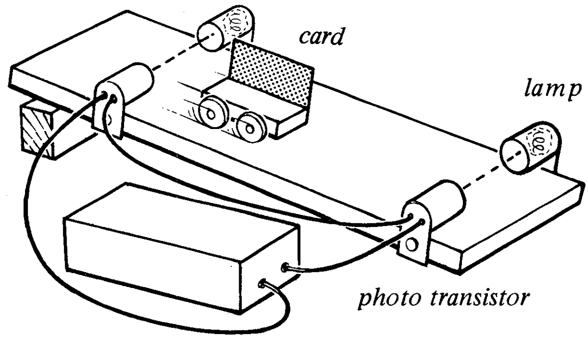
h. How far did the object in figure II move between dots 0 and 70?

Demonstration 7
Basic measurement of acceleration with a clock that ticks 1000 times a second

You may see the demonstration sketched. A built-in transistor device makes 1000 pulses of voltage a second, and the scaler counts them. That lets you measure speeds and from them calculate acceleration as

[GAIN OF SPEED]/[TIME TAKEN]

If you are going to see this experiment, try Questions 35a and 35b beforehand, to see the way the acceleration is worked out.



scaler to count milliseconds

Question

35a. A motor cyclist roars along a straight road, accelerating. He passes two observers, A and B, far apart. Each observer clocks his motion over a short test distance of 2 metres.

A's record: he took $\frac{1}{2}$ second to travel 2 metres. Then his speed at A was . . ? . . metre/second. (He *is* accelerating but you can find his *average* speed during that short period.)

B's record: he took $\frac{1}{20}$ second to travel 2 metres. Then his speed at B was . . ? . . metre/second.

A third observer, C, measures the time the cyclist takes to travel from A to B.

C's record: he took 10 seconds to go from A to B.

Calculation of acceleration

His *gain* of speed from A to B was . . ? . . metre/second. He made that gain of speed in 10 seconds. So his acceleration was . . ? . . metre/second squared.

b. Suppose the cyclist carries a board 2 metres long, above his head. Each of the observers A and B arranges an electric eye (photocell) on one side of the road and a small lamp on the other side, up at the height of the cyclist's board. The light from the lamp shines across the road and enters the electric eye, and that keeps the observer's clock stopped. But while the cyclist is passing by, the 2-metre board prevents the light from reaching the electric eye; and that lets the observer's clock run.

A's record: while the cyclist was passing, my clock ran for $\frac{1}{2}$ second.

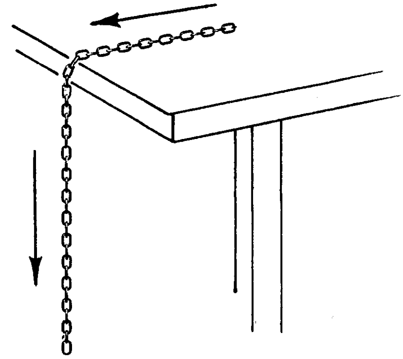
Then his speed here was . . ? . . metre/second. Explain why your calculation gives the cyclist's (average) speed past A.

(You need not continue the calculation with records from B and C. The point of this question is to see how the board and electric eye can tell you his speed. Then watch the real demonstration with an accelerating trolley.)

Experiment 8
Acceleration that is not constant
(OPTIONAL)

Lay a length of chain on a smooth table; stretch it out at right angles to the edge. Pull the end a little way over the edge until, on release, the whole chain slides. Then the hanging portion pulls the rest with increasing acceleration until it is all falling freely. Watch the motion.

To obtain a record, arrange a timer so that the upper end of the chain on the table pulls the tape through.



Progress Questions

SCALER USED TO MEASURE ACCELERATION

36.

(Do not answer this unless you saw the acceleration of a trolley measured by using a 'millisecond timer', which measures time intervals in thousandths of a second.)

a. What measuring instruments did you use or see used? (You probably used three.)

b. What did you measure with them (4 measurements not just 3), and how was it done?

c. How did you calculate the acceleration?

d. What (if anything) did you discover from the experiment?

ACCELERATING CAR

37. I sit in a car and look at the speedometer. I have a stopwatch in my hand. I find that the car's speed increases by 2 kilometre/hour in every second.

The car starts from rest, and I start my watch at the same moment.

a. What is its speed after 1 second?

b. What is its speed after 2 seconds?

c. What is its speed after 3 seconds?

d. What is its speed after 10 seconds?

e. What would its speed be after 60 seconds *if* it kept on accelerating in the same way?

f. It is unlikely that a car would keep up this same acceleration for as long as 60 seconds. Why do you think this is?

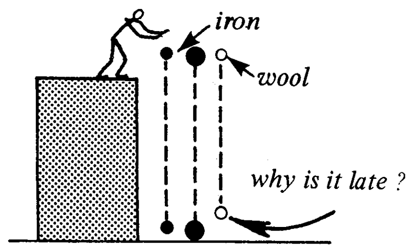
FREE FALL

Do heavy (dense) things fall faster than light ones?

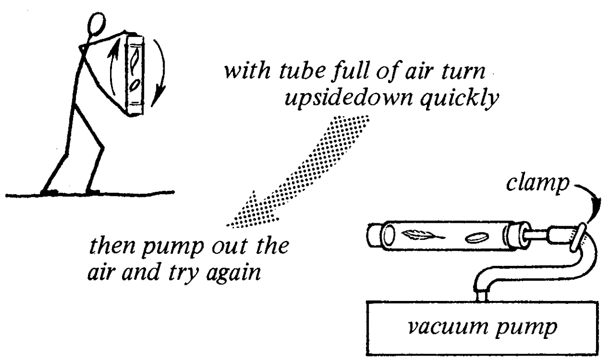
† Experiment 9a
Falling objects

Release a rock, a pebble, and a tiny bullet to fall freely. Start them together. Do they stay together?

Air resistance Why does a feather (or a scrap of paper) fall differently? Galileo suggested air resistance (air friction) makes the difference. He thought a scrap of wool and a scrap of metal would fall equally *in a vacuum*. He did not have a suitable



air pump for a trial. But Newton had a pump and did his 'guinea-and-feather' experiment. If you have not had that test in your own hands you should try it now.



† Experiment 9b
The guinea-and-feather experiment

Put a small coin (or other piece of metal) and a scrap of plastic foam in the tube. Close the tube with the rubber stopper.

Take it in turns with your partners to hold the tube upright and turn it upsidedown quickly. Watch the two falling objects.

Then bring your tube to the vacuum pump and have the air pumped out. Listen to the pump—you can hear the air being ejected in decreasing amounts. Seal the tube with a clip on its short rubber tube.

Again take turns at turning your tube upsidedown.

Then let air in again and try once more—that may be your best chance of seeing how great the difference is.

Free fall Is the free fall of a stone (or any other dense object) a case of *constant* acceleration? Make a test (Experiment 10). For that test, *either* use a formula that you will find developed in Chapter 1A

† From *Pupils' Text 3*.

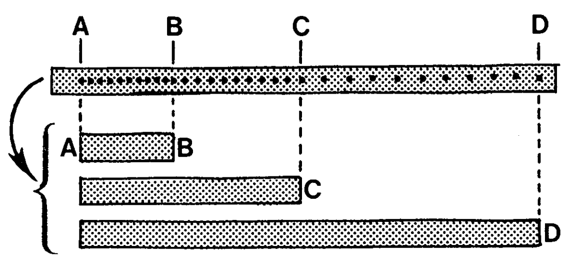
or obtain the hint that you need by doing the following preliminary experiment (Experiment 9c).

Experiment 9c
A different exhibit of tapes: total distance versus time *(OPTIONAL)*

Let a trolley run down a hill dragging a tape through a timer. Take special care to start the timer just at the instant when you let the trolley start. To make sure, keep a finger on the blade of the timer until you release the trolley. Each partner should make his own tape.

Mark your tape at every tenth dot (no. 0, no. 10, no. 20, . . .) thus marking off tentick lengths, *but do not cut the tape.*

Then from a fresh lot of tape, cut 'total strips' a length equal to the travel in the first ten ticks, then a length for the *total* travel in the first 20 ticks, then one for the *total* travel in the first 30 ticks from start, and so on.



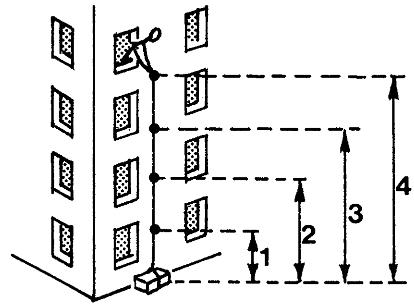
new 'total' strips

Look at your new 'total strips' and see what you can find out. There is a number secret among those lengths. (*Hint:* use the first strip (for one tentick from rest) as a measuring stick for the others.)

† Experiment 10
Testing free fall

Go to a window high above the ground. Take with you a long string that will reach from your hand down to a brick resting on the ground. Tie small stones or weights to the string 1 metre above the ground, 2 metres, 3 metres . . . .

Hold the string taut and let go. While everybody listens to the stones hitting the ground you will hear evidence of acceleration like this: bang . . . . bang . . . . bang . . . . bang . . bang .



To make sure the sounds are sharp and audible, place a sheet of metal on the ground.

Now try the experiment again but tie the stones on at different distances, chosen so that *if* the *acceleration of fall is constant* everyone will hear the bangs as a regular series equally spaced apart.

For that you have the brick at the ground (zero). Tie the first stone one quarter of a metre above the ground. How many quarters of a metre above the ground should you tie the next stone? How far for the next? You will need to calculate the distances for the stones from your knowledge of constant acceleration. Then you will be making a prediction which you test when you let go of the string.

Question

A TEST OF FREE FALL

38. A boy stands at the top of a flight of stairs and holds a string which is fastened to the floor below. He attaches three small weights to the string at points $\frac{1}{4}$ metre, $\frac{4}{4}$ metre and $\frac{9}{4}$ metre above the floor. He holds the string taut.

The boy lets go of the string and listens to the timing of the 'clonks' as the weights hit the floor.

a. What would he notice about the timing of the noises he hears?

b. If he were able to have a string going up *two* flights of stairs, where should he tie a *fourth* weight on the string?

c. Suppose, instead, he tied weights at heights of 1, 2, 3, 4 metres above the floor. What would he now notice about the timing of the noises made as the string arrives?

d. Suppose he did the experiment as in (a) and his partner recorded the noises on a tape recorder. Then his partner played the tape back, at $\frac{1}{4}$ of the original speed. What would you hear?

Experiment 11
Rough estimate of g

Time the free fall of a stone or some other object. Find a place where you can let it fall several metres. Time the fall with a stopwatch.

See Chapter 1A for a useful formula to calculate g from your measurements. Or make your record and proceed thus:

Distance of fall . . . . m
Time of fall . . . . s

$$\therefore \text{average speed during fall} = \frac{\ldots\ldots \text{m}}{\ldots\ldots \text{s}} = \ldots\ldots \text{m/s}$$

Assuming the acceleration was constant we can say:

$$\text{average speed} = \frac{0 + \text{final speed}}{2}$$

$$\text{Then FINAL SPEED} = 2 \times \text{average speed} = \ldots\ldots \text{m/s}$$

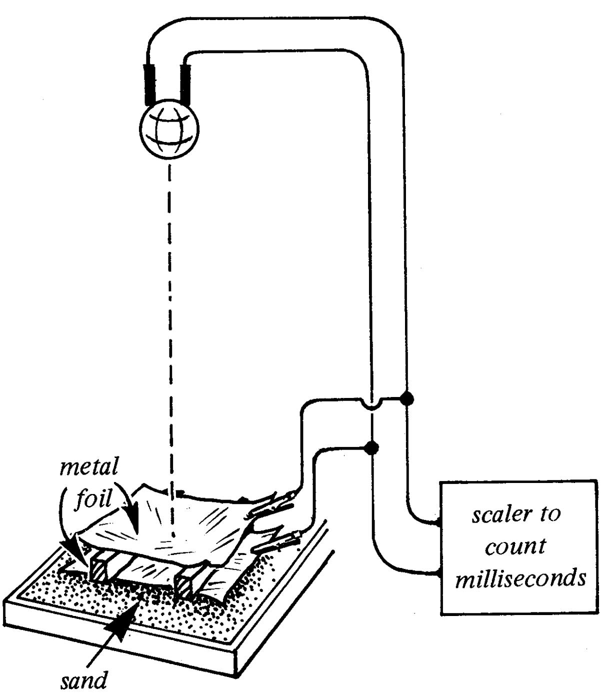
The object gained that final speed in . . . . s, from rest

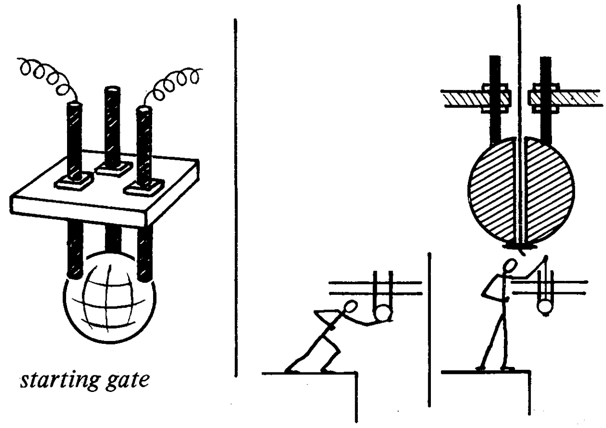
$$\therefore \text{its acceleration} = \frac{\text{final speed}}{\text{time taken}} = \frac{\ldots\ldots \text{m/s}}{\ldots\ldots \text{s}}$$

$$\therefore g = \ldots\ldots \text{m/s}^2$$

(rough estimate)

Experiment 12
Measuring g with scaler as a clock





You may see this as a demonstration or you may be able to try this yourself.

The scaler acts as a clock counting ticks which it manufactures at the rate of 1000 a second.

Hold the metal ball up against the starting post. While it touches the three pegs it completes a switching circuit that keeps the clock stopped.

Let the ball fall; the clock runs, timing the fall.

When the ball reaches the floor it completes a switching circuit and stops the clock. (In the simplest form the ball falls on two sheets of kitchen foil which are kept apart until the ball smashes them together. Or the ball may hit a small switch.)

Measure the height of the ball's fall. Use that and the measured time to calculate g. (See the hints for the previous experiment.)

Experiment 13
Estimating g from the multiflash picture
(OPTIONAL)

On a print of the multiflash picture, mark the successive positions of the falling object clearly. Measure the *total* distance of fall from the start to each mark. Plot a rough graph of total distance against time. You will see that the graph line must be a curve. *What could you plot instead, with hopes of a straight line?*

If the motion has constant acceleration, $s = \frac{1}{2}at^2$ for fall from rest. So you should plot distance s against . . ? . . Try that. Then the graph will tell you whether the motion did have constant acceleration.

Instead of that, you might assume you know the type of motion and just calculate acceleration from one measurement of your photo. That would be quicker, but less of a scientific investigation.

Progress Questions

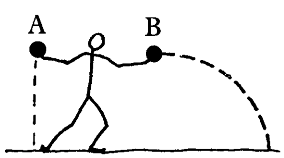
FALLING THINGS

39. A boy holds a 2p piece and a Smartie at exactly the same level. He drops them both at the same time. Do they hit the ground at the same instant, or does he hear one hit the ground before the other?

b. He tries the experiment again, but this time with a kilogram and a 2p piece. What happens?

c. He tries a similar experiment on a pier. He uses a round stone (about a kilogram) and a small flat pebble. This time he watches the splashes in the sea below. Probably the kilogram stone will hit the water a little before the flat pebble. Explain why you might expect such a result.

40. A girl holds two coins A and B in front of her so that she can see that they are at the same level. At the same instant, she drops A and gives B a sideways throw.



a. What does she see (and hear)?

b. What difference does it make when she throws B sideways with a bigger speed?

41. You have done Newton's 'guinea-and-feather' experiment.

a. What happens in this experiment?

b. Why was Newton's experiment important? (What did it tell you?)

c. When you did this in the laboratory, why did you have to remove the air from your apparatus?

42. Suppose you use a stopwatch to measure how long it takes a small object to drop from a height of 1.5 metres to the ground.

a. When should you start the watch?

b. When should you stop the watch?

You repeat the timing several times, and obtain these values: 0.50 second, 0.40, 0.60, 0.50, 0.45 second.

c. The watch is running properly. Why are these answers quite reasonable although they are not exactly the same?

43. A cricket ball dropped from the top of a block of flats, 45 metres above the ground. The ball hit the ground 3 seconds later.

a. What was the *average speed* of the falling ball for those 3 seconds?

b. If its starting speed was 0, what must its *final* speed have been to give the *average* you got in (a)?

c. It took 3 seconds to increase its speed from 0 to the final speed. How much did its speed increase in each second?

SCALER MEASUREMENT

44. *(Do not answer this unless you have seen this experiment.)* You saw an experiment done in class to measure the acceleration of a ball falling freely using a scaler. (The ball was falling a smaller distance and took much less time than the ball did in the previous question.)

a. How was the time of fall measured? Draw a labelled sketch of the arrangement.

b. How far did it fall?

c. How long did it take?

d. Show clearly how you worked out the acceleration.

e. What result did you get?

f. A stopwatch is good enough to measure how long it takes you to run up a flight of stairs. Why is it a good idea to use a scaler for the above experiment?

FREE FALL (ROUGH ESTIMATE)

†**45.** Find a small stone or other small dense object. Stand on a stool or chair or bench and drop the stone from a height of about $1\frac{1}{4}$ metres.

a. Make a guess at how much time (in seconds) it took to fall to the ground.

b. You cannot tell just by watching the stone, exactly what its motion is like—it could be a steadily increasing speed, or perhaps it falls faster and faster at first and then reaches a steady speed. But it cannot have a motion with constant speed (= steady, unchanging speed) all the time from when you release it until it reaches the ground. Why not?

MEASURING g

46. (This is something to do at home.)
You can count quarter-seconds by saying 'nought, one, two, three, four' (0, 1, 2, 3, 4) quickly but distinctly. Practise this while looking at the seconds hand of a watch or clock. Count for three seconds, saying 0 at the start and 12 at the end of the 3-second interval.

a. When you have the timing about right, repeat the stone-dropping described in Question 45, still from a height of $1\frac{1}{4}$ metres. Estimate the time taken. Say 'nought' as you release the stone, and notice which number you are saying, or have just said, when you hear the stone hit the ground. Make the best estimate you can of time taken; try to guess to the nearest $\frac{1}{4}$ second.

b. Describe briefly how you did this.

c. Calculate the average speed of the stone during its fall (in m/s).

d. *(Optional)* Assume you don't yet know whether the stone increased its speed steadily—that is whether it had a constant acceleration. Write down:
(i) The average speed (your answer (b) above).
(ii) The final speed. (Remember that the speed at the start, when you released the stone, was zero.)
(iii) Your answer (ii) is also the increase of speed, because the starting speed was zero. This increase took place in the time you estimated by counting.

Now calculate the increase of speed *in one second.* That *is* the acceleration.

Note: Of course this experiment is very inaccurate; but it does give you some idea of how big the acceleration is. (You get a 'rough estimate' which is like placing a village just by its county.)

e. Why is it a highly inaccurate experiment?

47. Make a rough estimate of the time taken for a stone to fall $1\frac{1}{4}$ metres as in Question 46.

a. Calculate g from $s = \frac{1}{2}gt^2$.

b. How do you get $s = \frac{1}{2}gt^2$ from the general equation $s = ut + \frac{1}{2}at^2$?

c. Why doesn't it matter much about measuring the $1\frac{1}{4}$ metres exactly?

MEASURING WITH MULTIFLASH

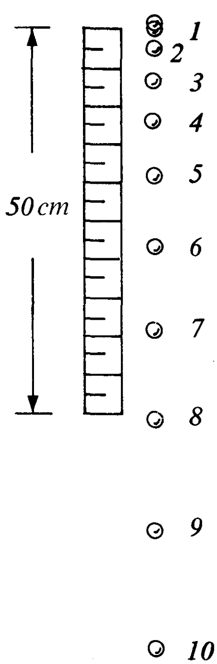
(Do not try these questions unless you have seen a multiflash picture taken and used.)

48. Here is the multiflash picture that was given earlier in Question 5. Assume it shows a ball falling freely. Assume the flashing rate is 25 flashes per second. Calculate:

a. The average speed, in cm per second, between the time of picture no. 4 and the time of no. 5;

b. The average speed, in cm per second, between 9 and 10;

c. The time interval, in seconds, between 4 and 9, or between 5 and 10;



d. The *increase* of speed in cm/second in this time interval;

e. The acceleration in cm/s^2.

f. The acceleration in m/s^2.

Suppose that, for the falling ball of the question above, the rate of flashing had been 5 flashes per second instead of 25 per second.
Suppose that the first flash comes as the ball is released, in position 0.
Draw a diagram to the same scale showing what the picture would now look like. (Start at position 0 or 1 and go only as far as the fourth flash.)

MEASURING g WITH SCALER

49. You have seen a measurement of g which was a great improvement on the rough experiment above. You measured time in milliseconds instead of guessing quarter-seconds.

a. Draw a sketch of the arrangement for releasing the ball. What did this do to the timer?

b. Explain how the timer was stopped by the ball at the end of its fall. Give a sketch.

c. How did you calculate g?

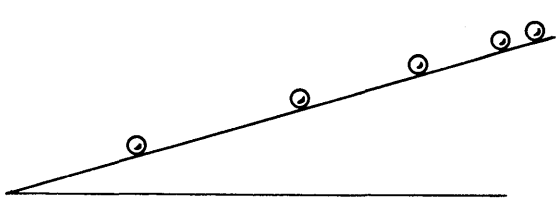
50. An experiment gave these measurements: a ball took 700 milliseconds to fall 2.36 metres.

a. What value does this give for g? (Use $s = \frac{1}{2}gt^2$.)

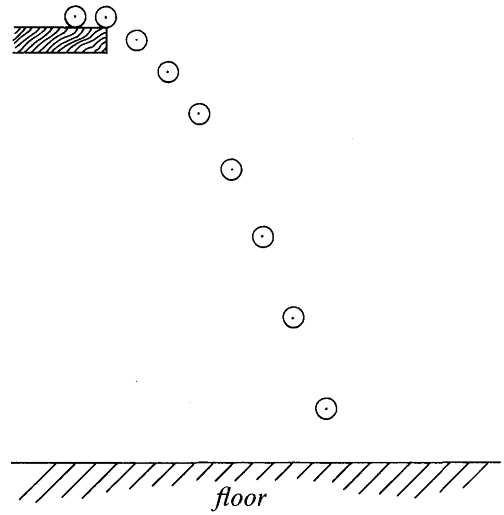
b. How long would it take to fall 25 centimetres from rest?

c. If it continued with the same acceleration, how long would it take in falling from a cliff 100 metres high?

d. In fact, it would not continue with the same acceleration for 100 metres. Why not?



51. *(Advanced)* For a ball rolling down a hill (see sketch) the flasher was set for 2.5 flashes a second, that is, one-tenth of what it was for the ball falling vertically in Question 50. By using the hill we have 'diluted gravity' to only a fraction of its 'free fall' value. We call the full gravity acceleration g; suppose the acceleration is a fraction of g, $(\frac{1}{x})g$. Compare this sketch with the sketch of Question 50. Knowing the rate of flashing in each case, find the fraction $\frac{1}{x}$. Explain how you got your result.



52a. The figure is a multiflash photograph of a ball which rolled along a table and off the edge.

Describe the motion of this ball and explain why it moved like that.

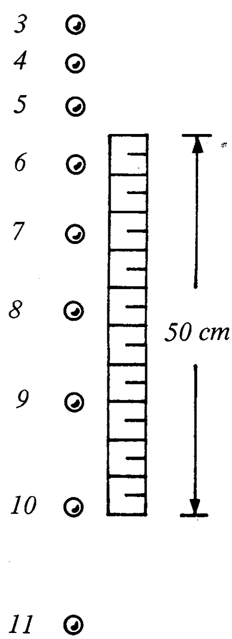
b. Suppose the table had continued all the way across to the right and the ball had rolled on, without slowing down, until it went out of the picture. Draw a sketch the same size as the figure and show on it the picture which the camera would have taken. (Leave a little space beneath your sketch and to the right of it.)

c. On a sketch draw the positions the ball in (a) would have had if it fell straight downwards from its first position, without any horizontal *velocity*.

d. *(Advanced)* In the figure there are *ten* pictures of the ball. Copy them. Suppose the paper had been larger, and the ball did not reach the ground. Then you would have seen an eleventh and twelfth picture after the ten in the figure. Mark on your copy (but, of course, outside the region of the printed picture) the eleventh and twelfth positions of the ball.

53. *(Advanced)* The figure shown for Question 48 was drawn so that the first flash, and therefore the first picture (flash no. 1), came exactly as the ball was released. That would be very difficult to arrange, and it is unlikely to happen by chance.

However, the method of calculation in Question 48 is correct, even if the ball was released at some instant between two flashes. This is because the calculation depends on the *difference* of speeds at two stages.



The sketch here shows nine positions (numbers 3 to 11) at $\frac{1}{25}$ second intervals of the same falling ball. We shall get *three* values of g from this diagram; and then we can average the results. Proceed as follows:

a. Find the average speed between flash no. 3 and flash no. 4 and find the average speed between flash no. 8 and flash no. 9. (Use the scale of centimetres, reduced from actual size, in the sketch above. Remember that each flash picture is $\frac{1}{25}$ second later than the one before.)

b. The time interval between those two measurements of the average speed is from 'flash $3\frac{1}{2}$' to 'flash $8\frac{1}{2}$', that is 5 lots of $\frac{1}{25}$ second. That is $\frac{5}{25}$ second.

Calculate g by using $g = \dfrac{\text{increase of speed}}{\text{time interval}}$

c. Repeat (a) and (b) using flashes 4 and 5 for one average speed and flashes 9 and 10 for the other, with the $\frac{5}{25}$ second interval between.

d. Repeat for flashes 5 and 6 and flashes 10 and 11.

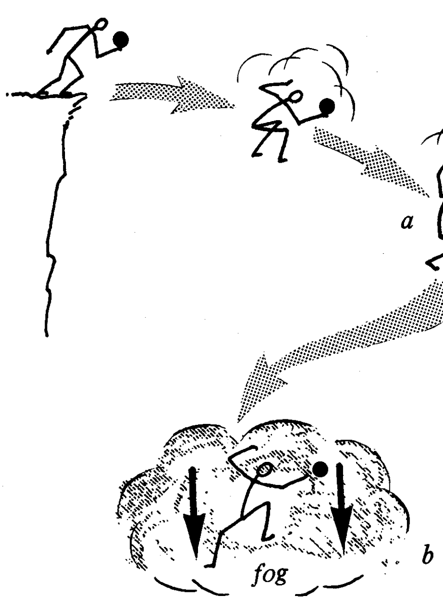
e. Average the three values for g found in (a), (b) and (c).

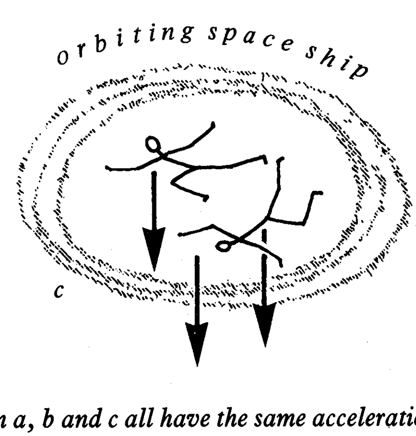
WEIGHTLESSNESS

If any two dense objects fall freely with the same motion they race neck and neck.

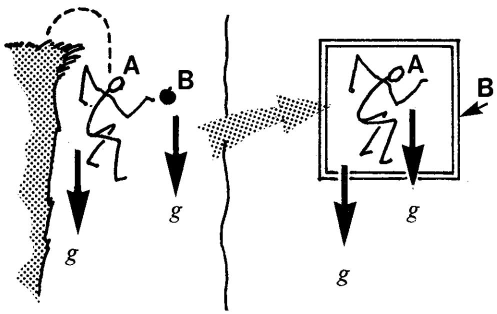
Suppose you are falling freely, holding an apple. You let go of the apple. The apple will stay with you, falling with the same motion as you. If there is fog all round, so that you only see the apple, the apple will seem to be weightless, free of gravity pull.

Think of astronauts in a space ship that is falling back to Earth (with engines and brakes shut off). They find things 'weightless', including themselves—because all things have the same falling motion.





in a, b and c all have the same acceleration towards the controlling Earth (local g)



A 'thought experiment'

Try a series of questions:

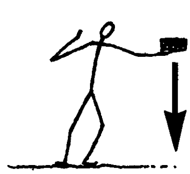
a. Imagine that you lean out of a window, high up, and release a small stone and a large one together. *(i)* Describe their fall. *(ii)* What do you think makes them fall?

b. Now imagine the larger stone replaced by a human observer. The observer and the other stone are released together, high above the ground. *(i)* Describe their fall. (The observer's parachute does not open until later in the fall.) *(ii)* What makes them fall?

c. Again let the human observer fall, but this time change the stone into a large box surrounding the observer. Release the box, with the observer inside. *(i)* What will the observer notice in the early part of the fall? *(ii)* Describe the motion of box and observer, in the early part of the fall.

d. The observer, inside the freely falling box, holds an apple in his hand. He lets go of the apple. *(i)* What does he see the apple do? *(ii)* Does he know the apple is falling? *(iii)* What does he mean if he says the apple is 'weightless'?

Put a heavy book on your outstretched hand. Lower your hand *with acceleration*, moving hand and book faster and faster downwards. Can you feel the book 'losing some of its weight'—approaching 'weightlessness'?*



* You may imagine places where there would be no gravitational pull, where an isolated object would be truly weightless. This would be somewhere very far from the Earth, Sun and stars or perhaps inside the Earth at the centre.

If you like, try the 'thought experiment' in the box. Thinking your way through it may help to clear up puzzles.

But do things really lose their weight? Is gravity shut off for a falling apple, on the book on your hand, on astronauts in a falling space ship? But if the Earth stops pulling them, why do they fall?

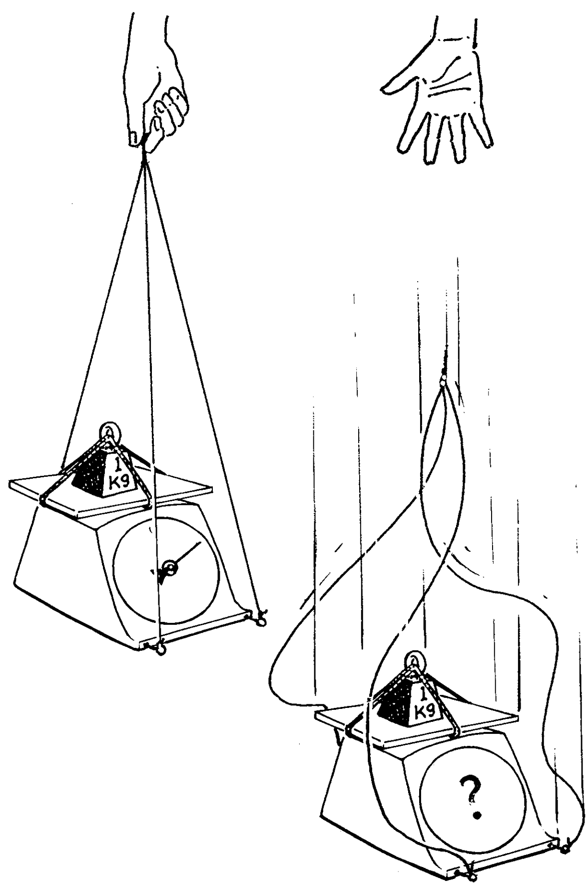
We are quite sure the Earth *does* pull every object whether it is at rest or falling. If the weight of an object is the pull of the Earth on it, objects do not lose their weight, they only *seem* weightless.

It is just a matter of choosing words. In our physics we shall not talk of true weightlessness but only of apparent weightlessness.

You may see a demonstration.

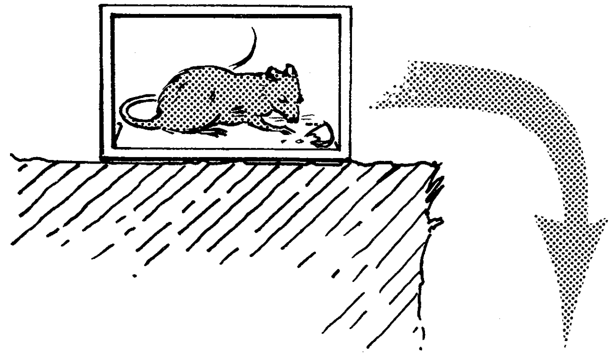
Demonstration 14
Apparent 'weightlessness'

See the sketch. A kilogram is placed on the weighing scale which shows the pull of the Earth on that load. Watch while scale and load fall freely.



Progress Question

WEIGHTLESSNESS



54. Here is a mouse in a box. The Earth pulls on the mouse, and when the box is stationary, the floor of the box pushes up on the mouse to hold it still.

a. Gravity pulls down on the mouse $\frac{1}{2}$ newton. How big is the upward push of the floor of the box on the mouse?

b. The box, with the mouse still in it, falls down a deep hole. The Earth's pull on the box makes it accelerate. As soon as the box starts to fall, what happens to the mouse? And the cheese? Draw the box, mouse and cheese as they all fall.

c. Does the MASS of the mouse change while it is falling? Does the pull of the Earth on it change?

d. Does the box push up on the mouse while both are falling together?

CHAPTER 1A

HELP WITH USEFUL MATHEMATICS AND METRIC MEASUREMENTS

CAN YOU USE MATHEMATICS WITH PLEASURE?

The algebra that we sometimes use in physics this year is just shorthand. If you could learn shorthand you could learn this algebra even quicker. Learn it as you would learn shorthand, and you will find it easy and useful. We shall just write t instead of writing *time*; and whenever you find that t puzzling, you may simply write the whole word *time*—more trouble but the same meaning. Think how useful ordinary shorthand can be:

for keeping a private diary
for writing lecture notes in college
for a doctor's quick notes as a patient tells his symptoms

as well as in a secretarial job, and for those authors who write their books in shorthand to save time.

Our use of algebra in science *is* just a shorthand which uses ordinary letters instead of special signs, and it is the same all over the modern world. Here are some examples to show you how we change to that shorthand.

Driving a car for a trip Suppose you drive for 2 hours at 50 kilometre an hour. How far do you go? Common sense tells you: 100 kilometres. Put that in other words:

DISTANCE TRAVELLED = SPEED × TIME

DISTANCE TRAVELLED

$$= 50\ \frac{\text{kilometre}}{\text{hour}} \times 2\ \text{hours}$$

You could work out another trip, 3 hours at 40 km per hour:

$$\text{DISTANCE} = 40 \times 3\ (\text{in } \frac{\text{km}}{\text{hr}} \times \text{hrs})$$

That is, 120 km.

The pattern of calculation is the same—always the same. Put the pattern in shorthand, using d for distance, v for speed or velocity, t for time: $d = v \times t$ (E.g., 10 km = 5 km per hour × 2 hrs)

In this shorthand you may leave out the multiplication sign (×) without making any confusion (just as some obvious syllables are left out in ordinary shorthand). Then

$$d = vt$$

That tells you the same thing as the examples with numbers; but now you can put any numbers you like for v and t in that 'formula' and work out d by multiplying. The formula doesn't tell you any new way of calculating—you still have to multiply!

The time needed for a trip Ask the question in another way: how long will it take to drive 100 kilometres at 50 kilometres per hour? (You can see the answer is 2 hours; but pretend you have more difficult numbers.) Here you need to know how many lots of 50 km fit into 100 km. That is: divide 100 by 50.

$$\text{The time needed is } \frac{100\ \text{km}}{50\ \text{km/hour}}$$

$$\text{or } 2\left[\text{km} \times \frac{\text{hr}}{\text{km}}\right] \text{or 2 hours}$$

Put that in words: TIME is given by DISTANCE divided by SPEED.

$$\text{Time equals } \frac{\text{DISTANCE}}{\text{SPEED}} \quad \text{or } t = \frac{d}{v}$$

The = sign means that the thing on the right of it is truly the same as the thing on the left.

An enthusiast for algebra-shorthand will suggest: once you have the = there, you can keep it true if you do the same thing to the left hand side and to the right.

Examples

$$3 = \frac{6}{2} \longrightarrow 3 \boxed{+5} = \frac{6}{2}\boxed{+5}$$

$$\longrightarrow 3 \boxed{\times 4} = \frac{6}{2}\boxed{\times 4}$$

$$\longrightarrow 3 \boxed{\div 2} = \frac{6}{2}\boxed{\div 2}$$

Then take $t = \dfrac{d}{v}$ and multiply each side by v.

$$t \boxed{v} = \frac{d}{v}\boxed{v}$$

Cancel the v, then $t \times v = d$

Reverse it, $d = vt$; we are back again with our first formula in shorthand.

Now for acceleration In shorthand, we shall use a for acceleration.

ACCELERATION is gain of SPEED divided by TIME taken to make the gain.

How do you deal with 'gain'? Think about gain of money. How much money have you gained if you had 60p in a money box last week and have 80p this week? Your money has grown from 60p to 80p, a gain of 20p, which you find by subtraction.

Your gain is 80p − 60p

In shorthand your gain is $v-u$ if, in this example, u is last week's money and v is this week's money.

Then, for acceleration, which is $\dfrac{\text{gain of SPEED}}{\text{TIME taken}}$

we say acceleration is

$$\frac{\text{later SPEED} - \text{earlier SPEED}}{\text{TIME between earlier and later}}$$

Then, in shorthand, $a = \dfrac{v-u}{t}$ where v and u are two samplings of speed and t is the time between them.*

* Mathematicians would consider it more tidy to call the early sample of speed v_1 and the later sample v_2—like naming two brothers in a school. Then

$$a = (v_2 - v_1)/t.$$

They would even like to use a special shorthand sign for 'gain of'. That is Δ, a Greek capital D for 'difference'. Then $a = \Delta v/\Delta t$.

Suppose you want to calculate a final speed, v, when you know the starting speed u and the acceleration a. How can you get v all by itself on one side of the = ?

$$a = \frac{v-u}{t}$$

multiply each side by t

$$a\{t\} = \frac{v-u}{t}\{t\}$$

Cancel t $\quad at = v-u$

Add u to each side

$$\{u\} + at = v - u + \{u\}$$

$$u + at = v$$

then $\quad \boxed{v = u + at}$ *

Averaging Suppose you do a small job and you earned £6 last month and £8 this month. What is your average monthly pay, over the two months?

Common sense says half-way between, £7.

Arithmetic says $\dfrac{6+8}{2}$, again £7. In shorthand you could use code signs u and v for last month's pay and this month's. Then the average is $\dfrac{u+v}{2}$

Average speed If a car speeds up from speed u to speed v in time t, its *average* speed over that period is $\dfrac{u+v}{2}$.

Distance travelled** That accelerating car has average speed $\frac{1}{2}(u+v)$ from the instant when its speed was u to the instant when it was v. To calculate d, just use that average speed and pretend the car has it for a span of time t. The distance it travels is $(\textit{average}\ \text{SPEED}) \times (\text{TIME})$ or $\dfrac{(u+v)}{2} \times t$

Example: a racing car speeds up from 10 metres per second to 30 metres per second in 5 seconds. How far does it travel in those 5 seconds?

Average speed, $\dfrac{u+v}{2}$ is $\dfrac{10+30}{2}$ m/s

Distance is $\dfrac{u+v}{2} \times t$ and that is $\dfrac{10+30}{2} \times 5$ metres.

* Use formulae when you find you need them. You may sometimes want to use one of these formulae that are printed in a box, like this. But there is no need to learn them by heart for examinations. You should find them printed on the front of any examination in which they may be needed.

** The simple average, $\frac{1}{2}(u+v)$, only leads to the distance travelled correctly *IF* the motion's acceleration is constant—does not change during the experiment. If the acceleration varies—for example, if it continually increases—a somewhat different average must be used, and the $\frac{1}{2}$ in the next two formulae in boxes is no longer the correct factor.

Notice we are just decoding (transcribing) the shorthand—there is no new mystery.

For the complete shorthand version of this, make one change of letter. By old tradition, we do not use d for distance travelled but s, meaning *space travelled* (and, in more advanced work, we use x).

Then $\boxed{s = \dfrac{(u+v)}{2}t}$

Using that, you can calculate s whenever you know u, v, and t.

Another formula Now suppose you know u, t and a the acceleration? You are often given those three and need to find s. How can you do that? Just calculate v first from $v = u + at$ and then use it in

$$s = \frac{(u+v)}{2}t$$

But you can make the shorthand do that for you, once and for all.

Write down the two stages, in shorthand:

$$v = u + at$$

$$s = \frac{(u+v)}{2}t$$

move in $\{u+at\}$ instead of $\{v\}$

$$\text{then } s = \frac{(u+\{u+at\})}{2}t$$

$$s = \frac{(2u+at)}{2}t$$

$$s = \frac{2ut}{2} + \frac{att}{2}$$

$$\boxed{s = ut + \tfrac{1}{2}at^2}$$

and that is a useful rule, in shorthand, for accelerated motion.

AN IMPORTANT FORMULA

In Chapter 5, you will need to know that the motion energy (kinetic energy) of a mass m moving with speed v is $\frac{1}{2}mv^2$. When you meet that in Chapter 5, look back at the following story.

There is another relationship which should be printed with the rest on examination papers. Here is a quick way to reach it. Read this, if you like algebra. (For help, see Question 15.)

Definition of acceleration $a = \dfrac{v-u}{t}$

Distance travelled $s = \dfrac{v+u}{2}t$

Multiply those: $as = \dfrac{(v-u)}{t} \times \dfrac{(v+u)}{2}t$

$$= \frac{(v^2-u^2)}{2}$$

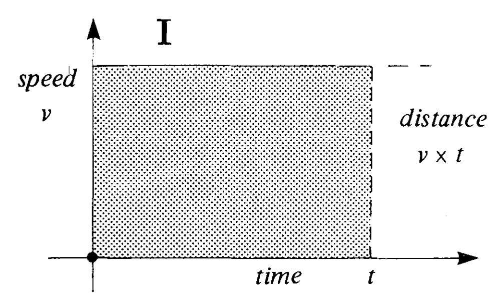
Therefore $2as = v^2 - u^2$

Therefore $\boxed{v^2 = u^2 + 2as}$

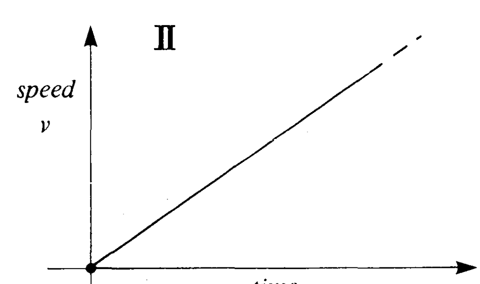
USING PICTURES TO FIND A FORMULA

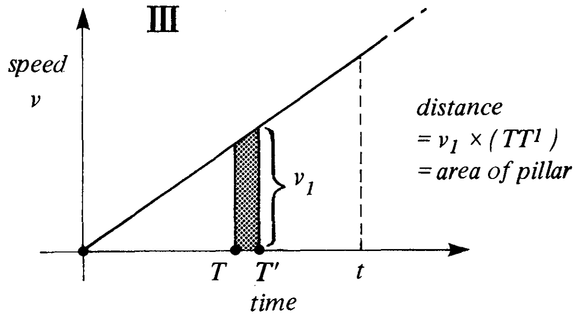
Here is a different method: using easy graphs as pictures of motion. Imagine a graph plotted with SPEED plotted upward against TIME along.

(i) **Constant speed** For an object moving along with constant speed v, the graph is just a horizontal line at height v above the axis. (See Graph I.) You already know that s, the distance travelled, is speed multiplied by time, vt; but on your graph $v \times t$ is the AREA of the shaded block of height v and length t. We shall use that area, which tells us the distance, for some other formulae.



(ii) **Constant acceleration** Plot a graph for an object starting from rest and moving faster and faster with constant acceleration. The line must slant upward as v increases. And if the acceleration is constant the line must be a *straight* slanting line. You already know that from your tape charts (Graph II).



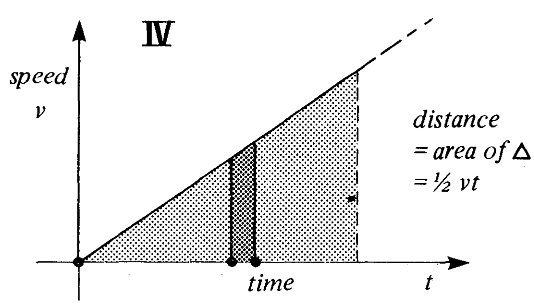


Take a tiny period of time from T to T' on the time axis when the speed was, say, v_1. Look at the pillar that sits on that and runs up to the slanting graph line (Graph III). The area of that pillar is its height v_1 multiplied by the short time TT'. That area *is* the distance travelled in that short time.

How big is the distance travelled in the *whole* time, t, from rest to final v? It is the area of all the pillars from start to finish. That is the area of the triangle (in Graph IV) of height final v and base t, the total time.

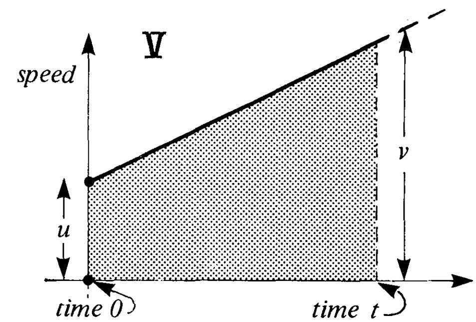
The area of any triangle is $\frac{1}{2}$(height) × (base)
So s is $\frac{1}{2}$(height, v) × (base, t)

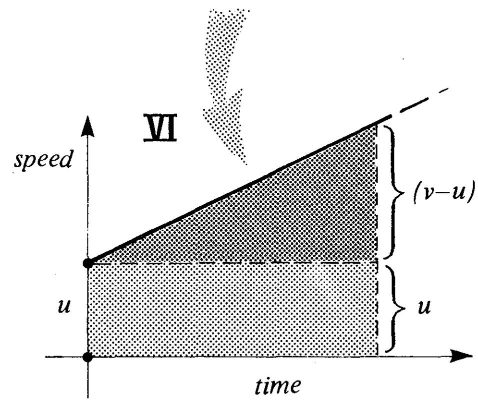
$$s = \tfrac{1}{2}vt$$



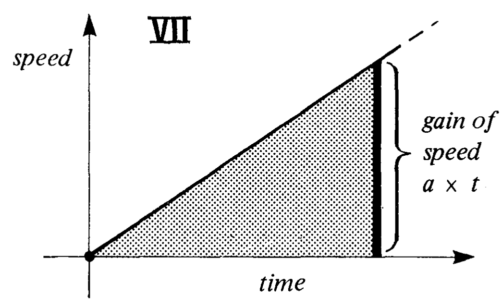
Suppose the object *does not start from rest* when the clock starts at 0 but is already moving with speed u. It accelerates to speed v in time t. Then the graph is like Graph V; and the distance-travelled is given by the shaded area. That is made up of two patches, a rectangle and a triangle (Graph VI). The rectangle's area is ut, the triangle's is $\frac{1}{2}(v-u)t$.

Then
$$\begin{aligned} s &= ut + \tfrac{1}{2}(v-u)t \\ &= ut + \tfrac{1}{2}vt - \tfrac{1}{2}ut \\ &= \tfrac{1}{2}vt + \tfrac{1}{2}ut \end{aligned}$$
$$\boxed{s = \frac{v+u}{2}t}$$





So far you have not reached anything you did not already know; but now try another game with acceleration, starting from rest. Mark the *gain* of speed on it with a heavy line (Graph VII).

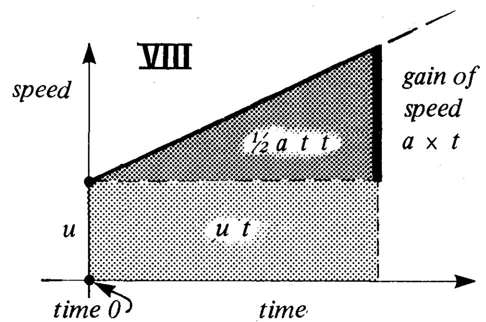


Acceleration is the gain in each second. So in t seconds the gain is $a \times t$ or at. Mark that heavy line of gain at. Now take the area for s again. It is the triangle as before. The triangle area is $\frac{1}{2}$base × height and that is $\frac{1}{2}(t) \times (at)$ or $\frac{1}{2}att$

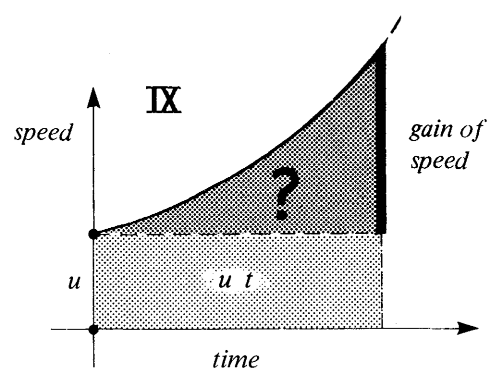
Then $\boxed{s = \frac{1}{2}at^2}$

If the moving object does not start from rest but has speed u when the clock starts at 0 and speed v after time t, the area (Graph VIII) is the rectangle + the triangle. The rectangle's area is ut and the triangle's area is $\frac{1}{2}(t) \times (at)$.

Then $\boxed{s = ut + \frac{1}{2}at^2}$



Why all this work with graph shapes and areas just to obtain that formula? Because now you can see why the formula is only true for *constant* acceleration. Look at Graph IX. Is the acceleration constant? Which part of the area for s is different now? What part of $ut + \frac{1}{2}at^2$ is no longer safe for calculating s?



METRIC MEASUREMENTS

Physicists make many measurements. They weigh some load and calculate a force; they measure the area of a patch of oil and estimate the length of its molecule; they measure the speed of light and use the result in designing radar.

Some of the measurements are so important in building new knowledge that other scientists wait for the results and want to use them as soon as they are published. Many scientists have now agreed to publish all their measurements in one set of chosen units—to save time and avoid confusion.

You have seen metric units coming into use more and more: the Post Office uses grams and kilograms for letters and parcels; medicines are bottled in cubic centimetres; signposts may be marked in kilometres. You will use such metric units in physics.

How wide is your hand in centimetres? How thick is a 10p coin in millimetres? How tall are you in metres? How far is it from Land's End in kilometres? How long is your lab in metres? How many grams of apple in an apple? How many kilograms of human being in you? How fast does a bus drive in kilometres per hour? How fast does a caterpillar crawl in millimetres per second?

All those questions ask for a measurement (or a guess) in *metric* units, but when scientists tell each other their measurements they now use just one set of metric units:

kilograms for masses (kg)
metres for lengths (m)
seconds for time (s)

(and then metre/second for speeds; cubic metres for volumes and so on).

You will not have to restrict your own work to those units—you will often use other, more convenient, metric units—but you should have a reliable feeling for the scientists' standard choice.

You already know what one second of time is like. If you are not sure of some of the others try the following:

Experiment X
Metric measurements

(i) feel a kilogram (2.2 pounds).
(ii) hold a metre rule (10% longer than 3 feet).
(iii) look at a metre cube.
(iv) put a plastic box $\frac{1}{10}$ metre × $\frac{1}{10}$ metre × $\frac{1}{10}$ metre on a balance and fill it with water. It will hold 1 kilogram of water.
(v) think how many kilograms of water would fill a metre cube.
(vi) try walking at a speed of 1 metre/second.

Progress Questions

SPEEDS

1. Here is a set of speeds:

4 km/h or 2.5 mph
7 km/h or 4.5 mph
40 km/h or 25 mph
64 km/h or 40 mph
850 km/h or 530 mph
1200 km/h or 750 mph

km/h = kilometre per hour
mph = mile per hour

Copy out these speeds and write next to each one the most likely of the following cases:

A fast race horse
A small child on a tricycle
A fairly slow walking pace
The speed of sound in air
A fast sprint for a human being
A passenger-carrying jet aircraft

SUMS WITH SPEEDS

2. The following examples are all for *steady* speeds. Copy out the table and fill in the gaps.

	Distance gone	*Time taken*	*Speed*
Man, walking	30 metres	20 seconds	. . ? . .
Man, running	60 metres	. . ? . .	6 m/s
Horse, racing	. . ? . .	15 seconds	20 m/s
Aeroplane	7000 metres	20 seconds	. . ? . .
Spot in Britain turning with the Earth	2400 kilometres	24 hours	. . ? . .

3. A car is travelling steadily at 50 kilometres per hour.

a. How far does it travel in $\frac{1}{2}$ hour?

b. How far does it travel in 2 hours?

AVERAGE SPEED

4. Often things don't in fact travel with *steady* speeds. But it is still helpful to know their 'average' speeds.

a. What is the *average* speed of a car that goes 150 km in 2 hours?

b. A bus moves at an average speed of 15 km per hour. How long would we expect a journey of 5 km to take?

c. A rabbit runs at an average speed of 3 metre per second and takes 20 seconds to cross a field. How wide is the field?

d. Describe how you think the car, the bus, and the rabbit really did move.

e. Try to explain in your own words what the average speed tells you.

SUMS WITH FORCES

5. Re-write and fill in the gaps in the following table:

Force used	*Mass*	*Acceleration*
. . ? . .	2 kg	5 m/s^2
60 newtons	. . ? . .	2 m/s^2
3000 N	100 kg	. . ? . .
. . ? . .	$\frac{1}{2}$ kg	20 m/s^2

6. Note: Every kilogram of mass is pulled by the Earth with a force of 10 newtons.

a. What is your own mass in kg, roughly? (If you do not know it in kg, you can take 8 stone as close to 50 kg.)

b. What is the pull of the Earth on you, in newtons?

Questions

CALCULATING ACCELERATION (OPTIONAL NOW)

7a. Suppose a trolley travels at a speed of 5 *cm/tentick*, how fast is it going in *cm/second*?

b. Later on its speed is 8 *cm/tentick*. How fast is this in *cm/second*?

c. What is the INCREASE OF SPEED in *cm/second*?

d. If this INCREASE took two seconds, then write out the following sentence using your answer to (*c*) in the space:

The trolley was accelerating at . . ? . . *cm/second in each second.*

COMPARE TWO METHODS (OPTIONAL)

8. An accelerating trolley starts from rest (speed 0); and after 3 seconds its speed is 8 metres per second.

a. How much does its speed increase in each second (that is, what is its acceleration)?

b. What is its *average* speed, in m/s?
Hint: What is the average of 0 and 8?

c. Use the average speed to find how far it travels in those 3 seconds.

d. Sketch a speed: time graph for the trolley, and use that to find how far the trolley goes in 3 seconds.

Do your two results for (c) and (d) agree?

PLAYING WITH ARITHMETIC (OPTIONAL NOW)

9. A car has a speed of 30 kilometre per hour. Two seconds later its speed is 34 km/hour. Two seconds after that, 38 km/hour. We can tabulate this:

time, seconds	0	2	4	6	7	....	10
speed, km/h	30	34	38	?	?		?

a. If it continues to accelerate like this, what is its speed at time 6 seconds? At 7 seconds? At 10 seconds?

b. Guess what its speed was at time (-2) seconds. **Note:** $t = 0$ s is not the instant when this car started. It is simply the instant when the stopwatch was started and just then the speedometer happened to read 30. And $t = 2$ s is the instant 2 seconds later.

What can $t = -2$ s mean?

10. For the car in the question above:

a. How much *increase* of speed is there in each lot of 2 seconds?

b. How much increase of speed is there in 1 second?

c. Which of the above answers is the acceleration?

d. What is meant, in physics, by 'acceleration'? (Explain in a few words.)

11a. A train increases its speed steadily from 40 kilometre per hour to 50 km per hour in 5 seconds. What acceleration has it got? (Give the number and its units.)

b. A train increases its speed from 12 metre per second to 15 metre per second in 5 seconds. What is its acceleration?

PLAYING WITH ALGEBRA (OPTIONAL)

12. An object is moving with a steady (constant) acceleration. It has a speed u at the instant the clock starts and, after accelerating steadily with an acceleration a for time t, its speed is v. We can say:

$$a = (v-u)/t$$

a. Define 'acceleration' in words, and show how the above equation fits your definition.

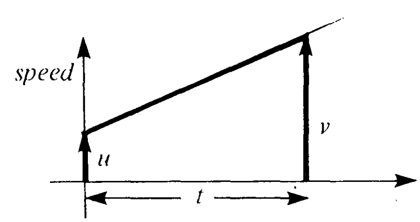
b. Show how you can change the equation above to the equation below:

$$v = u + at$$

13. An object has a velocity u at the instant the clock starts. After time t, it has reached a final velocity v.

Suppose its speed has increased at a uniform rate. The straight line in the figure shows you that. Use the symbol s for the distance covered in time t.

Then: $s = ut + \frac{1}{2}(v-u)t$



a. Obtain that equation from the figure. Use the figure and *GEOMETRY*, not *ALGEBRA*.

b. In terms of the acceleration a:

$$s = ut + \tfrac{1}{2}at^2$$

Show how you can obtain that from the equation just above.

14. There is another method of obtaining the equation $s = ut+\frac{1}{2}at^2$. This time we use algebra. We use the symbols u, v, t, a, s with the same meanings as before, and the acceleration a is constant.

The average velocity during time t is $\frac{1}{2}(v+u)$

a. Therefore $s = \frac{1}{2}(v+u) \times t$. Explain why.

b. Finish the proof by using

$v = u+at$ (from an earlier equation)

and so get $s = ut+\frac{1}{2}at^2$

MULTIPLYING TWO TRUTH STATEMENTS

15a. If $x=2$ and if $y=5$, is it also true that $x \times y = 2 \times 5$?

b. Make a small sketch of a table 2 metres wide by 5 metres long. Draw lines on your sketch to mark square metres. Count the square metres to find the area.

If a table has width x and length y (each measured in metres) why does $x \times y$ tell us the area (measured in square metres)?

c. $\text{Volts} = \dfrac{\text{joules}}{\text{coulomb}}$

$\text{amperes} = \dfrac{\text{coulombs}}{\text{second}}$

Multiply those statements. What do you obtain? Give the result its short name.

CHAPTER 2

FORCE, MASS, ACCELERATION

Newton's Second Law; problems; Bernoulli paradoxes

PROGRAMME

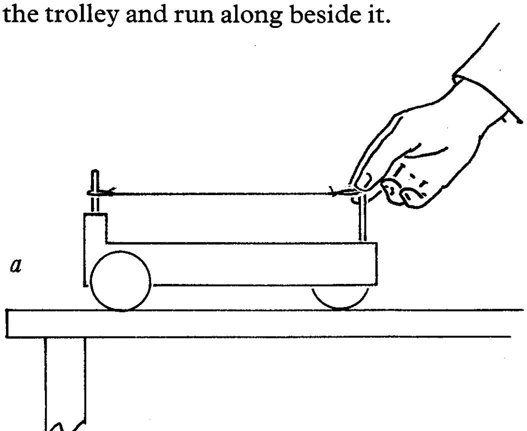
This is a chapter about the way forces make things move. It will lead you to Newton's Second Law of Motion, a great general rule for accelerating cars, trains, rockets, spacecraft, planets . . . including the Earth itself.

You have been using a timer and tape for investigating motion down a hill, in free fall, etc. Now look at the motion of a trolley pulled along a level table.

Experiment 15
Short preview: pulling trolleys
(OPTIONAL)

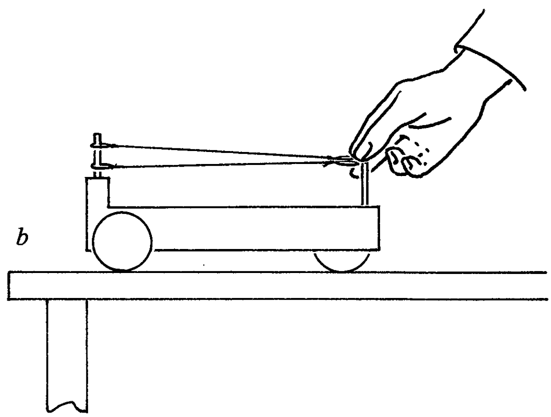
This is a preliminary experiment to see the kind of motion you will be measuring next. Just to remind yourself, try pulling a trolley WITHOUT MEASUREMENTS. You do not need a timer—just watch the motion each time.

(i) Pull a trolley along the table with a stretched elastic. Stretch the elastic until it is as long as the trolley and keep it stretched like that while you pull the trolley and run along beside it.



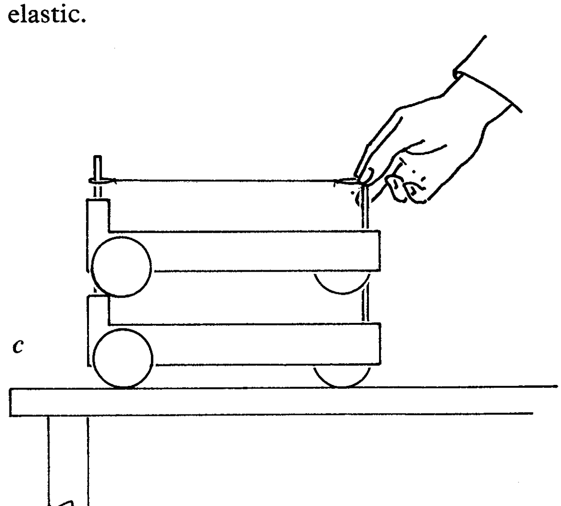
a

Then pull with two stretched elastics side by side; and then with three.



b

(ii) Then try a single elastic's pull on more stuff-to-be-pulled. Pile one trolley on another and try pulling that double mass with one stretched elastic.



c

WHY BOTHER WITH TROLLEYS: WHY WORRY ABOUT FORCE, MASS, ACCELERATION?

The knowledge you are surveying with trolleys is an important part of science that has been worked out in the past three centuries from some experiments—and with some thinking and imagination. It is satisfying knowledge of how things behave, from atoms to planets. It has also been turned to practical use in trains, pumps, jet engines, surgical instruments, refrigerators. . . . Unless you plan to be an engineer you may be content to take those uses of physics for granted; but whatever your plans, this part of science can do two things for you:

(a) help you to understand some skills, in car driving, kitchen cookery, athletic contests, home medicine etc.;

(b) give you reassurance that nature is reasonable.*

In your present work in physics this year, your knowledge of force and motion will enable you:

to build a fuller kinetic theory of gas, by treating molecules with the Laws of Motion—thus leading you to remarkable predictions and fuller understanding;

to read a new discussion of energy and conservation of energy with the nature of heat really understood at last;

to extend your work with electric circuits to using voltmeters and making measurements of power;

and finally to study an experiment that demonstrates single electron charges.

In the following year, Year 5, you will again use knowledge of force and motion to make measurements on a stream of electrons pulled into an orbit by a magnetic field; and you will deal with the orbits of planets and the laws that describe them.

This year and next you will learn about our *models* (thinking pictures) of atoms and the insides of atoms. Your work on force and motion will help you to understand how we get the information that we use in designing our models. You should be able to see how science can be trusted.

* Two thousand years ago, the Latin poet Lucretius said that science 'frees man from the terror of the gods'.

QUESTIONS THAT LOOK AHEAD

Here are some special questions that ask for knowledge of motion. So you will not find you are ready to answer them fully. Yet you may find it interesting to look at them now. Read them, if you like, think about them, leave them unfinished until later when you find you have the skill to answer them. You can already guess some answers by common sense.

Special Questions to look ahead

PUSHING A CAR

1. *(i)* A family car has run out of petrol and is standing outside the house some distance from the garage. Fortunately the road to the garage is smooth and level. Two boys, who are equally good at pushing a car, offer to get the car into the garage. When one boy pushes alone, with the car brakes off and the gear in neutral, the car will not move. A second boy gives the car a push for a short time to help start it; then one boy, pushing alone, can keep the car moving steadily along with his (maximum) push. What forces are acting on the car now? What can you say about those forces? (Remember the road is level.)

(ii) Now suppose the two boys push together (each with the same maximum push), what type of motion would you expect the car to have, if both boys keep up a steady push?

(iii) Suppose that, with both boys pushing fully, it travels 10 metres in 10 seconds starting from rest. How far would you expect it to travel, starting from rest, if the two boys pushed for 20 seconds, that is, twice as long?

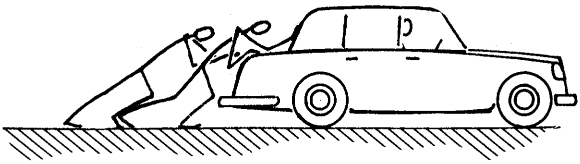
(iv) Now suppose a third (equal) boy arrives. All three boys push together. How far would you expect the car to travel, from rest, in 10 seconds? In 20 seconds?

(v) Now suppose that, owing to a misunderstanding, two boys are pushing forward at the back of the car while the third boy is at the front of the car, pushing it *backward.* If the boys are silly enough to continue this arrangement, how far will the car go, from rest, in 10 seconds? (Answer: 0.)

Now suppose one more (equal) boy joins them. Three boys push forward and one pushes backward. How far will the car go from rest in 10 seconds?

(vi) Finally suppose that two of the four boys climb into the car and the other two push the car

forward. Will the car travel the same distance from rest in 10 seconds as when two boys push it with no extra boys inside? If not, will it travel a greater distance or a smaller one and why?



ROCKET

2. Suppose a large rocket has its rocket motor running—that is, blasting out gas downward—so that the rocket is pushed with enough force to give it a considerable upwards acceleration. Later in its flight, the rocket is to be turned from that direction to a 'horizontal' direction and given enough speed to make it an Earth satellite. When the rocket has turned, will the same blast from its motors give it the same acceleration as before? (Remember the Earth pulls the rocket too.)

While the rocket motors are running, large quantities of exhaust gas are being blasted out from the tail of the rocket. What does this change about the rocket? What effect will that change have?

Does anything else change as the rocket gets farther away from the Earth? (*Hint:* if somebody far away from the Earth, out among the stars, released a stone, would it fall towards the Earth just as usual?)

And here is the overall question: how *do* the rocket motors push the rocket to make it accelerate? (You will need to know about gas molecules and energy to answer that.)

DAMAGE

3. Suppose you know the force, F, needed to change the motion of a certain object in a known time, from some given speed, v, to zero (rest), describe the force needed to make the *same change of speed* in half the time? In $\frac{1}{10}$ of the time? In $\frac{1}{100}$ of the time?

Any object pulled by its own weight (*the pull of the Earth on it*) falls with an acceleration g, 9.8 m/s^2. Its weight tells us the size of force needed to give it that acceleration. What size of force would be needed to give it 10 times that acceleration?

Or, if it is already moving fast, what force would be needed to give it a negative acceleration (a deceleration or retardation) 10 times g?

Can you suggest an easy way of giving some moving object a big negative acceleration? You might let it fall and, when it is moving fast, let it hit a hard floor. Or put it down abruptly on a table.

Try making some guesses about the force when: a watch falls on the floor from your hand; someone puts a wineglass down on the table suddenly; someone drops an ammeter a few centimetres on to a hard table;* a baby rolls off a sofa on to the floor.

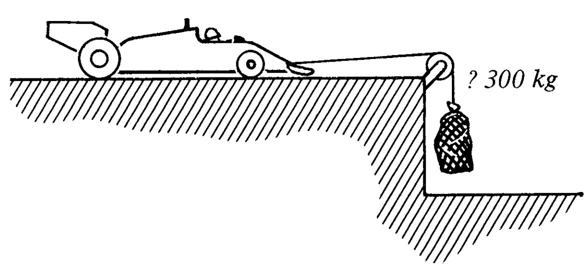
RACING CAR

4. (*This question needs knowledge that you will not reach till later; so you would have to leave your answer unfinished now. If that seems infuriating, please leave this question untouched now. If it seems intriguing to try it, see how far you get, and find what more you will need, just give it a brief trial now.*)

A 1000-kilogram racing car is being tested. When it is running at 80 kilometre/hour, with the throttle fully open—the accelerator on the floorboard—it can just keep going at 80 if the brakes are on at half pressure.

To find out the force the brakes were exerting then, the testing people stop the car, stop the engine, put the gears in neutral and then drag the car forward with the brakes still at half pressure. They keep the car moving forward by a rope which runs from the front of the car to a pulley wheel over a pit, over the pulley, and down to a load of scrap iron hanging on the end. The car continues to creep ahead as the load falls.

What acceleration would that car have, with the throttle open and brakes off, when driving at 80 km/hour? And with that acceleration how long would it take to speed up from 80 to 100 km/hour?



* Just the weight alone of the coil of a small ammeter can make a PRESSURE on its tiny pivots of more than 1 tonne per square centimetre.

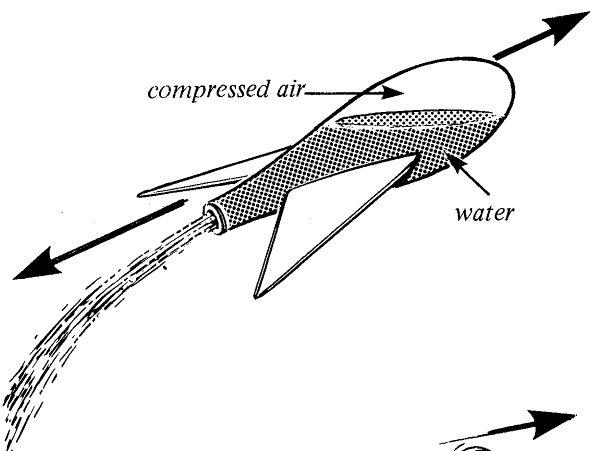
(You can see that one piece of data is missing: the force pulling the rope. Would you like to guess about the scrap iron? In fact, 100 kilograms would be reasonable for an ordinary car and 500 kilograms would be unreasonably big for any car. We might suggest 300 kilograms of scrap iron as a high testimonial to that racing car. But what FORCE would that exert on the car? Here the solution must wait till you know about mass, weight and force-units.)

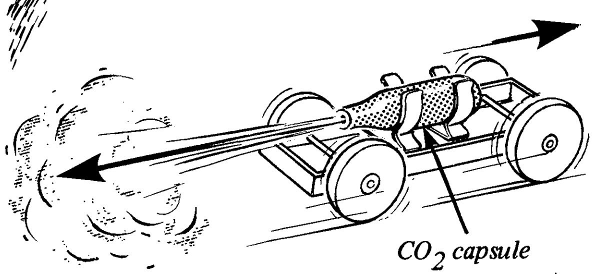
PENDULUM IN SPACE

5. Would a pendulum be able to swing to-and-fro if we carried it to a place far away in outer space (where the gravitational pull is negligible)?

Demonstration 16
Toy rocket

The rocket fires out water (or carbon dioxide gas) backwards. In thus bouncing backwards the water (or gas) has pushed the rocket forwards.

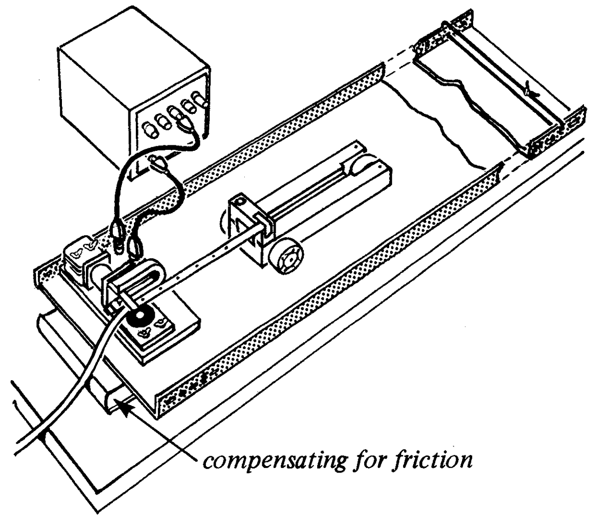




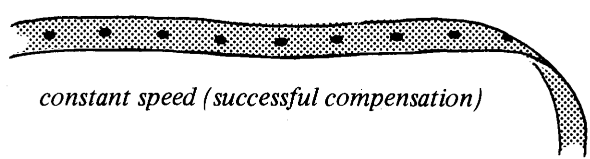
Experiment 17a
Force and acceleration

This is going to be a long, careful experiment in which you pull a trolley with a steady pull and find out about its acceleration for different amounts of pull.

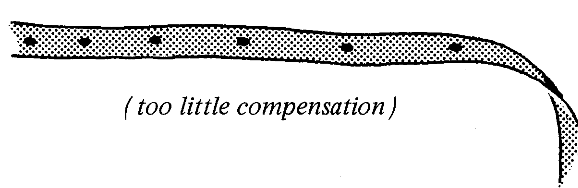
Friction compensation Before you start pulling the trolley you must make sure that friction will not spoil your experiment. Compensate for friction by raising the starting end of your runway a little so that the runway slopes gently downhill. Put one thin book (or piece of wood) under the starting end. Let your trolley run down the hill, pulling some tape (because that adds friction). If it moves faster and faster you have tilted the runway too much. If it moves slower and slower you have not tilted the runway enough.



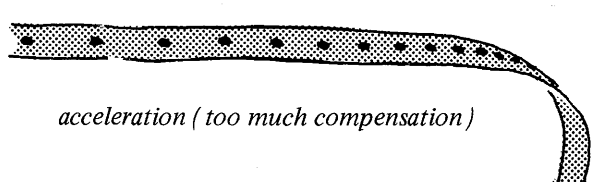
To see whether you have succeeded in arranging that friction compensation, look at the tape and see whether the dots are spaced apart at equal distances.



constant speed (successful compensation)

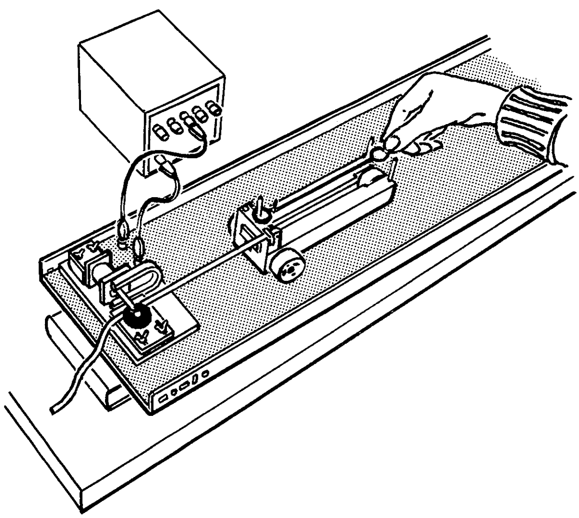


(too little compensation)



acceleration (too much compensation)

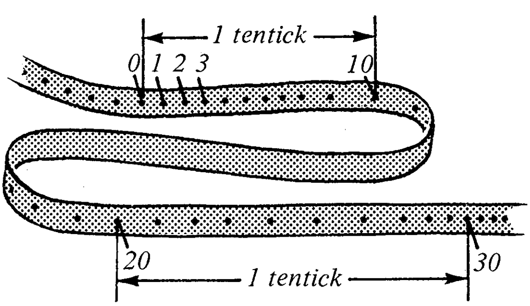
The pull Now attach about two metres of tape to the back of your trolley so that you can record its motion. Pull your trolley with one elastic stretched to standard length. You may find this easiest if you put the ring at one end of the elastic on the post at the back of the trolley, and pull the other end until the ring is just level with the front of the trolley. (If you like, put a pencil through the front ring and pull with the pencil, holding it vertical.)



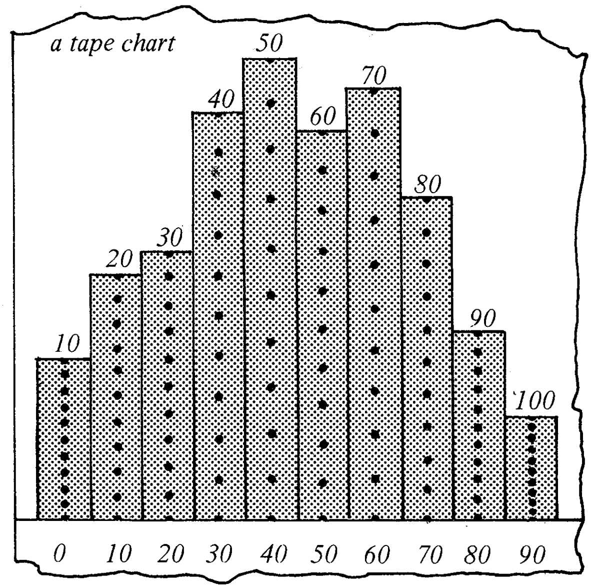
Walk and run with the trolley, keeping the force steady.

If you work with partners, each partner should make his own tape record.

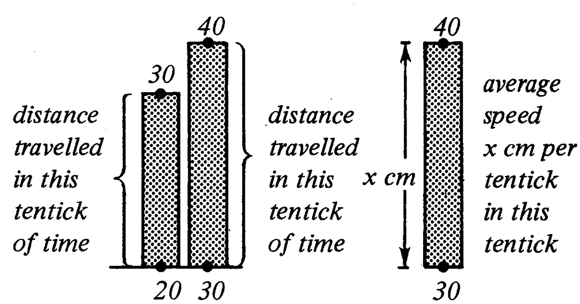
Choose a clear dot near the beginning of your tape, mark it 0. Count along the tape to dot 10. Mark that, and mark dots 20, 30. . . . Cut your tape at the marked dots so that you have a set of tentick strips.

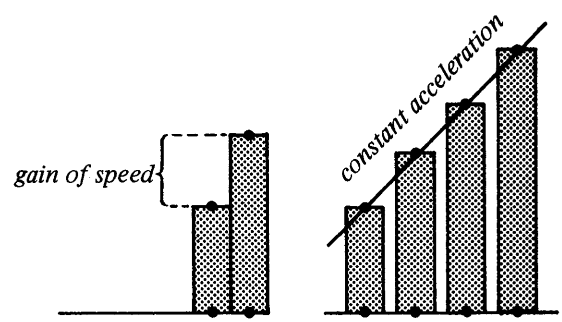


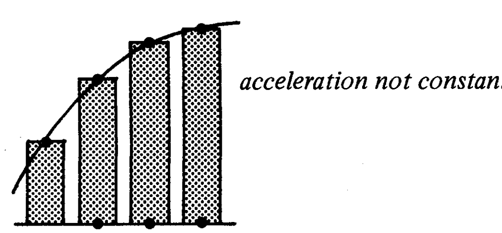
Tape-chart Paste your set of strips side by side on a sheet of paper, with their feet all on a horizontal line.



Look at the heads of your strips. Do they make an even 'staircase' of strips? What can you say about the motion of your trolley?

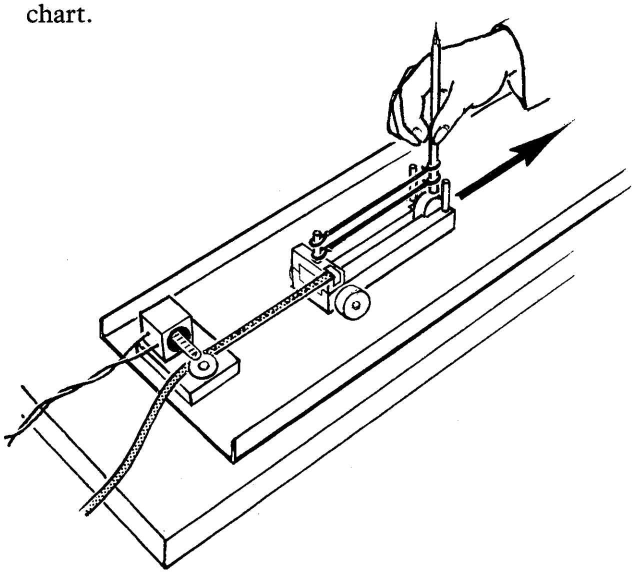






Double pull Then start again, pulling the same trolley with two elastics side by side to make double force. Make a tape-chart of strips from that.

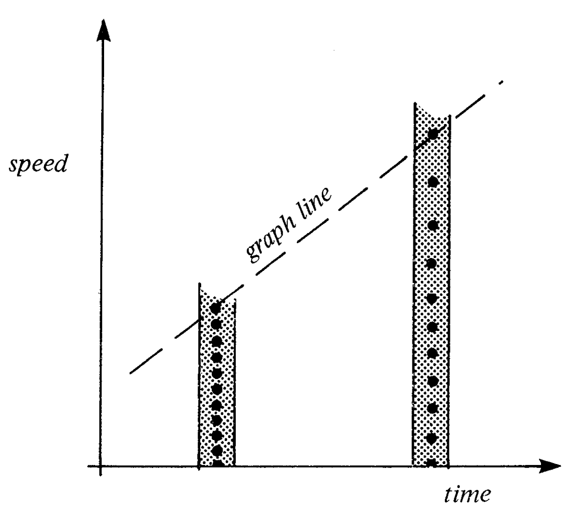
Triple pull Then start again and pull with three elastics side by side. Again make a tape-chart.



Experiment 17b
Graphs to show the story of the tapes

You pulled a trolley with a single pull, double pull, triple pull and obtained three tape records.

Look at your tape-chart for each of those three runs. Is the line through the heads of your tape-strips fairly *straight*, on each chart? If it is, that means the trolley ran with *constant* acceleration; because your tape-strips make an even staircase of equal jumps in speed from every strip to the next.



If each chart shows fairly constant acceleration you can now change to a quick way of showing the story that the three charts tell about force and acceleration.

Choose two tentick strips on a chart, one near the beginning, the other much later, say 50 tenticks later. Measure their lengths in centimetres and millimetres. Plot each LENGTH (upward) on a graph against TIME in tenticks (along). Join your two plotted points with a straight line.

Treat the other two tapes in the same way. Plot points and draw lines *on the same sheet of graph paper* for all three tapes.

(Each time you draw the straight line through just two points you are taking something for granted. What is it?)

The slope of one of those lines is like the slope of the staircase of heads of strips. It tells you the acceleration of the trolley.

Measure the slope of each line. You used pulling forces in proportions 1:2:3. Can you see any simple proportions among your three slopes?

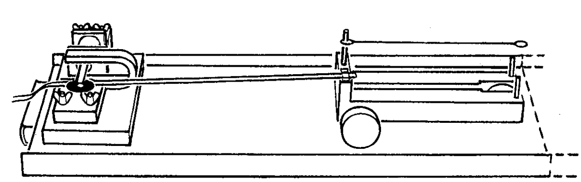
What does your experiment seem to tell you about acceleration and force? Discuss this question with your teacher.

Class Experiment 17c
Accelerating more passengers: the cunning test

Preparation

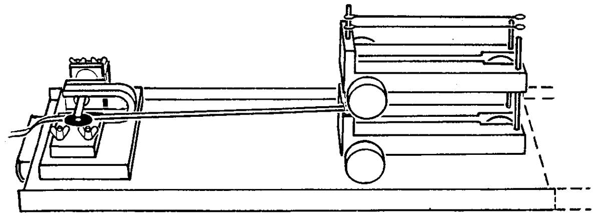
Set up the runway and compensate it for friction. Test your compensation carefully.

Set up the timer at the higher end. Arrange a trolley to pull tape through it. This trolley must have good wheels. It should be the trolley that you used in arranging friction compensation.

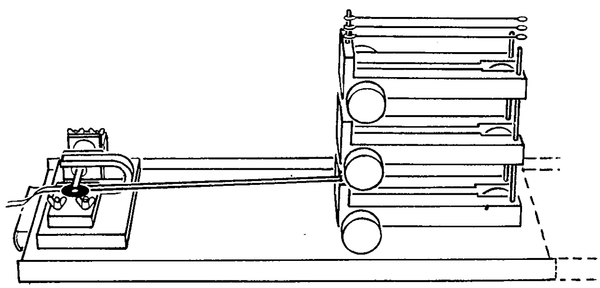


Thinking and planning

In this experiment you will see what happens when you pull more MASS. Try doubling the mass. That means having twice as much stuff to accelerate. You can arrange this by piling one trolley on top of another. Then you will be pulling two trolleys, twice as much stuff.



After that you can arrange three times the mass, by piling one more trolley on top. (If necessary borrow the third one for that.)



It may be difficult to see the relationship between acceleration and the mass you pull. You might pull with one stretched cord each time: first on one trolley, then on two trolleys, then on three trolleys. But you would have to calculate very carefully from your measurements to see the connection between acceleration and mass.

A clear, quick, test

Here is an easier method instead. *Try imagining the answer first*; then make a simple test of it. (This is very good science. If you have a hunch, or can make a guess, use it to predict what will happen in an experiment. Then try that experiment as a test.)

Guessing with a hunch

Instead of using the *same force* each time, try to get the *same acceleration*. Ask yourself:
'How much should I pull on *two* trolleys to get the *same acceleration* as when I pull *one* trolley with *one* stretched cord? And how much should I pull on *three* trolleys to get the *same acceleration*?'

Guess the answers and try them.

(If you want double pull you can pull with two equal rubber cords side by side.)

The experimental test of your thinking

(i) Pull the trolley by a single rubber cord and obtain a trace. Start the trolley from rest, and start the tape when the trolley starts. (To do this, set the timer going, but hold the blade with a finger. Release the timer's blade at the same instant as the trolley.)

If you are sharing with partners, *each partner should make his own tape.*

Keep your tape carefully.

(ii) Then stack another trolley on top of your first trolley to make a double mass, twice as much matter to move.

Check the friction compensation. (You now have twice as big a load on the wheels and the slope for friction compensation may be the same or it may be different.) Therefore you must check it and if necessary change the slope of your runway.

Pull the double mass with whatever force you *guess* will give it the *same acceleration.*

Look at your new tape. Does it confirm your prediction?

If you have the same acceleration, the new tape must look just like the old one. On each tape, count five (or ten, or twenty) tenticks from the start. Then compare the total distances.

(iii) Continue your test, pulling three trolleys with the force that you *hope** will give the *same acceleration.* Make the test.

What does this experiment tell you? Discuss it with your teacher.

Mass In Experiment 17c you double the amount of stuff being accelerated when you change from one trolley to two trolleys. And with three trolleys you have three times as much stuff, compared with a single trolley. The scientific name for 'amount of stuff', which is here being judged by number of trolleys, is MASS.

The more mass you have the bigger the force needed to give it some standard acceleration. Or, if you stick to the same force you get less and less acceleration when that force pulls more and more

(* Yes, *hope*. It is quite respectable in science to *hope* you will find a simple story. Then it is good if you find your guess is true. But it is bad if you find your guess does not fit and yet go on sticking to it because you hoped!)

mass. So mass tells you about the 'un-accelerability' of a collection of trolleys or anything else being pulled. That is not like friction which drags back against motion and may actually stop it. Mass is *not* something that stops you from getting an object moving; it is only something that tells us how difficult or slow it is to build up the object's motion. As a slang description of mass, you might even say it is 'difficultness of getting goingishness'. It is a very important characteristic of every kind of matter and of every kind of energy. (It is the m in $E = mc^2$.) You will find mass easier to understand and more and more important as you get to know it from your own experiments.

Progress Questions

FRICTION COMPENSATION

6. Suppose you want to find out how a trolley moves when you pull it with a steady force.

a. Describe how you could pull a trolley with a steady force.

b. Can you think of any other ways of pulling a trolley with a steady force?

c. Does the trolley move along with steady speed when you apply a steady force?

d. If you have a trolley on a level runway, and give it a push to start it off, and then apply no force at all, how does it move?

e. There is another small force acting backwards all the time when the trolley moves. What is this force called?

FORCE AND ACCELERATION

7a. You want to find out exactly how a trolley accelerates when it feels *only* the effect of a steady forward pull with an elastic. But in a real experiment friction always acts backwards too. What can you do to the runway so that there is an equal sized forward force to cancel friction?

b. How do you know when this forward force is just the right size to balance friction backwards?

8. Now you have 'got rid of' the effects of friction, as in Question 7 you can concentrate upon the effects produced by the steady force which you apply by the elastic.

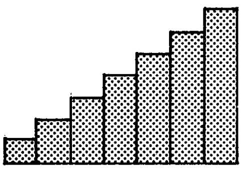
a. How did you make sure that you used the *same* force all the way?

b. Sketch the chart you got, and explain what it tells you about the acceleration of the trolley. (Did it stay steady? How big was it?)

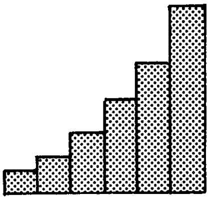
c. How did you arrange to have *double* the force you were using to pull the trolley?

d. Sketch the chart you got and explain what it tells you about the acceleration this time.

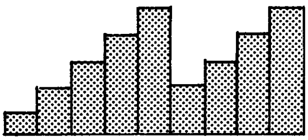
9. A class was doing experiments on using trolleys connected to tape and timers. Each trolley was pulled by one stretched elastic. An experiment was carefully done with a straight board. It gave a tape chart like A but some of the pupils got charts like B, C, D.



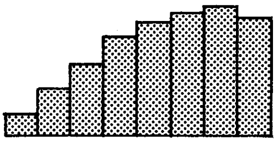
A



B



C



D

a. One trolley scraped along the side of the trolley board about half way along. Which chart do you think shows this?

b. One tape got tangled so that for a moment the trolley almost stopped, but the pupil continued pulling. Which chart do you think shows this?

c. One pupil stretched his elastic further and further as he went, instead of keeping it stretched at the same length. Which chart do you think was his?

10. Chart A was made by pulling one trolley with a steady force of one stretched elastic.

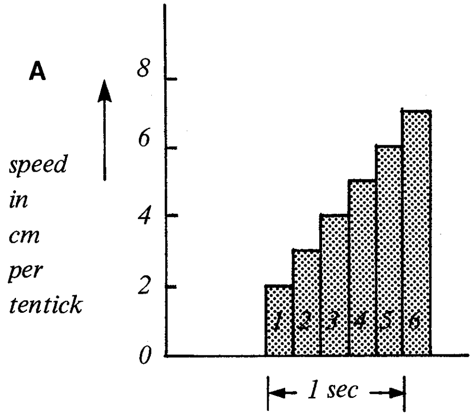
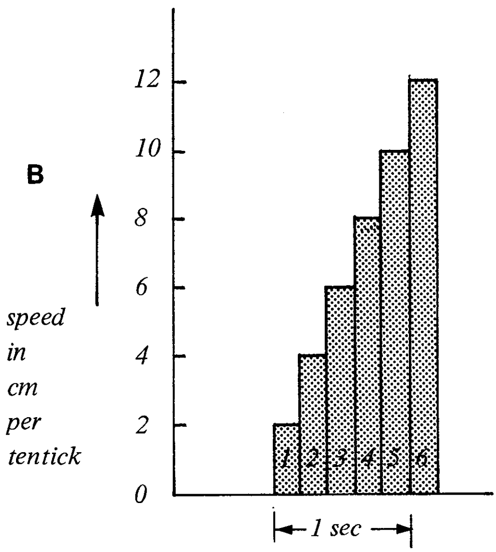


Chart B was made by pulling one trolley with a steady force of two stretched elastics.



a. What do you notice about the sizes of the steps in Chart A? What do the steps show you?

b. Is the acceleration in B bigger or smaller than the acceleration in A? How can you tell?

c. What is the increase in speed every tentick in Chart A? (Your answer will be in cm per tenticks every tentick.)

d. What is the increase in speed every tentick in Chart B? (Write your units carefully.)

In another experiment, C, the same trolley was pulled with a steady force of three elastics.

e. What increase in speed every tentick, do you expect? *Sketch what you expect Chart C to look like.* (Label the axes carefully.) Write a sentence or two underneath saying in words all that it tells you.

f. Copy and fill in this table:

Force	*Increase* in speed every tentick—that is, ACCELERATION
One elastic	. . ? . .
Two elastics	. . ? . .
Three elastics	. . ? . .
Four elastics	. . ? . .
Five elastics	. . ? . .
Ten elastics	. . ? . .

g. You could also write out a table of results from your own experiments. Do they show the same pattern? They probably don't show it so clearly. Write a sentence or two to explain why not.

h. Write in your own words the pattern made by the numbers for force and acceleration, for one trolley.

i. It would be very hard to get sensible results for an experiment with ten elastics (or even five!). Explain why.

MASS AND ACCELERATION

11. A trolley is pulled with a steady force by one stretched elastic. The acceleration is 6 *cm/tentick in every tentick.*

a. Draw a speed-time chart to show this for the first 6 tenticks.

A second trolley is put on top of the first one, and together both trolleys are now pulled by one stretched elastic.

b. What acceleration will the trolleys have?

c. Draw a speed-time *chart* to show this, for the first 6 tenticks.

d. Draw a speed-time *graph* for one trolley, one elastic. (You can draw in the first and sixth tape strips if you like.) On the *same* axes, draw a speed-time graph for two trolleys, one elastic.

e. Look at your two graphs. Which graph is steeper? Which shows the bigger acceleration?

f. Now a third trolley is put on top of the other two, and all three are pulled with one elastic. What acceleration will the trolleys have?

g. Now copy and complete this table:

Number of trolleys	Acceleration with one elastic
1	6 cm/tentick in every tentick
2	
3	
4	
10	

h. Now write in your own words the pattern made by the number of trolleys and the acceleration, for a steady force of one elastic.

i. You could also write out the table of your own measurements. Do they show the same pattern? They may not show it so well. Write a sentence or two to explain why not.

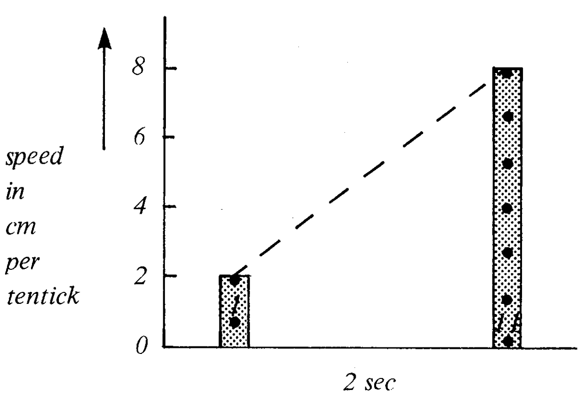
12a. Two elastics give one trolley an acceleration of 8.6 cm/tentick gain of speed in each second. What acceleration will two elastics give *two* trolleys?

b. One elastic gives three trolleys an acceleration of 9.3 cm/tentick gain of speed every second. What acceleration will one elastic give *one* trolley?

c. One elastic gives one trolley an acceleration of 12.8 cm/tentick in every second. With a pile of trolleys the same elastic gave an acceleration of 3.2 cm/tentick in every second. How many trolleys were there?

13. Here is a tape-chart with a gap in it. It was made by pulling a trolley with one elastic. Tentick tapes numbers 1 and 11 are given, and the tapes in between went up in even steps.

a. What was the speed when tape 1 was taken? (In cm per tentick.)



b. What was the speed when tape 11 was taken?

c. What was the increase in speed in that 2 seconds?

d. What was the increase in speed in 1 second, i.e. what is the acceleration?

In another experiment, the trolley was pulled with two elastics.

e. What will be the increase in speed every second now?

f. Copy and complete:
For one elastic, the acceleration is ..... cm/tentick every second.
For two elastics, the acceleration is ..... cm/tentick every second.

g. What will be the increase in speed in *two* seconds, with two elastics?

h. Copy the chart. On the *same* axes draw the sort of chart you expect for the second experiment. (Draw it like the first one with a gap in it. Label it carefully.)

14. One elastic gives one trolley an acceleration of 3 cm/tentick, every tentick.

a. Another trolley is put on top of the first. How many elastics do you need, to give the two trolleys the same acceleration 3 cm/tentick in every tentick?

b. How many elastics to give the *same* acceleration to 3 trolleys?

c. Copy and complete this table:

Number of trolleys	Number of elastics to give acceleration of 3 cm/tentick in every tentick
1	. . 1 . .
2	. . ? . .
3	. . ? . .
4	. . ? . .
10	. . ? . .

d. Write in your own words the pattern made by the number of trolleys and number of elastics, to give always the same acceleration.

15a. A force of one elastic gives a trolley an acceleration of 2 cm/tentick, every second. What acceleration will three elastics give the same trolley?

b. A force of four elastics gives an acceleration of 8.4 cm per tentick, every second. What acceleration will one elastic give to the same trolley? And three elastics?

c. A force of 1 elastic gives an acceleration of *a* cm/tentick every second. What acceleration will N elastics give?

d. A force of two elastics gives an acceleration of 2.1 cm/tentick, every second. How many elastics will be needed to give an acceleration of 6.3 cm/tentick, every tentick?

Note: There are some progress questions in Chapter 1A on average speeds and acceleration.

Questions

TAPE RECORDS

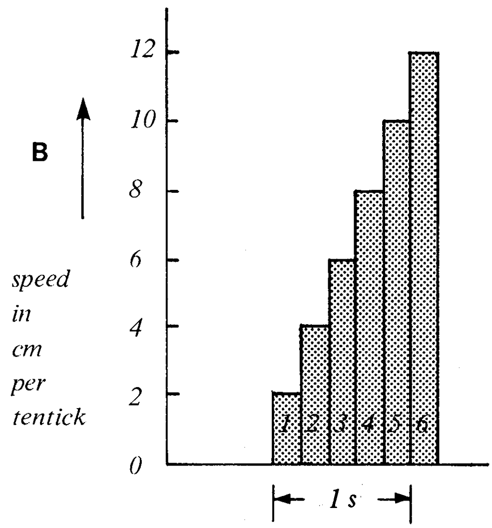
16. You have done acceleration experiments with trolleys pulled by elastic. You used a timer and tape. But now suppose you have no timer. However, you have apparatus for taking a multiflash photo instead. (You could install a small bright pillar on the trolley.)

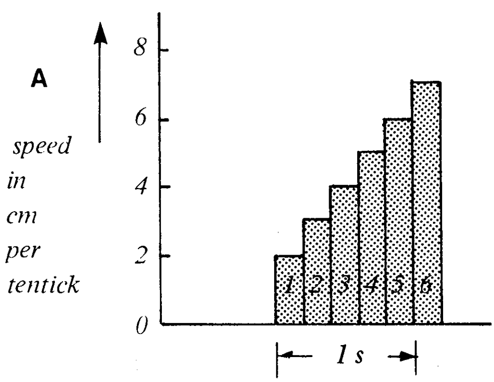
a. Draw a rough sketch of the trolley being pulled, the camera, and any other apparatus you consider essential.

b. Make a rough sketch of a multiflash photo of the accelerating trolley.

c. Explain how you would make something like a tape-chart from your photo.

17. Here are parts of two charts made by pulling one trolley with a steady force of one elastic, and then with double that force. (In each chart a time of five tenticks is marked, which is 1 second of time.)





a. What is the size of each STEP in chart A?

b. What is the size of each STEP in chart B?

c. In chart A, the trolley was going at a speed of 2 cm per tentick when the tape-strip marked 1 was going through the ticker.

d. How fast was the trolley going during tentick 1 in chart B?

e. How far did the trolley go in the 1 second marked on chart A?

f. How far did the trolley go in the 1 second marked on chart B?

18. Suppose you tilt a runway a little, so that a trolley rolls down it with constant acceleration.

a. What is the *name* of the force acting on the trolley and pulling it down the sloping runway?

b. What can you do to the runway to 'dilute' or lessen the effect of this force on the trolley?

c. Roughly what effect does this lessening of force have on the trolley's acceleration?

d. The force of friction between the wheels and the runway acts backwards, all the time too.

How does the trolley move if the force pulling it forwards is so dilute that it EXACTLY BALANCES the force of friction backwards? (*Hint:* There are two possible answers here.)

FORCE AND ACCELERATION

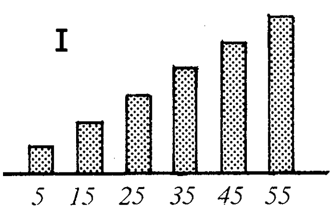
†**19.** You have done acceleration experiments with trolleys. First you pulled a trolley with a steady force F, unchanging from start to finish. You did this by using a piece of elastic. Then you pulled with a force of $2F$; then, perhaps $3F$.

a. How did you make sure that the force F was steady (= did not change)? Describe exactly how you did this.

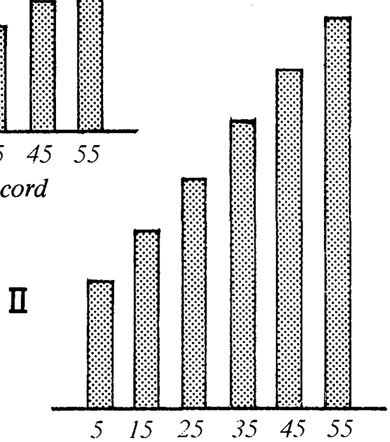
b. How did you make forces $2F$ and $3F$?

c. For these experiments you made the runway slope slightly, to compensate for friction. How did you find the correct amount of tilt?

†**20.** Two pupils did a trolley and tape experiment in which they pulled the trolley first with one elastic cord, and then with two elastic cords each kept stretched just as much as the first one.



one elastic cord



two elastic cords

They took the first tape and cut the middle part of it into six tentick strips, dot 0 to dot 10, dot 10 to dot 20, 20–30, 30–40, 40–50, and 50–60. They pasted them at regular intervals on graph paper, with the result shown (figure I is one-quarter of actual size).

They then did the same thing with the second tape. The result is in figure II, also one-quarter of actual size.

a. Do these charts show that 'steady force gives steady acceleration'? How do you know?

b. Do these charts show 'twice the pull gives twice the acceleration'? How do you show this from the graphs given?

c. *(Advanced)* The first strip in II is more than twice the length of the first strip in I. Similarly for the last strips. How do you explain this?

FORCE AND MASS

21a. How did you arrange to pull one trolley with a force F, then two trolleys with $2F$, then three trolleys with $3F$? Give sketches. Say briefly how you measured the accelerations.

b. What did you notice about the results for the acceleration?

22. If one trolley requires a force F to give it an acceleration a; what force is required to give 3 trolleys, piled on top of each other, an acceleration of $2a$?

23. You answered the last question by common sense, backed up by the results of experiments you have done. You can now bring together all these results in one relation between: FORCE & ACCELERATION & NUMBER OF TROLLEYS.

a. Write down this relation, using those names and the symbol $\propto$ for 'varies directly as', or 'is proportional to'.

b. Write the relation, using the symbols F for force, a for acceleration and m for number of trolleys.

24. Three stretched elastics give 1 trolley an acceleration of 6.1 cm/tentick in every second. How many stretched elastics are needed to give *two* trolleys (one piled on top of the other) the same acceleration?

25. 6 elastics give 3 trolleys an acceleration of 2.7 cm/tentick every second. How many elastics will give *one* trolley the same acceleration?

26. An elastic is used to apply a steady force F to a trolley, and a steady acceleration *x cm/tentick in a tentick* is produced.

a. What acceleration would be produced by applying the same force F to
(i) two trolleys piled one on top of the other?
(ii) three trolleys piled one on top of the other?

b. How many elastics would you have to use to give acceleration *x cm/tentick in a tentick* to
(i) two trolleys piled one on top of the other?
(ii) three trolleys piled one on top of the other?

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† From *Pupils' Text 3*.

27. The table shows part of the results of an experiment to find the acceleration produced by pulling one, two or more trolleys piled on top of each other with steady forces. 'm' stands for 1 trolley, '$2m$' stands for 2 trolleys etc. Copy this table and fill in the blanks.

Force applied	No. of trolleys pulled	Acceleration produced
F	m	a
$2F$	m	$2a$
$3F$	m	?
$2F$	$2m$	?
$3F$	?	a
?	$4m$	a
?	$3m$	$2a$

28. When two objects are equally slow or difficult to accelerate, we say they have equal masses. And when two masses are equal they have the same acceleration when we apply the same force to each.

You have two trolleys, A and B, elastic, tape, a vibrator and a runway. The maker says the two trolleys have the same mass.

a. Give a brief outline of an experiment you could do with this apparatus to see if the maker is right.

b. In any accurate experiment of this sort, you should compensate for friction between the trolley and the runway. How do you do this for trolley A?

c. You attach a tape to trolley A and pull with a steady force. How do you get a steady force? How do you make a speed-time chart with the tape?

d. How can you arrange to pull B with the same force as you pulled A?

e. You do the experiment with B, using the same force, and make a speed-time chart. What do you expect to notice about the two charts if the maker is right and A and B do have equal masses?

f. And what would you expect if B's mass was a bit bigger than A's?

Question

'NEWTON'S LAWS'

(Here are some questions to help you to sum up the knowledge that your experiments with trolleys gave you, or illustrated. Use your own words—avoid official wording from some book.)

29a. If we leave some object alone, with no force acting on it, and it is at rest, *it stays at rest*. But, if it is already moving, it . .? . . .

b. If there are several forces acting on an object, it still behaves as in (a) provided that those forces . . ? . . .

c. If a constant *resultant* force acts on an object the object's motion has . . ? . . .

d. For the same acceleration, double mass requires . . ? . . .

DISCUSSION OF NEWTON'S LAWS OF MOTION

Newton wrote his Laws of Motion three hundred years ago, as working rules when he built his theory to explain the behaviour of the Moon, the planets, and many other things—all in one grand 'package' story.

What do you infer* from your tape charts and graphs?

You see that a constant force gives a body constant acceleration. This is a fact of nature. We could not have decided just by thinking about it that this must be so; but careful experiments tell us that this *is* so.**

Small medium and large forces make different accelerations. Now put that story in definite form.

'Accelerations are proportional to the forces' meaning 'double force makes double acceleration, etc.'

In algebra-shorthand that is:

$$a \propto F \quad \text{or} \quad F \propto a \qquad \ldots(1)$$

Then, with different masses, the forces needed, for the *same acceleration*, are proportional to the masses. Or, in algebra-shorthand,

$$F \propto m \qquad \ldots(2)$$

Each of those two relationships (1) and (2) has

* *Infer* means *deduce* or *argue out logically*, or *extract*. It does not mean the same as *imply*. It is a useful word in science.

** But is it *completely* true? If you could go on pulling with a constant force on some object so that it moved faster and faster and faster and still faster . . . would there be any limit? Would the simple story change? Certainly not up to any ordinary speed up to the speed of a bicycle, or a jet aeroplane, or an air molecule. But how can we be sure for still higher speeds unless we can do special experiments to find out?

been illustrated by your experiment. They can be combined in one relationship.*

$$F \propto m \times a \quad \text{or} \quad F = Kma$$

where K is a constant number for all forces, masses and accelerations. (But the value of K does change if you change to different units; e.g. from centimetres to metres.)

The final form, $F = ma$ To make that result seem still simpler we compel the general constant K to have the value 1. We pay for that by taking a special unit for forces, the *newton*. You have already met newtons on spring balances and now you can see how the newton is arrived at. We write $F = Kma$ with $K = 1$ so that it is

$$F = ma$$

Then to see what one newton is, make $m = 1$ kilogram and $a = 1$ metre/second per second.

$$F = 1 \times 1 = 1 \text{ newton}$$

So 1 newton is the force that gives 1 kg an acceleration of 1 metre/second^2.

Problems Use $F = ma$ to calculate accelerations from forces and masses. Or calculate forces from accelerations and masses. Remember F will always be in *newtons* if m is in kg and a is in m/s^2.

Units When you calculate a FORCE in *newtons* you multiply MASS in *kilograms* by ACCELERATION in *m/s*^{2}. So *newtons* are an economy name for *kilograms·metres/second*^{2}. Just 'dictionary work'.

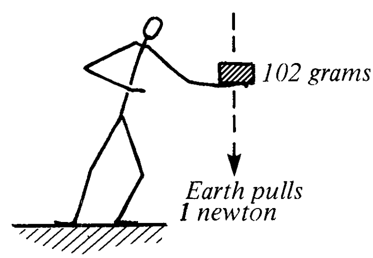
If you forget that, put $m = 1$ kg and $a = 1$ m/s^2 in $F = ma$. Then F is, as you know, 1 newton, and 1 newton $= 1 \text{ kg} \times 1$ metre/second^2.

How big is a newton? One newton gives one kilogram 1 m/s^2 acceleration. The pull of the Earth gives a kilogram an acceleration g, 9.8 m/s^2. That is nearly 10 m/s^2; so the Earth must pull a kilogram with a downward force nearly 10 newtons. The Earth must pull with 1 newton on about $\frac{1}{10}$ kg or 100 grams ($\approx\frac{1}{4}$ pound).

A newton is universal Since 1 newton will give 1 kg an acceleration 1 metre/second^2 it must be the same everywhere, at different places on the Earth, on the Moon, even far out in space, because the mass of that kilogram does not change when you take it somewhere else, and your measurements of acceleration with a metre rule and a clock showing seconds would still use the same units. If someone pulls your ear with a force of 1 newton you can feel that but it would not hurt; if he pulls with 100 newtons that will hurt, and it will hurt just as much if you are living comfortably on the Moon or are voyaging in a space capsule where you would notice no gravity. You could take a spring balance marked in newtons to any other place and it would still measure forces in standard newtons.

Experiment 18
Feeling a newton of force

Hold 100 grams in your hand.



WEIGHT

The weight of an object is a force, the pull of the Earth on it. That weight is just like any other kind of force except for two peculiarities: it is *vertical* and *unavoidable*. We measure an object's weight in newtons.

As you can see by hanging objects on a spring balance, the weight of 1 kilogram is 9.8 newtons.

Pupils' Demonstration 19
Forces box

Hold the ring marked 1 newton. Pull.

---

* Combining two proportionalities may seem a puzzling business but you can check it here by arguing backwards from the result $F = Kma$.

(1) Use the *same single trolley* with different forces. The mass m is constant.

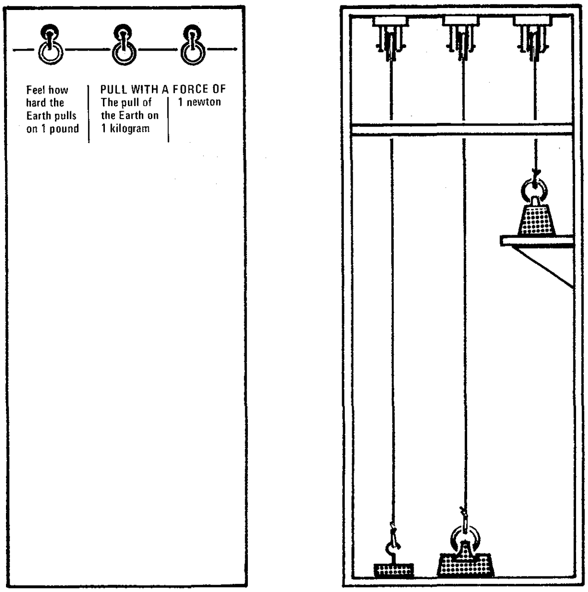
$$F = \{Km\}a$$

and $\{Km\}$ is constant, so $F \propto a$.

(2) Insist on the *same acceleration* with different masses. Then a is constant.

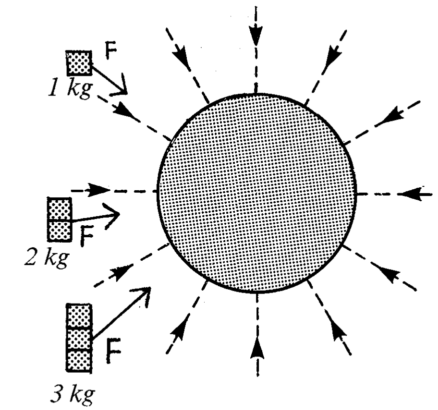
$$F = \{Ka\}m$$

and $\{Ka\}$ is constant, so $F \propto m$



GRAVITATIONAL FIELD STRENGTH

We picture a *gravitational field of force* spreading out from the Earth, a 'readiness to pull'.



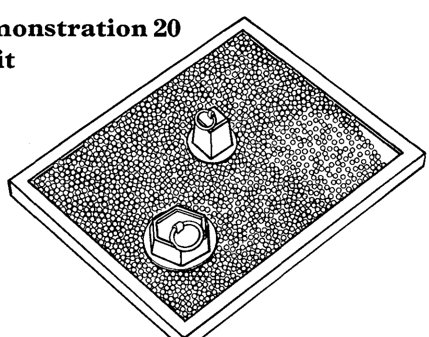
Earth's gravitational field

MASS

The mass of an object tell us how much stuff there is in the object. We measure mass in kilograms. A kilogram of chocolate (more than 2 lbs) is the same big block of chocolate on the Moon as on Earth; the same amount to eat; the same number of atoms; the same 'stuff' to accelerate.

The mass tells us how small the acceleration will be when a given force acts on the object. So we might coin a slang description of mass as 'unaccelerability' or 'difficultness-of-getting-it-going'! Some people call it 'stodginess of stuff' but that fails to remind you that you must push or pull an object to find out about its mass. Remember that a large mass does not mean the object is fixed and cannot move; even the smallest resultant force will make a massive object accelerate—though the motion may increase very slowly.

Pupils' Demonstration 20
Mass exhibit

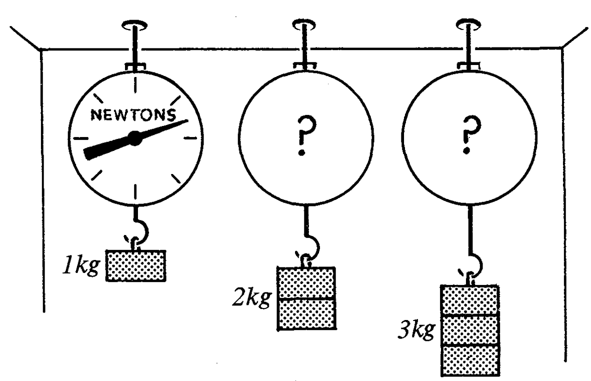


Here is a kilogram riding on a sea of small metal balls. Give it a push, so that you feel its mass.

There is no actual force at a place near the Earth until we put some stuff there for the field to pull on. Then it pulls like a giant invisible spring. The field itself is always there, a state-of-affairs-waiting-to-pull on matter.

You will see the effects of another kind of field, an electric field, which is a state of waiting to pull on electric charges.

A spring balance (already marked in newtons) will tell you that the Earth pulls 9.8 newtons on 1 kilogram; and twice as much, 19.6 newtons, on 2 kg; and so on. The Earth's field pulls 9.8 newtons *on every kilogram*. We call that the Earth's *gravitational field strength*, 9.8 newtons per kilogram. (Think of that as rather like a price, such as 5p per orange. The field strength is the field's price of force per kilogram of stuff.)



how many newtons on each kilogram?

Now that you know $F = ma$ you can see how we know the Earth's field strength, and how we mark a spring balance in newtons.

A NEW MEANING FOR g

In Experiment 21 you use the acceleration of free fall, g, to calculate the pull of the Earth on a kilogram, the pull that makes it fall with acceleration 9.8 metre/second per second. Now you can calculate the pull on any mass, m, even when it is not falling. You imagine it falling with acceleration g (the same for all masses), and calculate the force $F = \text{mass} \times \text{acceleration} = mg$. Then you know the pull is the mass (measured in newtons) on each kilogram of stuff. Thus g is the Earth's gravitational field strength. You already know g as an *acceleration* 9.8 metres/second^2; but now you can use it as a *field strength* 9.8 newtons per kilogram. When an object is at rest you may want to know its weight, the pull of the Earth on it; and it would be silly to say g is 9.8 metres/second^2 when the object is not accelerating. But it is necessary and sensible to say g is 9.8 newtons/kg.

Thus g has a new meaning, even more important than its meaning for acceleration.

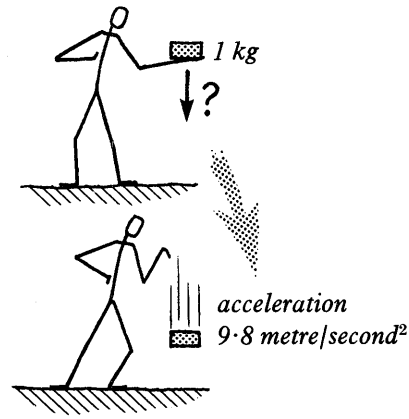
How can g have the same number but two different units—for two different uses? To see that the units are equivalent, remember that 1 *newton* gives 1 *kilogram* an acceleration 1 *metre/second*^{2}. Then newtons are the same as *kilogram·metres/second*^{2}.

So $g = 9.8 \dfrac{\text{newtons}}{\text{kilogram}}$ is the same in size as $g = 9.8$ metres/second^2. Yet the uses of the two different forms are different. Whenever you need to calculate a weight, you should use the field strength, 9.8 newtons/kilogram.

When a load hangs on a string at rest, the pull of the Earth on that load makes a tension in the string. All strings stretch a little when pulled—and so do wires and even metal rods—and they stretch more and more until their tension just balances the pull of the load that is hung on them. To calculate the tension in a string that carries a load, use the Earth's field strength.

Experiment 21
Weight and field strength

(i) Hold one kilogram in one hand. Feel the force on your hand. *What causes that force?*



(ii) Then let the kilogram fall. You need not measure the acceleration, because you already know it. The kilogram falls with acceleration 9.8 metres/second per second.

Use $F = ma$ to calculate the FORCE that makes the falling kilogram accelerate. That is its WEIGHT, the pull of the Earth on it.

How big was the force you felt on your hand? How many newtons?

(iii) Now look at the force in a different way. Let it show you the Earth's gravitational field strength. Copy and complete the following in your record:

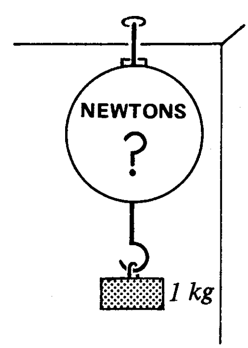
Pull on 1 kg (mass) is . . ? . . newtons

$\therefore$ Earth's field strength $= \dfrac{\text{. . ? . . newtons}}{1 \text{ kg}}$

If I use 5 kg the pull is . . ? . . newtons

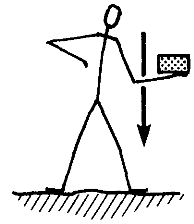
$\therefore$ Earth's field strength $= \dfrac{\text{. . ? . . newtons}}{5 \text{ kg}}$

$=$ . . ? . . newtons/kg



(iv) Now test a spring balance. Hang the kilogram on a spring balance that is marked in newtons. How big is the pull of the Earth on the kilogram, according to the balance? Is the balance correctly marked?

A puzzle Hold one kilogram in your hand. Try to move your hand downwards with an *acceleration* about $\frac{1}{2}g$. What force would you expect to feel pressing down on your hand? Do you feel a force like that?



Progress Questions

$F = MA$

30. This table shows some results from a trolley experiment. The accelerations are given in cm/tentick in every tentick.

Number of elastics	Number of trolleys piled up	Acceleration of trolleys
1	1	3
2	1	6
3	1	?
2	2	?
3	?	3
?	4	3
?	3	6

a. Fill in the gaps in the table, and add two or three more rows of results which fit in the pattern.

b. Copy and complete:
When you double the mass, you need . . ? . . the force, for the same . . ? . . .
When you double the force, you need . . ? . . the mass, for the same . . ? . . .

31a. Use your completed table from Question 30 to make a new table starting like this.

Number of elastics	Number of trolleys (multiplied by acceleration)
1	3
2	6

Continue the table, using all the rows of the table above.

b. Look for a pattern in the numbers and describe the pattern in your own words.

c. Copy and complete:
In this experiment the . . ? . . tells us about the size of force, and the . . ? . . tells us about the mass of the moving object.

32a. The forces box, which you should have in the Lab. as an exhibit to try, has a concealed load inside, hung on the cord marked 'feel 1 newton'. How large should that load be?

b. If you took your forces box to the Moon and set up a school to teach physics there, what concealed load would you hang on the cord for 1 newton: the same, or more, or less? (Remember that the newton is a universal unit, the same size of force everywhere.)

33. You measure force in newtons
mass in kilograms
acceleration in (metre/second in every second)

the pattern for calculations can be written very simply:

FORCE	=	MASS	× ACCELERATION
in newtons		in kilograms	in metres/second every second

or $F = M \times a$

A force of 1 newton will give a mass of 1 kilogram an acceleration = 1 (metre/second in every second)

a. What force will give a mass of 2 kg an acceleration = 1 (metre/second in every second)?

b. What force will give a mass of 3 kg an acceleration = 1 (metre/second in every second)?

c. What force will give a mass of 3 kg an acceleration = 2 (metre/second in every second)?

d. What force will give a mass of 3 kg an acceleration = 5 (metre/second in every second)?

e. What force will give a mass of 12 kg an acceleration of 3 (metre/second in every second)?

f. A force of 2 newtons acts on 1 kg. What will the acceleration be (in metre/second in every second)?

g. A force of 12 newtons acts on 1 kg. What will the acceleration be?

h. A force of 12 newtons acts on 2 kg. What will the acceleration be?

i. A force of 20 newtons acts on 5 kg. What will the acceleration be?

34. When a car speeds up, there must be a force to make it accelerate.

a. A car accelerates, at a steady rate, from 0 metre per second to 20 metre per second (about 45 mph) in 5 seconds. What is the acceleration, in metre per second every second?

b. The mass of the car is 1000 kilograms. Now use $F = ma$ to find out what force is needed.

Note: The force would have to be about 25% larger than that to counter-balance friction.

35. When something is already moving, a backward force will slow it down, and give it a 'backwards acceleration' (sometimes called a 'negative acceleration' or de-celeration or retardation).

a. A lorry is travelling along at 20 metre/second. The brakes are put on, and after 1 second the speed is 18 m/s, and a second later it is 16 m/s. What is the 'backwards acceleration', in metres per second every second?

b. The lorry's mass is 2000 kg. Use $F = ma$ to find the backwards force which is slowing it down.

36. When you fire a cannon, gases from the explosion give the shell a big acceleration.

A shell of mass 2 kg is fired from a cannon. Its speed rises from 0 to 40 metre/second in $\frac{1}{4}$ second.

a. If its speed went on increasing steadily, what would it be after 1 second?

b. So what is the shell's acceleration, in metres/second in every second?

c. Now find the size of the force driving the shell.

Questions

GRAVITATIONAL FIELD STRENGTH

†**37.** A 100 kilogram man goes from England where he was in a gravitational field of strength 9.81 newtons per kilogram, to the equator. At the equator he is in a gravitational field of strength 9.78 newtons per kilogram.

a. State the change of his weight (the pull of the Earth on him in newtons).

b. *(Advanced questions for thinking)* Suppose he takes with him a bathroom weighing scale (which works by a spring inside). At home in England the scale reads 100 kg when he stands on it. At the equator, will it read more or less or the same?

c. What is it that is measured in kilograms? (For example, the 100 for a 100 kilogram man.) (*Note:* the answer is *not* his WEIGHT WHICH IS A FORCE measured in newtons.)

†**38A.** A space traveller, complete in his space suit stands on a spring weighing scale on Earth. His WEIGHT is 980 newtons.

In the same suit on the same spring balance on a smaller planet his WEIGHT is 245 newtons.

On a larger planet his weight is 1960 newtons.

The gravitational field strength at the surface of the Earth is 9.8 newton per kilogram. What is the gravitational field strength on:
(i) the smaller planet;
(ii) the larger planet?

38B. A spaceman, in his space suit, weighs 1000 newtons on Earth, where the gravitational field strength is 10 newton per kilogram.

a. How much stuff is he made up of? (That is, what is his MASS—including his suit?)

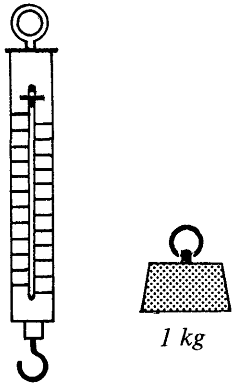
b. What would he weigh (in newtons) on a smaller planet where the field strength is 2 newton per kilogram?

39. The value arrived at in Experiment 21 for the Earth's gravitational field strength is the value at sea-level.

a. Will the value at the top of a high mountain be more, or less, or the same?

b. Give reasons for your answer.

40. The sketch shows a spring-balance marked in newtons. The manufacturer did not get this marked by using a trolley and ticker-tape.



a. How do you think he did get it marked in newtons?

b. Suppose you had a trolley with a mass of exactly 1 kilogram. How would you use it, together with the usual ticker-tape and vibrator, to test whether the 1 newton mark is correct? (Give just a brief outline of the method.)

c. How would a spaceman who had landed on the Moon or on Mars use the apparatus to find the value of g there?

d. How would he find g on a planet where g is more than 10 newtons per kilogram? (Assume he has a 100-g mass, as well as the 1 kg.)

$F = ma$

41. A 70-kilogram sprinter starts from rest and reaches a speed of 8 metre/second in 2 seconds.

a. What is his acceleration during those 2 seconds?

b. What is his WEIGHT (pull of the Earth on him) in newtons? (Take $g = 10$ newton per kilogram.)

c. What force is required to give him this acceleration?

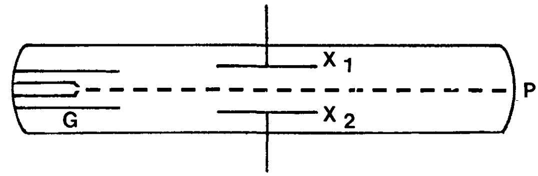
d. Express this force as a fraction of his weight. That is, say whether the accelerating force is $\frac{1}{10}$ or $\frac{1}{4}$, or what, as a fraction of his weight.
(Take $g = 10$ newton per kilogram.)

42. A racing swimmer uses his feet to get a quick start. He pushes with his feet against the end of the bath for $\frac{1}{10}$ second, with a horizontal force 3 times his weight.

a. What is his acceleration?

b. What speed does that start give him?

c. Why not encourage him to push for $\frac{3}{10}$ second? (This is a practical puzzle).



43. *(Important advanced question)* Electrons are shot from an electron gun G at high speed in a vacuum tube in a horizontal stream. They travel down the tube to the point P. On the way they pass between two horizontal plates X_1 and X_2 which are 0.020 metres long.

a. Suppose we connect X_1 to the positive terminal of a battery and X_2 to the negative terminal. What is the general effect on the electrons?

b. How does an electron move when it has passed *beyond* the plates? (Think carefully. It is best to give a sketch and some words.)

c. How much time does an electron spend travelling in the region between the plates, if its velocity is 3×10^7 m/s? (*Hint:* That is its *horizontal* velocity. The data give the *horizontal* length of the region between the plates as 0.020 metres.)

d. If the vertical force on an electron, while it is between the plates, is 10^{-15} newtons, and the mass of the electron is 9×10^{-31} kilogram, what is its vertical acceleration?

e. What is its vertical displacement *while between the plates*? (Remember the electron was originally moving in a *horizontal* direction. So its *vertical* motion *starts from rest.*)

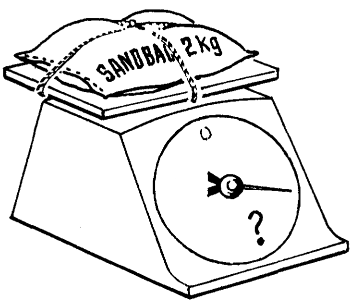
f. Suppose the distance from the centre of the plates to P is 0.2 metre. Roughly how far from P would the electrons strike the end of the tube while X_1 and X_2 are connected to the battery?

APPARENT WEIGHTLESSNESS

44. Think about the 'weightlessness' demonstration again (Experiment 14 at the end of Chapter 1).

A 2-kilogram sandbag is tied firmly on a spring balance. The Earth's pull on the sandbag makes the sandbag exert a force on the spring balance.

a. The Earth's gravitational field strength is 10 newton per kilogram. That means the Earth pulls 10 newtons on each kilogram.



(i) How big is the Earth's pull on the sandbag?
(ii) What will the spring balance read?

b. What force holds the sandbag still?

Now the two together, balance and sandbag, are allowed to fall (into a blanket!).

c. What does the balance read while both are falling?

d. Does the MASS of the sandbag change while it is moving?

e. Does the Earth's PULL on the sandbag change while it is falling?

f. The sandbag falls with an acceleration of about 10 metre/second per second. What is the acceleration of the balance, while it is falling?

g. During the fall the balance seems to read zero. Why?

MASS, WEIGHT AND GRAVITY

45. Suppose we want to make a rocket travel upwards at a steady speed. The rocket needs to be lifted with just enough force to balance the Earth's pull downward.

a. A rocket (including its fuel) has a mass of 1500 kg. What is the pull of the Earth on the rocket?

b. What force (in newtons) must the rocket jets provide, to make it rise at a steady speed? Remember, the Earth pulls 10 newtons on each kilogram of stuff.

c. As the rocket rises it burns up fuel, so its mass gets less. Suppose 400 kg of fuel have been burnt (and the products have been hurled out). What is the mass of rocket together with fuel left?

d. If the jets go on providing the *same* force as in (b), there will be a resultant upward force. What is the size of that resultant force?

e. Would the rocket go on travelling at a steady speed?

Special Questions

PROBLEMS WHICH NEED $F = ma$

46. A boy wants to pull a 5-kilogram cart loaded with 95 kilograms of bricks. He can pull with a force of 200 newtons.

a. Neglecting friction, estimate his acceleration.

b. How far can he pull the cart, starting from rest, in 2 seconds? Use a formula from Chapter 1A.

c. Trusting your 'formula' calculate how far he could pull the cart, from rest, in 10 seconds. And find how fast it would then be moving. Then say whether those answers are impossible.

d. To see whether the boy in this problem has reasonable strength, suppose he pulls with the same horizontal force, 200 newtons, as before, but on a rope that runs over to a pulley and down a well to a bucket of water. Calculate how heavy a load he can raise.

47. The boy in Question 46 pulls the same loaded cart but this time friction drags the cart back with a constant force of 50 newtons. Repeat the calculations for (a) and (b).

48. A 20 000-kilogram goods wagon is at rest on a railway which runs from east to west. The railway slopes downhill just enough to compensate for friction for a wagon moving westward. A child pushes the wagon steadily westward with a small force. The child can just lift 1 kilogram upwards. He pushes horizontally with a force of just that size. Having nothing else to do, the child continues to push for 5 minutes (300 seconds).

a. What speed will the wagon acquire in those 5 minutes?

b. How far will the child walk in the 5 minutes? (Pretend that the child gives a small extra push to deal with friction at the very beginning.)

49. If the brakes of a car are in fairly good order they can exert a retarding force of $\frac{1}{4}$ the *weight* of the car (that is one quarter of the pull of the Earth on the car). How long would such brakes take to stop a 1600-kilogram car moving 12 metre/second (about 27 miles per hour)? To find out, answer the following questions:

a. What is the pull of the Earth on 1600 kilograms, in proper units for use in $F = ma$?

b. What is a quarter of that pull of the Earth, in proper units?

c. What (negative) acceleration would that braking force give to the 1600-kilogram car?

d. With that (negative) acceleration, how long would the car take to slow down from 12 metre/second to rest?

50. A 1500-kilogram car moving 20 metre/second (about 45 miles/hour) crashes into a wall and comes to rest. The whole collision takes 0.10 second.

a. Calculate the collision force as follows; by writing the answers that would fill the blanks.
The final speed after the crash is . . ? . . .
The initial speed, just before the crash is . . ? . . .
Therefore the change of speed is . . ? . . .
The time taken for that change is 0.10 second.
Therefore the acceleration during the crash is −. . ? . . .
Using $F = ma$, the force making that acceleration is . . ? . . newtons.

b. To get a feeling for the size of that force find out how big a lump of metal would be pulled by the Earth with that force (answer: about 30 tonnes).

51. A 60-kilogram boy jumps off a window ledge $1\frac{1}{4}$ metres above the floor. He lands on a hard floor. Estimate the force exerted on him by the floor while he is stopping, by answering the questions below.

Suppose that he foolishly forgets to bend his knees while landing so that the total 'give' of his feet, etc., is only 0.025 metre (1 inch), in compression of floor, shoes, feet, ankles, spine, etc., during the stopping process.

a. Calculate his time of fall (answer: $\frac{1}{2}$ second).

b. Calculate the speed of the boy at the end of his $\frac{1}{2}$ s fall, just before landing (answer: about 5 m/s).

c. To calculate the time taken by the landing process find the boy's *average* speed during the stopping process. (Write down his speed just before he lands and his speed when he has finished landing. Take the average.) Use that average speed to find the time he takes for the process of landing; that is, the time he takes to travel 0.025 metre.

d. You know his speed before landing (5 m/s) and his speed (0) after landing, so you know his CHANGE OF SPEED; and you now know the TIME he took to make that change of speed. Calculate his (negative) acceleration during landing.

e. Using $F = ma$ calculate the force the floor exerted on him during landing. (Answer about 30 000 newtons, or the weight of about 3 tonnes of any material.)

51A. A carpenter swings a hammer, with a light handle and a 1.2-kilogram head, to hit a nail. The head, moving with speed 5 metre per second, strikes a horizontal nail in a piece of wood, without any rebound. The nail is driven 3 millimetres (=0.003 metre) into the wood.

a. Find the average deceleration of the hammer. (*Note:* This problem can be solved with the same steps as the problem above about the boy who jumped off a window ledge. There the motion was vertical, here it is horizontal.)

b. Find the average force acting on the nail, during the impact.

c. What difference, if any, do you think it would make if the hammer did rebound? Give a clear reason for your answer.

52. A player kicked a $\frac{1}{2}$-kg football. The ball started from rest and left his boot with horizontal velocity 20 m/s. The kick lasted $\frac{1}{100}$ s. (That is: his boot was in contact with the ball for $\frac{1}{100}$ s.) What was the (average) force between boot and ball?

a. The ball speeded up, from 0 to 20 m/s in $\frac{1}{100}$ s. Its acceleration was . . ? . . m/s^2.

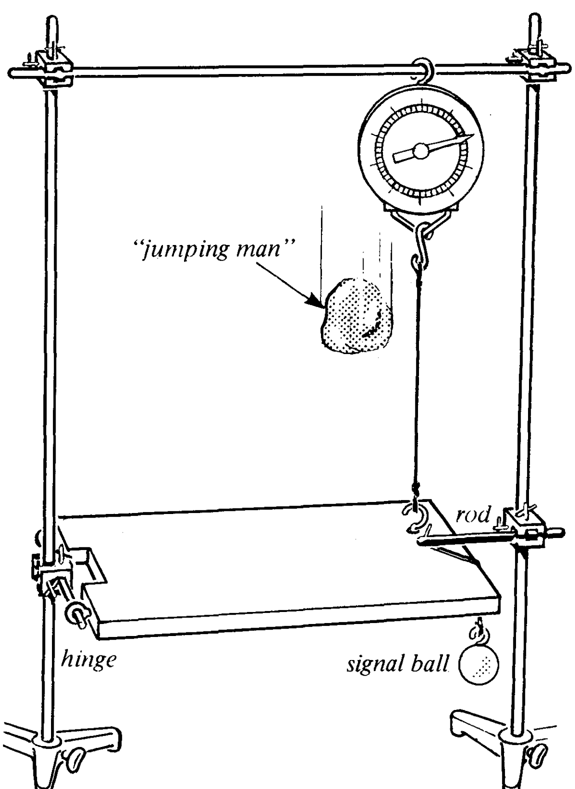
b. The force was . . ? . . newtons.

DEMONSTRATIONS

Landing from a jump See the following demonstration which illustrates the painful fate of the foolish person who fails to bend his knees.

Demonstration 22
The jumping man: force of impact on floor

The man is represented by a ball of Plasticine. Drop him from a small height on to a platform. The platform is hinged on a pivot at one end and pulled up at the other end by a string and spring balance above. When the man lands on the platform he exerts a strong downward force for a short time. But the spring balance exerts a strong upward force. Unless the man's downward force is greater than the pull of the spring balance, the platform cannot budge enough to release the thread and signal ball.

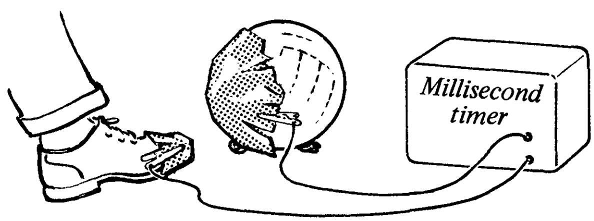


Although the model man is only, say, $\frac{1}{2}$ kg of clay, so that his weight is only 5 newtons, you will see that in landing he exerts dozens of newtons on the platform. Therefore the platform exerts dozens of newtons on him—an enormous force for the small model man.

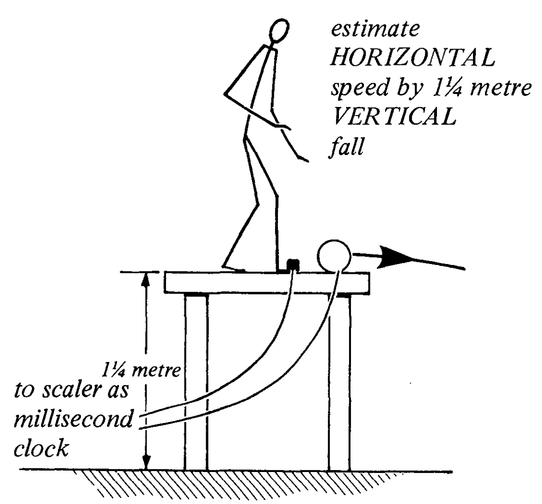
Kicking a football You should not think that the data for a problem are just made up to give you home-work. See the following experiment in which measurements are made.

Demonstration 23
Kicking a football *(OPTIONAL)*

Cover the player's boot with kitchen foil; cover the football with kitchen foil. Then the time-of-contact between boot and ball can be measured with a scaler which counts thousandths of a second.



The ball starts at rest; and to calculate its acceleration you need to know its final speed at the end of a kick. Kick the ball from a table $1\frac{1}{4}$ metres above the floor. If the ball flies out horizontally it will take $\frac{1}{2}$ s in its accelerated vertical fall to reach the floor. Measure the distance the ball travels horizontally, estimate it took $\frac{1}{2}$ s to do this, and calculate its speed.* Find the mass of the ball in kilograms by weighing it. Use $F = ma$ to calculate the force.



* Or you might measure the speed by taking a multiflash photo of the flying ball.

In Chapter 4 you will find still another way of measuring the ball's speed, by kicking it into a box on roller skates. Then you apply conservation of momentum.

PARADOXES

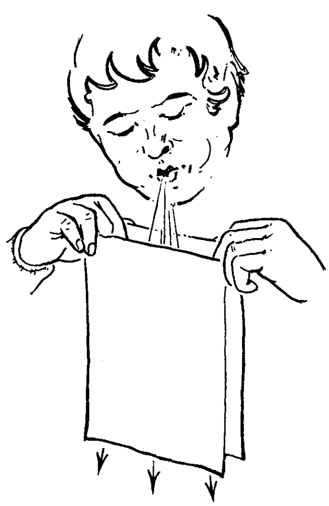
A paradox is a surprising absurd thing, that seems the wrong way up. When you drink some water, it *falls* down your throat as you swallow. If you stand on your head you can still drink water. There is a paradox.

Here is a 'Bernoulli paradox'—named after a Swiss mathematician. Try it; see or try some more then find a simple explanation.

Experiment 24
Bernoulli paradox

Hold two sheets of paper 2 or 3 centimetres apart. Hold the top edges with two hands and let the sheets hang down. Keep them apart with two fingers between them. Bend your head down and hold the sheets just under your mouth.

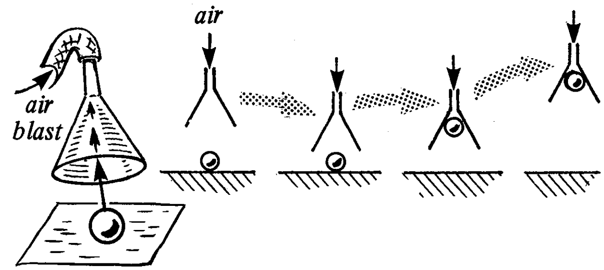
Blow down hard into the space between them.

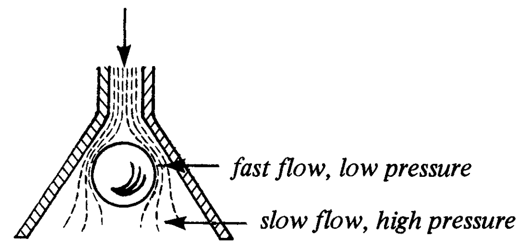


Some squeaker toys make their noise with blades like those two sheets of paper. The reed of a clarinet is kept vibrating by the player's breath in a similar way. And your own vocal cords act in the same way when you talk or sing.

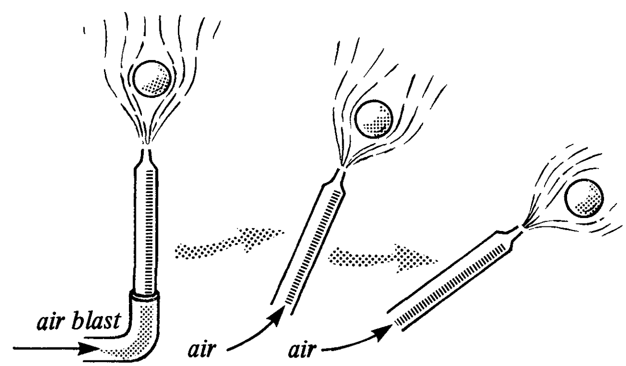
Demonstrations 25
Surprising Bernoulli effects

a. *Ball picked up by a funnel* Air blasts down through the funnel. Yet it picks up a light ball. How?





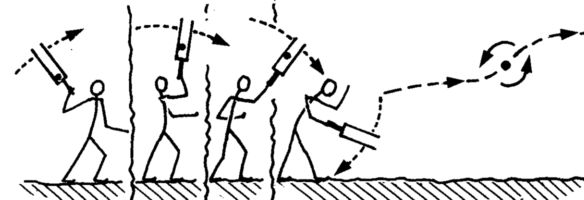
b. *Ball supported by an air jet* Even if the jet is tilted it still holds the table-tennis ball. Why? How?



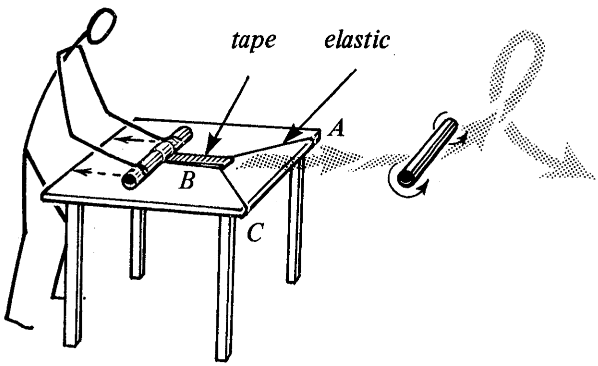
Air jet supports ball, even when tilted

c. *Ball on a water jet*

d. *Ball swerves* Give a light ball a spin as it is thrown—it swerves like a 'cut' tennis ball.



e. *A spinning tube swerves* Wrap a length of tape round a light cardboard tube. Project the tube forwards by a catapult of stretched elastic. The tape makes the tube spin as it is being hurled.

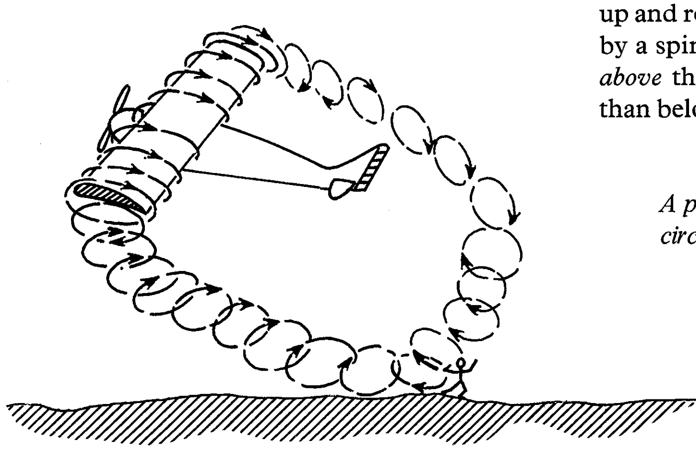


The tube may even loop the loop.

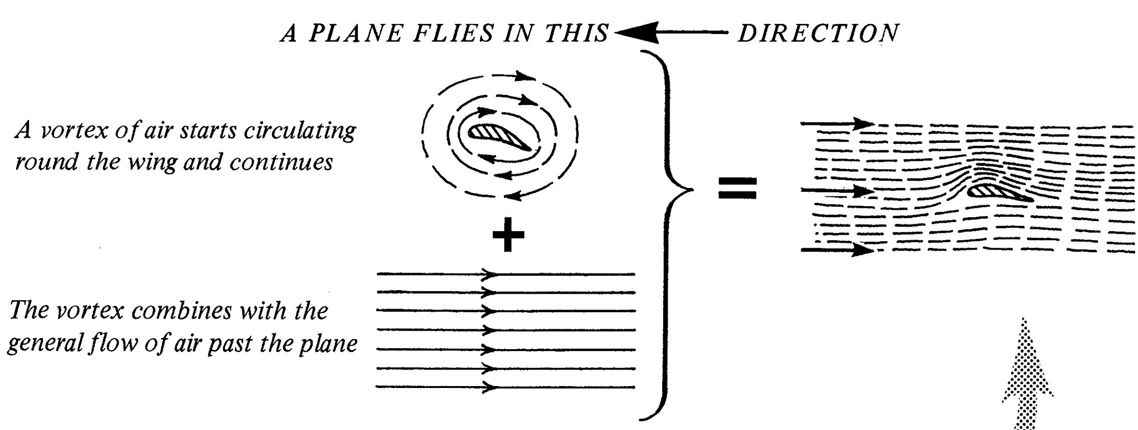
Experiment 26
How do aeroplanes stay up? Another Bernoulli effect

Hold one end of a long narrow sheet of paper with both hands. Bring that end against your chin, just under your lips. (The paper should be fairly thin so that the other end sags under its own weight.) Blow a steady blast of air *over the top of the paper*.

This shows the way an aeroplane wing is given 'lift', so that the plane can fly. An air current moves up and round the wing, like the whirl of air carried by a spinning ball. The resultant air flow is faster *above* the wing, so the pressure is smaller above than below—and that provides lift.



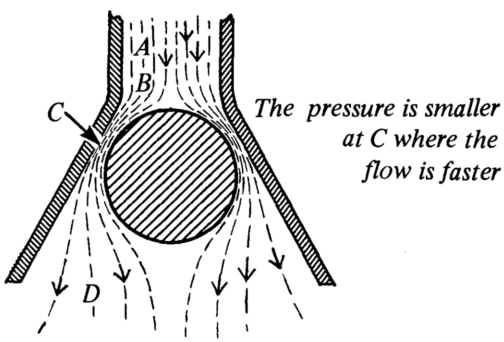
A plane taking off starts a vortex of circulating air (as in a smoke-ring)



The combined pattern is like this with faster flow above the wing. Hence less pressure above; and therefore LIFT

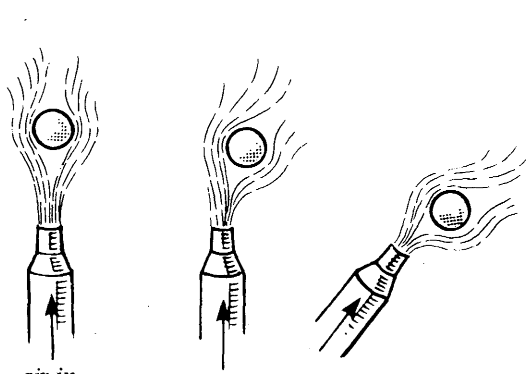
Explanation by simple assertion Those and other surprising effects, can all be 'explained' by appealing to the qualitative form of Bernoulli's principle: that *in flow of fluid the pressure is smaller where the flow is faster.*

When an air blast holds a ball up in a funnel the flow is fastest in the narrow space where the ball is close to the funnel. So the pressure there is less, pressures below are greater and support the ball.

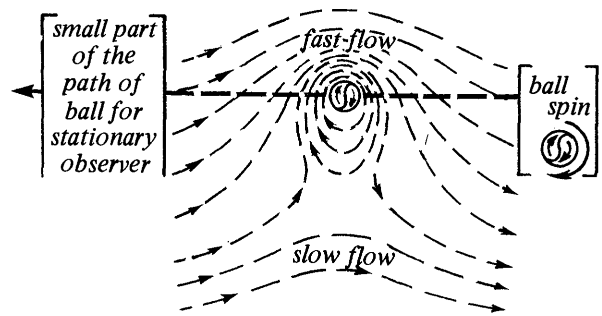


Streamlines of air around ball in funnel

If the ball on an air jet starts to fall out to one side, the flow is faster in the centre of the jet, so the pressure is less and the ball is pushed back to the centre.



A spinning ball (or tube) carries air round with it; and as it flies along a projectile's path it has a combined air flow that is faster above it than below. So the pressure . . . .



streamlines of air past a spinning ball

When you blow air fast between two sheets of paper . . . .
When you blow air fast above a sheet of paper . . . .

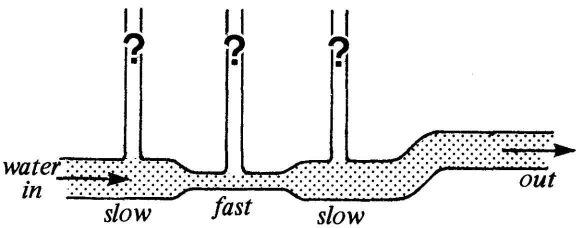
The general principle *Faster flow smaller pressure* sounds surprising and almost wrong. Yet it *is* an 'explanation' because it links together several phenomena which look unlike. But it is not a very good scientific explanation in this form because it drags in a new, strange principle. If we could link this principle in turn to something familiar, we should feel we are much more powerful scientists. We should be farther from superstition and nearer to the assurance of Lucretius that 'science frees men from the terror of the gods'. We can do that and lead you to a good reason for it.

Explanation by linkage to earlier knowledge First see one more experiment to illustrate the principle.

Demonstration 27
To explain Bernoulli's principle by water flow through a tube

Drive a rapid flow of water through a wide glass tube which has a narrower section half way along the tube to show the water pressure at several places.

The same volume of water has to get through each part of the pipe, every second. So where the pipe is narrower the water must flow faster.



You will see lower pressure in the middle section where the flow is faster—an example of Bernoulli's principle. But still there is the question why.

To see why, imagine there is a little submarine that is carried along with the water itself. The submarine might be a small oblong block of wood of the same density as water.

Suppose the submarine has flat ends. In the wide tube A, the submarine is carried along fairly slowly with the water. It does not change its motion. In the narrow part C, the submarine is carried along much faster, and it does not change its fast motion.

But in the knee, B, where the tube is narrowing, the water has to change from slow flow to faster flow and *the little submarine must change speed too.* In the knee *it must accelerate.*

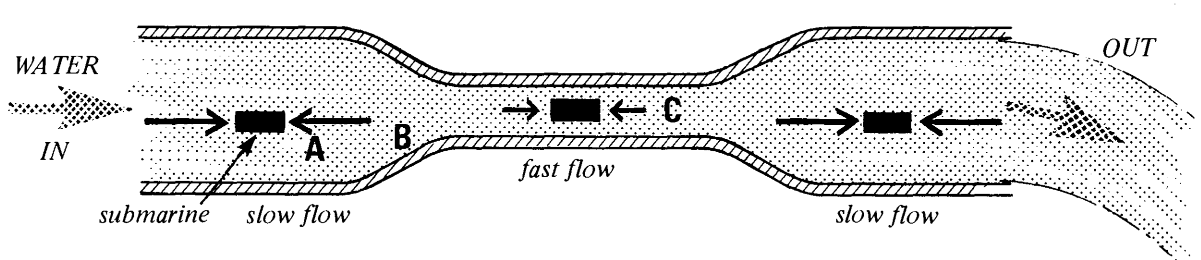
Where the submarine is accelerating, there must be a resultant forward force pushing it to accelerate it.

The submarine has water all around it and the only agent to push it is water exerting a pressure on it. The water pushing on the sides of the submarine cannot help it forwards or backwards. The water pushing on the back end of the submarine pushes it forwards, and the water pressing on the front end of the submarine pushes it backwards. When the submarine is in the knee those two pushes must be unequal. The submarine *must* feel a bigger pressure of water on its back end than on its front end.

Therefore the pressure must be bigger in the wide part than in the narrow part of the tube.

Now forget about the submarine and think of the water itself. In going from wide to narrow it changes from slow flow to fast, it *accelerates*. There must be a force to make it accelerate and that force is provided by water pressure. The water pressure must be bigger in the wide part than in the narrow part. Therefore: faster flow, lower pressure.

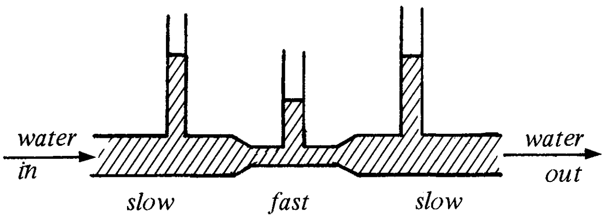
Thus the Bernoulli effects are only a matter of force being needed to accelerate the fluid from the slow-moving regions to the fast-moving regions: just a matter of $F = ma$. There is a full explanation.



Questions

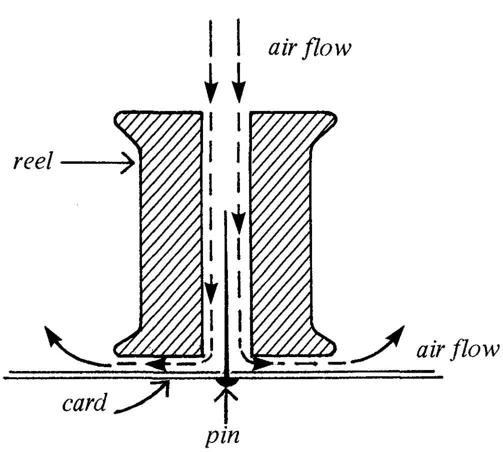
BERNOULLI EXPERIMENTS

53. The sketch illustrates an experiment. If you watched it, describe the experiment and say what happened.



54. Newton's Second Law, $F = ma$, reminds us that anything having mass (including liquids and gases as well as solids) needs FORCE to *accelerate* it. PRESSURE is FORCE PER UNIT AREA. Now use the sketch of Question 53 to explain why 'pressure is smaller where flow is faster'. It will help if you imagine a little submarine moving along with the water (an oblong piece of wood of the same density as water).

55. *Apparatus:* cotton reel (with or without cotton) having a clear central hole; postcard; pin. Draw the diagonals of the postcard and so find its centre. Stick the pin through the centre.

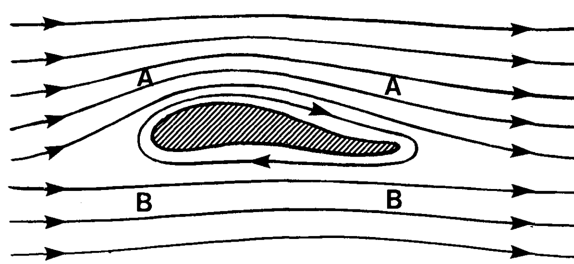


Hold the reel in one hand and the card in the other, so that they are in the position of the figure, but touching each other. Blow hard down the hole, and at the instant you start to blow, let go of the postcard. What happens? How do you explain it?

56a. Look at a Bunsen burner and take it to pieces. Then draw a sectional diagram of it (a vertical slice). Show the gas-jet and the air-hole.

b. You might think that the gas-jet would push air and gas *out* of the air-hole, but in fact air comes *in* at the hole, mixes with the gas and is burnt at the top of the burner. Explain why air comes in at the hole.

57. The sketch shows the section of the wing of an aircraft. The arrows indicate air moving past a stationary aerofoil as in wind-tunnel experiments; but it makes no difference if the aerofoil moves and the air is at rest, as for an aircraft in flight.



Notice first, that the aerofoil deflects the air stream downwards, that is, it exerts a downward force on the air. So, what is *one* reason why there is an upwards force on the aerofoil?

Secondly, the air *above* the aerofoil has to move a greater distance round the top of the aerofoil than the air *under* the aerofoil has to move round the bottom of the aerofoil. Therefore the stream *above*, at AA′, moves faster than the stream below, at BB′. So what is the *second* reason why there is an upwards force on the aerofoil?

(Now you have explained how an aircraft stays up.)

58. Two ships attempt to steam on parallel courses, very close together. If they do this they may *collide*. Why? Illustrate your answer with a sketch.

59. Examine a scent-spray, fly-spray, hair-spray, paint-spray or any simple type that sprays when air is blow over the top of a tube dipping into liquid. Draw a simple diagram and explain why the spray works.

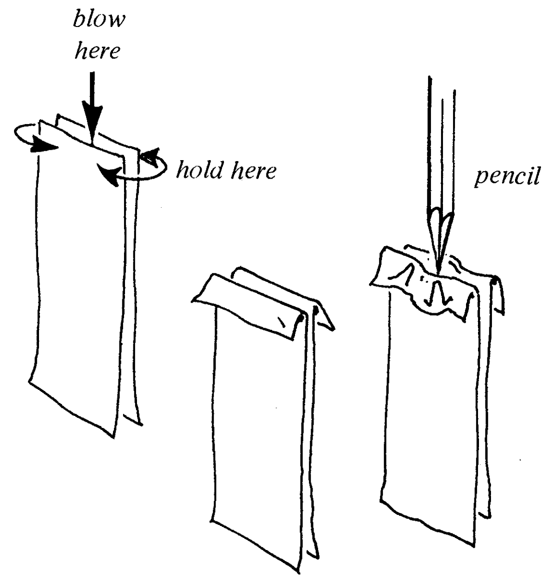
60. *Squeaker* Put two scraps of paper together to make a squeaker; blow into it and make it squeak. Then explain why it squeaks. Here are instructions:

a. Take two strips of paper about 5 cm wide, 15 cm long. Hold them together, in contact, and put one end of the pair in your mouth and blow.

The squeaker will succeed more easily if you make a simple mouthpiece. Fold about 1 cm of each strip over at the mouth end, to make a thicker edge for your lips. Push a pencil between the strips at the middle of that end, to open up a pipe for your breath. Blow through that pipe.

b. Write a few lines explaining how or why the squeaker works. Use some physics that you now know.

c. If you like, be a design-engineer: invent better paper squeakers and test them. Think about improving the mouthpiece, without making it difficult or expensive to make. Think about changing the size of paper strips. Try out your suggestions.



improved mouthpiece

Note: This is the way the vocal cords in your throat make the basic sounds of your voice. While you are speaking or singing you drive air from your lungs through a narrow gap between two springy strips of muscle.

CHAPTER 3

NEWTON'S FIRST LAW

Mass and inertia; notes on mass

NEWTON'S FIRST LAW OF MOTION

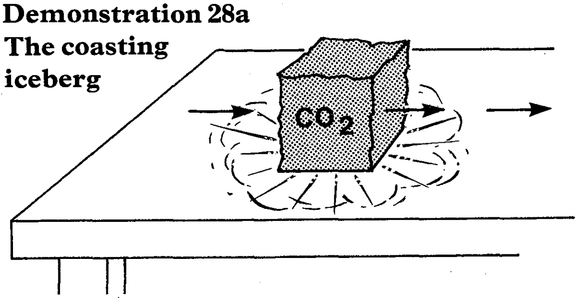
You have been doing experiments to illustrate Newton's *Second* Law. Now look at his *First* Law which tells us that *THINGS GO ON MOVING IF YOU LEAVE THEM ALONE*—though he wrote it more carefully, in Latin.

That was a startling surprise to the astronomers in those days, who thought a constant push was needed to keep the Moon moving, as well as a constant push for Venus, Mars and each of the other planets.

Everyone knew that one has to go on pushing a chair to keep it moving across the floor; and one has to go on pulling a cart to keep it moving. . . . But they forgot the opposite force that is there all the time there is motion, friction dragging the chair or cart backwards. Newton suggested that the forward force and the backward drag may sometimes just cancel to make a resultant zero—and yet the motion continues.

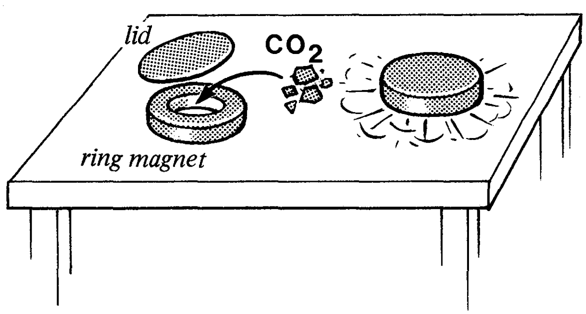
Nowadays you can see hovercraft experiments in which an object moves practically without opposing friction. A stream of gas evaporates from some solid carbon dioxide ('dry ice') and supports the moving object like a hovercraft. There is no friction dragging back, and the object slides on and on. See one of the demonstrations sketched.

Demonstration 28a
The coasting iceberg



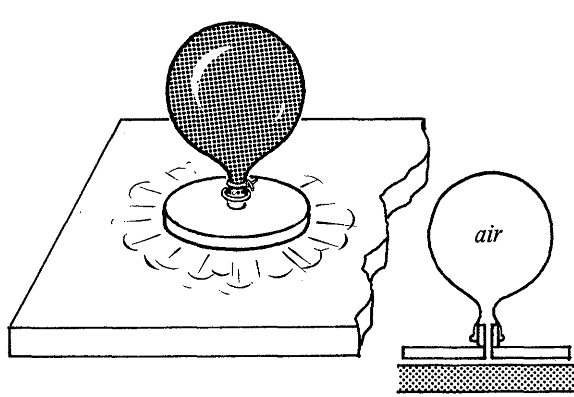
Demonstration 28b
Ring hovercraft

Ice hockey is played with a puck which slides on a frozen pond with very little friction. So we give the name 'puck' to some special objects which slide, almost without friction on a smooth table. Our ring pucks can even be magnets that repel in collisions.



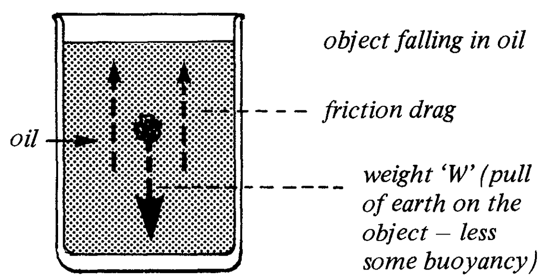
Experiment 29
Home-made hovercraft: the poor man's puck

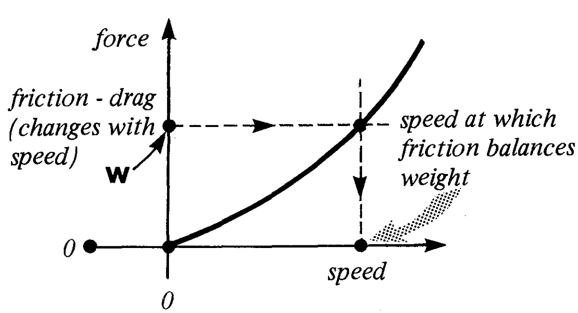
Blow up a balloon and attach it to a short pipe through a flat piece of wood. Place the wood and balloon on a smooth table and watch its motion.



Friction and gravity balancing out Instead of constant velocity with no friction—so that there is no horizontal force—we can have constant velocity with two large forces that just balance: the Earth pulling downward and friction dragging upward. We must use *fluid* friction for that. Friction of gases and liquids has a special behaviour: *it increases with speed.* Friction of solids hardly changes with speed.

If you let something fall in air or water it moves faster and faster and friction drags harder and harder until the friction force just balances the gravity force*—and then you see constant speed.



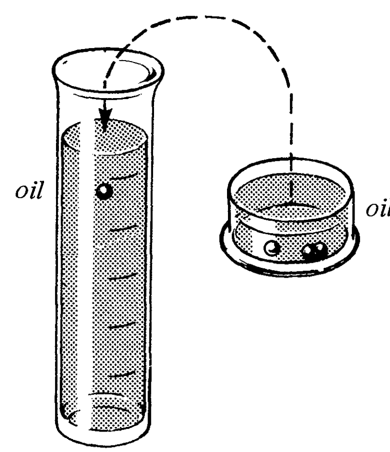


But, when something is pushed along at steady speed, *do* those friction forces balance the push exactly? You may see a demonstration.

* There are also buoyancy-forces due to fluid pressure, forces which support ships and balloons but are smaller for a sinking object. In this discussion we can lump those in with the weight of the object, like a discount reduction of gravity, since they are proportional to the gravitational field strength and would disappear if there were no gravity.

Demonstration 30
The invisible parachute

Drop a small ball of steel or glass into a tall jar of viscous* motor oil or glycerine, and watch it fall. The ball must accelerate at first but does it continue to accelerate or does it soon reach a constant speed? What forces act on it?



FRICTION OF SOLIDS

Friction of solid surfaces rubbing on each other—atoms pulling atoms—is important and often useful: friction between shoes and floor for walking without slipping; between ships' mooring ropes and bollards, ...

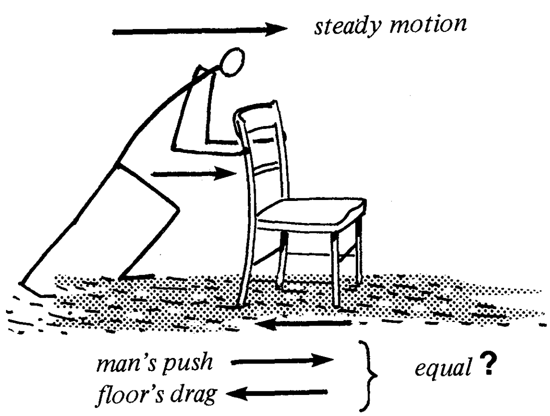
Friction is often a nuisance: it lets mechanical energy turn into waste heat when tyres skid or axles run dry.

And, in brakes on bikes and cars, friction is both useful and wasteful.

Suppose you push a chair across the floor, keeping it going with constant velocity. You know you are pushing it with a force which is needed to keep it moving. But a physicist tells you there is no resultant force on the chair because friction is dragging it with an equal force backward. How do you know friction is acting on the chair? You know

* Viscous means 'stodgy' or 'sticky'. The viscosity of a liquid (or a gas) is judged by its slowness of flow when pressure is applied; it is measured commercially by dropping a steel ball through the liquid.

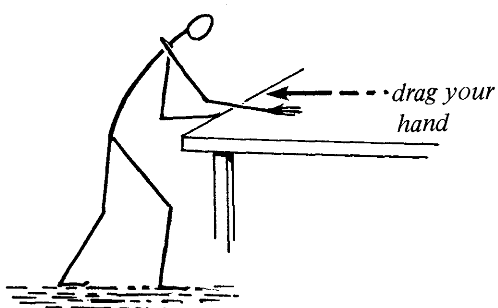
Could you arrange the following in order of increasing viscosity: water, treacle or golden syrup, light motor oil, alcohol, pitch? (Pitch seems to be a hard black solid, but if you give it lots of time a lump of it will sag over the edge of a shelf, or even pour through a funnel.)



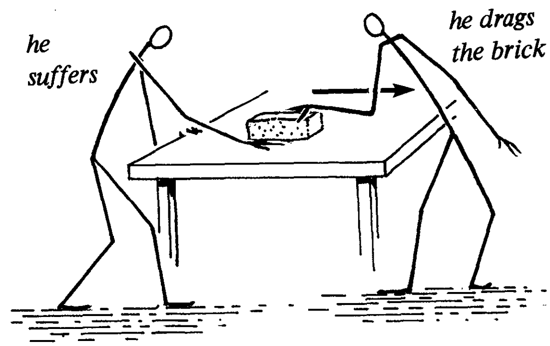
that you have to push the chair. You know that the floor is rough, so you may think you are pushing against something we call friction. But how do you really know the force of friction is there? Try a simple experiment to feel dragging forces of friction yourself.

Experiment 31
Feeling friction yourself

a. To feel friction for yourself, put your hand loosely on the table, palm down, and drag it along.



Then ask a neighbour to hold your wrist and drag your hand along the table. That may make it easier for you to pay attention to the forces at the surface.



b. Now use your skin as the table top. Place your hand, *palm up*, on the table and hold it still there. Let a neighbour place a heavy load (a brick or a pile of books) on your upturned hand. What do you feel when your neighbour drags that load along your hand?

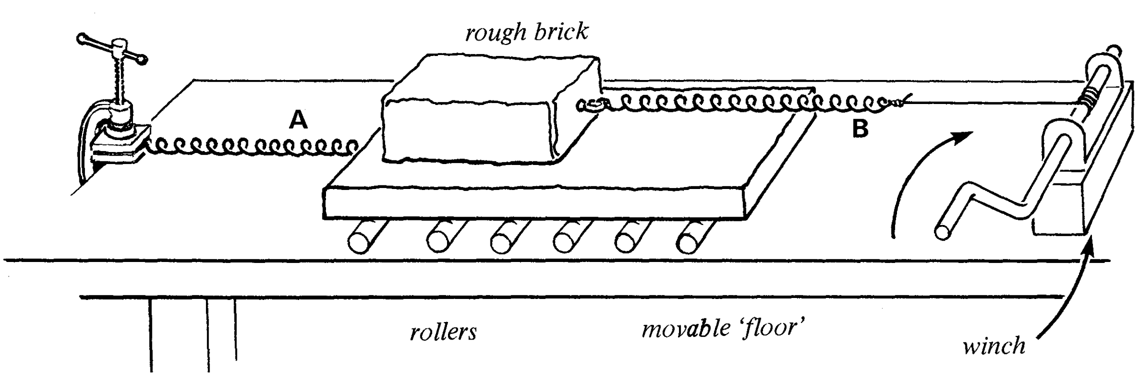
Demonstration 32a
Balancing forces?

See the sketch. The rough brick carries a light spiral spring, B, which serves as a spring balance. The brick is winched along a plank which serves as a floor. The plank rests on rollers so it could slide freely. An equal spring, A, holds the plank tethered to the end of the table.

Spring B shows the force pulling the brick along at steady speed.

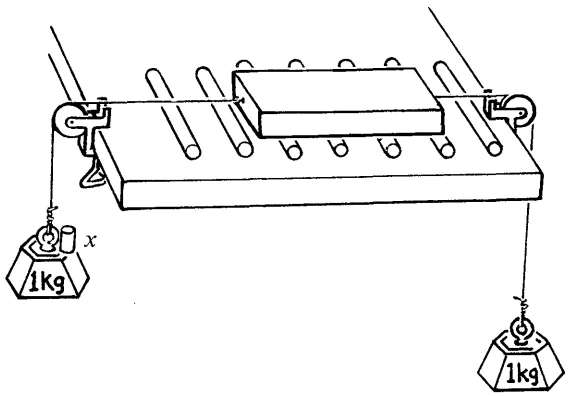
Spring A shows (indirectly) the friction force between the brick and the floor plank.

Look at the stretched lengths of A and B. How do they compare? You need to be charitable: this is a difficult rough demonstration.



Demonstration 32b
Steady motion: balancing forces?

You may see another demonstration, this time without friction. (See the sketch.) Two cords pull a movable 'trolley' in opposite directions. The 'trolley' is just a large smooth plank. It rests on rollers so that it can move freely to left or right. The two loads are equal and a small extra load x is added 'to pay for friction'.



Watch the motion and compare the readings of the spring balances which measure the forces pulling the trolley opposite ways.

Law I emerges You can see now why Newton could say in his Law I that an object with no resultant force on it would just go on moving straight ahead.

Newton received that idea from Galileo, the great Italian thinker and teacher of science. Galileo had guessed at it much earlier—he died in the year that Newton was born.

Progress Questions

FRICTION AND STEADY MOTION

1. Have you seen any examples of movement where there is no slowing down or speeding up? Describe at least one way of getting this kind of motion on a flat surface.

2a. You put a solid block of carbon dioxide on a level glass sheet. You give it a push to set it sliding across. Describe how it travels.

b. Explain why there is almost no friction between the block and the glass.

3. A spaceship is travelling in outer space far from the pull of any planet. The jets are suddenly switched off. Does the spaceship slow down? Explain why your answer is reasonable.

4a. You drop a coin onto the floor. Does it drop at a steady speed?

b. What downward force is acting on the coin?

c. What upward force is acting on the coin?

d. Which force is much the bigger of the two?

5. When there is no friction, and no other sort of force a moving object goes on moving steadily. It keeps a steady velocity. 'No force, steady velocity.' (Here, 'velocity' means 'speed straight ahead'.)

Think about pushing a chair over the floor, so it moves with a steady velocity. Is this another example of 'no force, steady velocity'? Explain as fully as you can what you think is happening.

NEWTON'S FIRST LAW OF MOTION

6a. *(i)* A bus is moving along a road at a steady 50 kilometres per hour. What can you say about the forward force due to the engine and the backward force of friction?
(ii) What happens when the force due to the engine is made greater than the force of friction?
(iii) What happens when the force of friction is made greater by putting on the brakes?

b. *(i)* A polystyrene bead drops at a steady speed through a tall jar of water. What can you say about the downward pull of the Earth on the ball and the upward force of friction?
(ii) What happens if the pull of the Earth is greater than the friction?

c. During a tug of war, both teams are pulling hard, the rope is taut and does not move. What can you say about the pull exerted by one team compared with the pull of the other?

7. Scientists say that if anything is travelling at a steady velocity it will just go on and on with the same speed unless something pulls or pushes it, in other words, unless there is some resultant force acting on it.

Suppose that statement is true and consider the following cases:

a. A car is travelling at 60 mph along a motorway. The driver shuts off his engine. Will the car go on running at 60 mph even on a flat road? If not, what force is changing its velocity?

b. A satellite has been boosted away from the Earth by rockets, and is going upwards at high speed. The rockets stop firing when it is say 50 miles up. Will it then continue at steady speed or slow down? If it slows down, what force is slowing it?

c. A cyclist starts pedalling down a hill, then stops pedalling. Will he continue at steady speed down the hill? If not, what force is changing his speed?

8. Scientists also say that if an object is not moving, it will stay not moving unless a force acts on it. Think about the following cases:

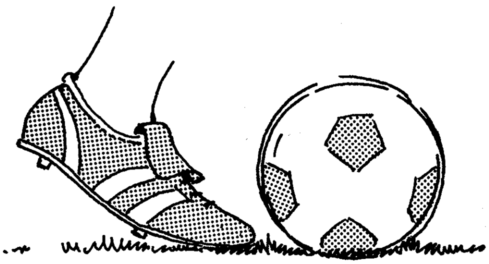
a. You lift a brick up into the air, hold it steady there, then take your hand away. Will the brick stay still? If not, what force is acting on it?

b. A dry leaf is lying on the ground. Suddenly it moves away. Is this a thing you expect a leaf to do by itself, or do you think there must have been some force acting on it. If so, what force could have set it moving?

9. Going back to Question 7, scientists make their statement even more precise. If something is moving, and there is no resultant force acting on it, it will go on moving steadily *in the same direction* (i.e. in a straight line).

Suppose this is true, consider the following cases:

a. A football is kicked into the air like this. Will it just go on and on in the same direction? . . . or what will it do?



If it changes direction, what force is making it change direction?

b. A train travelling on a straight track comes to a place where the rails curve round, and the train goes round the curve. What force do you think is changing its direction?

c. Add one example yourself of a moving thing changing direction (perhaps going round in a circle) and explain what force is making it turn.

Questions

MOTION WITHOUT FRICTION

† **10.** You may have seen an experiment in which a special puck is placed on a level sheet of glass and is given a gentle push. *If* you have seen this:

a. Describe what happens; and explain what happens.

b. Say what you think 'friction' is. (Do not look in books—make up an answer of your own.)

c. Explain how the puck is prevented from feeling any friction.

† **11a.** A space ship is moving far out in space, far away from any large bodies like the Earth or the Sun or the planets. Its jets are shut off. Describe its motion afterwards.

b. What similarity is there between the motion of the space ship, and the motion of the puck in Question 10. Also, what differences are there?

† From *Pupils' Text 3*.

† **12a.** Suppose you have, on a glass surface, a special puck which slides perfectly, so that there is no friction at all. There are still *two* forces acting on the puck. What are they? Which is the larger? Or, are they equal?

b. Suppose a locomotive pulls a train along a flat horizontal track with a forward pull (force) which exactly equals in size the backward drag of friction, air resistance, etc., on the train. What can you say about the motion of the train?

CONSTANT VELOCITY

13. Suppose that each of the following *OBJECTS* is seen to be moving with constant speed and is not changing the direction of its motion, (that is, its velocity is constant):

(i) a *CHAIR* being pushed across a level floor,
(ii) a *BARGE* being pulled along by a tug-boat,
(iii) a *CYCLE* going downhill *WITH THE RIDER* freewheeling,

(iv) a carbon dioxide *PUCK* moving over a glass surface,
(v) a *SPOON* dropping slowly through thick syrup,
(vi) a *MAN* descending with an open parachute,
(vii) a *LOCOMOTIVE* pulling a train up a gradient,
(viii) a *SPACESHIP* far away from all other bodies,
(ix) a *GIRDER* being hauled up at a steady speed by a crane.

a. Write down, for each of *(i)* to *(ix)* above, the forces acting on the object named in *CAPITALS*. Or, if no forces at all are acting on it say 'None'.
Example : (i) Forces on CHAIR :
pull of Earth, down ; push of floor, up ;
push of person, forwards ; drag of friction, backwards.

These balance out to zero (when velocity is constant).

b. Look at your answers in *(a)* for *(ii)–(ix)*. What can you say about the forces in each of those cases, *IF* the velocity is constant?

c. An object *at rest* is a special case of an object having *constant velocity*, (that is, its constant velocity is zero). What can you say about the forces acting on an object which is not moving *and remains not moving*?

(c) moving in a curve,
(d) both *(a)* and *(c)* together,
(e) both *(b)* and *(c)* together.

Give one example of each of the possibilities *(a)* to *(e)* above. In each case, say in which direction the resultant force must be acting. Give a sketch for each. (Cases *(a)* and *(b)* are easy; *(c)*, *(d)* and *(e)* are more advanced.)

15. See the diagram below. A rough brick rests on a plank, and the plank rests on rollers on a level table. The brick is pulled to the right steadily, and one spring, A, measures this pulling force. The plank is held back by a spring, B.

There is friction force between the block and plank.

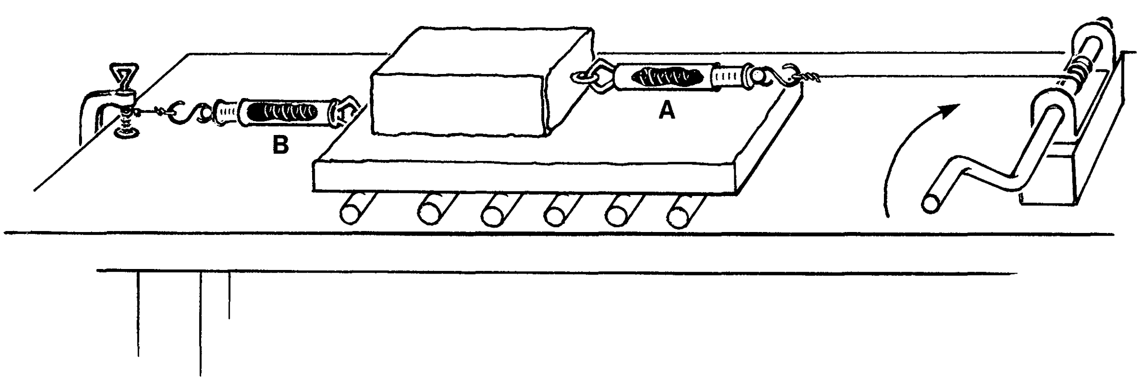
a. Which way is this friction acting on the *block*, to the left or to the right?

b. Which spring balance tells us how much force is needed against the friction force on the *block*?

c. Which way is the friction force acting on the plank?

d. Which spring balance tells us how much force is needed against the friction force on the *plank*?

e. If the two spring balance readings are about equal, what does this tell us about the friction forces on block and plank?



14. If an object moves with constant velocity (or remains at rest), then there are no forces acting on it, or the forces on it cancel out: they add up to 0. That is, there is no *RESULTANT* force.

But if the object is *not* moving with constant velocity, then a resultant force must be acting on it. The object might be:
(a) accelerating,
(b) decelerating (slowing down),

16a. A man jumps out of an aeroplane without opening his parachute. He travels faster and faster. What can you say about the size of the force of friction acting upwards?

b. Later in his fall the force of friction upwards becomes equal to the force of gravity downwards. What happens to his speed then?

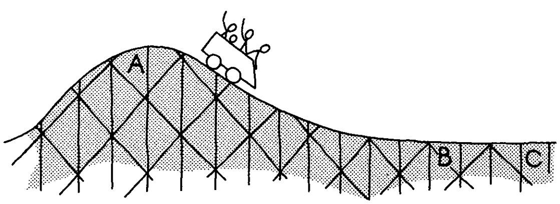
17. A car on a 'Big Dipper' track in a fairground is freewheeling, that is, travelling without using any fuel. The part of the track marked BC is horizontal.

a. How does its speed change as it travels from A to B?

b. How does its speed change after B?

c. The man in charge oils all the wheels, so the car runs much better. What difference does this make
(i) from A to B?
(ii) after B?

d. If there were absolutely no friction slowing the car down, what happens to its speed?
(i) from A to B?
(ii) after B?



ZERO RESULTANT FORCE

† **18.** You can now draw a general conclusion from the experiments you have seen and heard about.

a. If all the forces acting on a moving body exactly balance each other (*OR* if there are no forces at all acting on the body) what do you expect to find about the motion of the body?

b. What difference does it make if the body we were talking about in (a), is at rest?

† **19a.** Give one different example (not in these questions) of a moving body for which all the forces acting on it are exactly balanced. Say what happens to it.

b. Give one example of an object which is at rest, and stays at rest, but has forces acting on it. The forces are exactly balanced. Say what happens as time goes on.

† **20.** Lastly—and this is important—if you happened to see a body *either* at rest *or* moving at a steady speed in a straight line (e.g. a car moving at a steady 50 kph), what can you say about the forces acting on it?

LAW I

21. Newton's First Law states: 'Every object continues to move with constant speed in a straight line, or to remain at rest, unless some resultant force acts on it.'

Suppose you write that Law in those words in your notebook and a neighbour sees what you have written and says, 'This is plain nonsense. Here am I with a wheelbarrow full of garden rubbish. It won't move with constant speed. It soon stops if I stop pushing it.' Then he states two Laws A and B which he says are better and more sensible than Newton's.

A. Everything slows down and stops unless someone pushes it (he means, on level ground).
B. Everything that goes up comes down again—or tries to.

Do you agree that the neighbour's laws are good science? Or do you disagree? Suppose you are getting ready to discuss his laws with him. *Write a few notes for your discussion.*

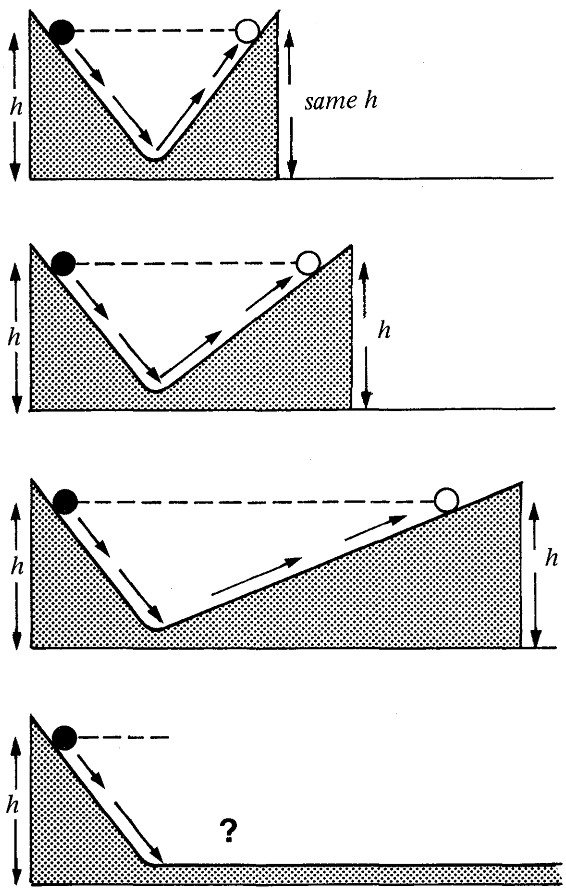
22. Look at the statement of Newton's First Law. Here are some questions you might like to think about:

a. If the Moon circles the Earth and the Earth circles the Sun, is this evidence against the Law, or can it be fitted in?

b. Does 'no force' really mean no force at all, or does it mean there could be two equal forces in opposite directions cancelling each other out?

c. Suppose a force acts on a table tennis ball and the *same* force acts on a solid lump of lead of the same size for the same time. Will they each have the same change of motion?

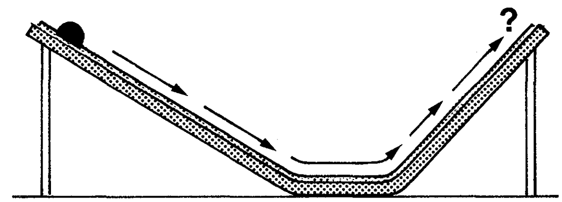
Galileo's idea Galileo made what would seem to him a common-sense guess about an object sliding or rolling down one hill and up another hill.



He guessed that, apart from friction troubles, the object would reach the same height on the opposite hill as its starting height on the first hill. (See Demonstration 33.) He believed that this must happen *whatever the slopes of the hills.* Then he extrapolated this to the case where the second hill is a level plain—with no slope at all. In trying to reach the original height the object would go on for ever—it would never stop moving.* That was Galileo's thought experiment.

Demonstration 33
Downhill-and-uphill motion: Galileo's guess

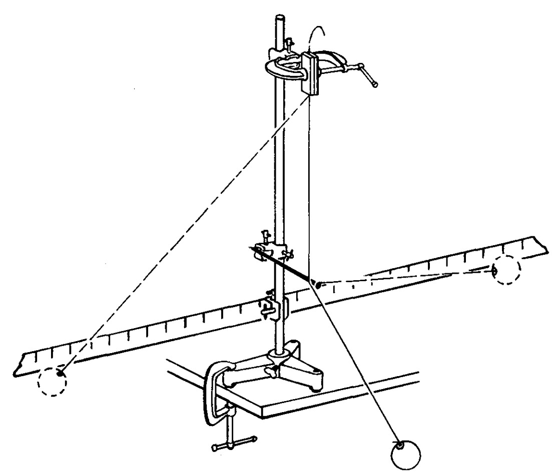
This only demonstrates the idea roughly, because friction does a lot of damage.



But isn't that experimental test hopelessly disappointing, spoiled by friction? No; Galileo had a brilliant demonstration that suffers only a very little air friction. See the demonstration sketched.

Demonstration 34
Galileo's frictionless invention: pin-and-pendulum experiment

This is his brilliant frictionless test. The peg catches the pendulum's cord and makes the bob swing up a steeper 'hill'. Does the bob rise to the same height?



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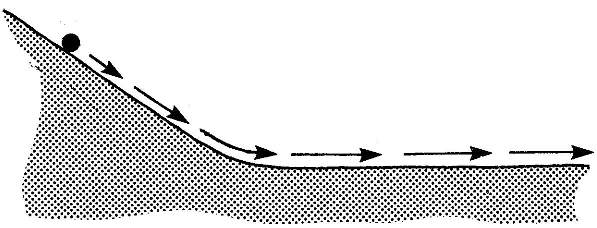
* A puzzle for Galileo and for us: which kind of going-on-for-ever should this predict, round the Earth in a circle, or off along a straight line tangent?

Questions

GALILEO'S IDEA

23. The sketch shows a hill. A ball rolls down the hill and on to a flat horizontal surface, which goes on as far as you like.

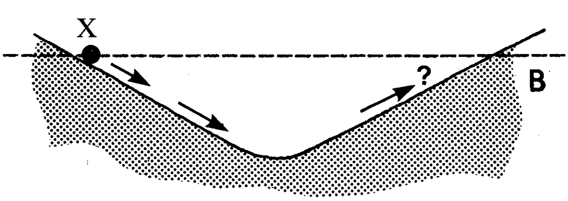


a. What happens to a real ball on a real surface?

b. What would happen if there were no friction or air resistance at all?

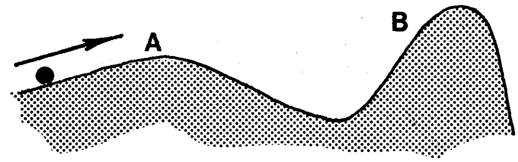
24a. Sketch A shows a shallow glass bowl, like a large 'watch-glass' from the chemistry lab (or a large curved mirror). It lies on the bench. A small steel ball is held near the edge and then released. What does the steel ball do?

b. Sketch B shows a length of curtain rail, bent as shown. A ball is placed at position X and is let go. How far does it go up the other side? What happens then?



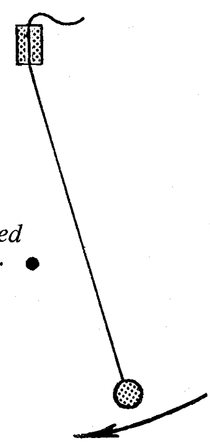
HILLS

† **25.** The sketch shows a small hill A followed by a higher hill B. A ball is given a push so that it rolls up and over the first hill. Describe what happens:



(i) if the ball is given only *just* enough speed to get over the small hill;
(ii) if it is given enough speed to shoot over the small hill with plenty to spare.

† **26a.** The pendulum bob is released from the position shown. Copy the sketch and show on your sketch the position that the bob has swung to when it is next motionless.



b. Draw a curved 'hill' down (and up), such that a ball could roll on it and follow a path just like the path of the bob.

Note: You should use a pair of compasses.

INERTIA

Leave a moving object alone and it will go on moving. Try to slow it down or stop it; it resists the change. Try to make it go faster and it resists that change.

We give a special name to that property of every mass. We say the mass has *inertia*.

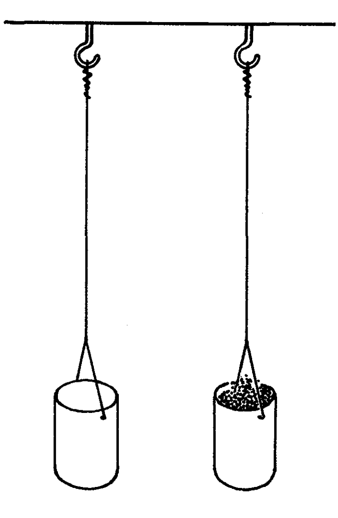
Inertia means opposition to change. Inertia makes the change slow but never stops it. There are many forms. Electromagnets have electrical inertia—they oppose *changes* of the current through their coils; flutes and organ pipes have acoustic inertia—the vibrations take time and a changing force to start, but they also hesitate to stop. The human mind has inertia—a necessary safeguard: we do not change our mind at every suggestion, like the Vicar of Bray. And in our science all masses have inertia: they oppose every change of velocity.

It would be a mistake to speak of a force 'overcoming' inertia as if inertia were an internal armed guard, which once vanquished would allow lightning changes. Inertia only demands force and time for a change: even the smallest *resultant* force maintains an acceleration.

Pupils' Demonstration 35
Feeling inertia

Try pushing each can in turn to feel the force needed to give a can some motion. Give each can a knuckle-flip and watch the effect.

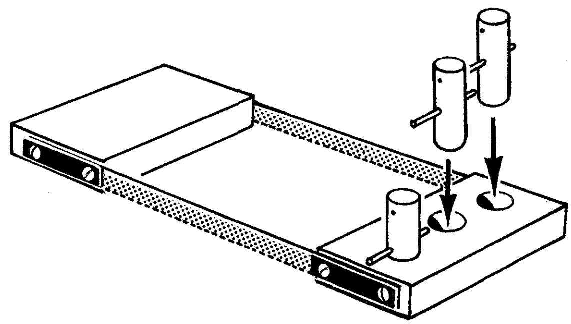
Also try stopping the cans when they are moving.



Experiment 36
The 'wig-wag'

Clamp one end of the wig-wag to the table with G-clamps so that the blades project out horizontally from the table. The outer end of the wig-wag acts as a platform that can vibrate to-and-fro horizontally.

Make sure the fixed end is clamped firmly to the table. Otherwise energy will leak away and the motion will die down very fast.



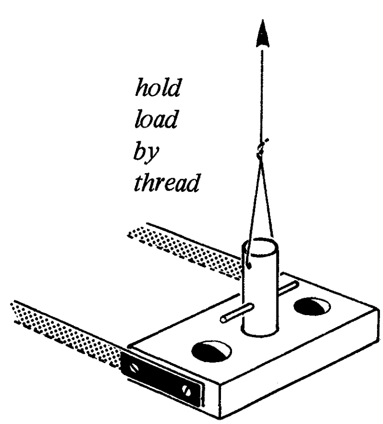
If the loads rattle or jump about, try holding them with a rubber band.

Pull the platform to one side; release it and watch it vibrating.

Then increase the mass by adding loads to the platform.

Advanced extra experiment Can you invent a scheme to relieve the platform of the *weight* of the load while you still keep the *mass* of the load there? If so, try it.

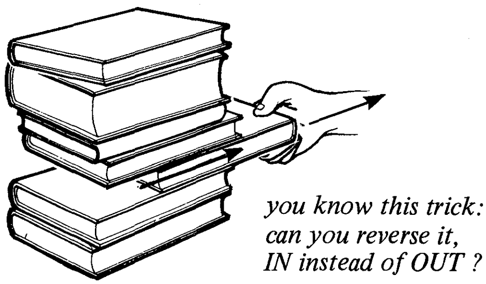
If you try this, which do you find settles the frequency of the wig-wag's vibrations, the *mass* of the load, or its *weight*, or *both*?



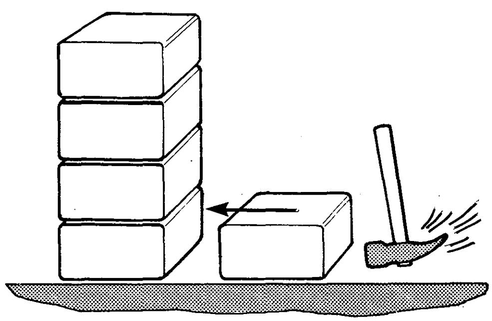
Experiment 37

Tricks that illustrate inertia *(OPTIONAL)*

a. *The simplest trick* Pull one book out from the middle of a pile of books.



b. *A reverse form of (a)* Push a wooden brick in at the bottom of a pile of similar bricks.

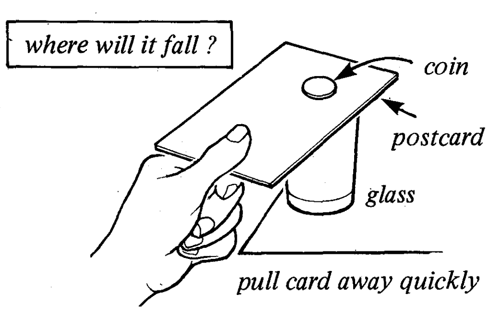


Build a pile of 4 bricks, then push a fifth brick, quickly, straight at the bottom brick of the pile. The fifth brick goes in and the bottom brick goes out.

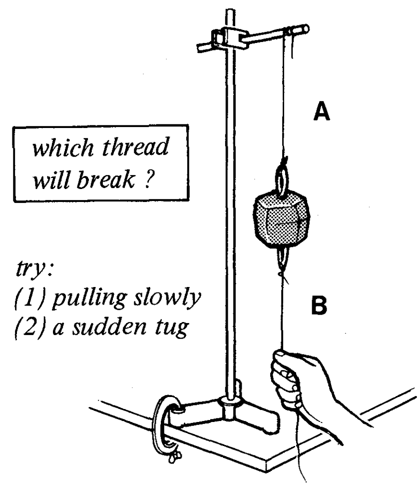
This is most dramatic if the fifth brick is projected along the table towards the pile by a 'croquet hit' from a small mallet.

Repeat, using the ejected brick as the projectile.

c. *A coin on a card on a glass* Whip away the card and the coin falls into the glass.

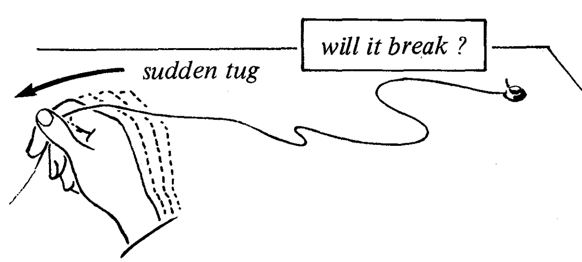


d. *Breaking threads* A thread is hung from the bottom of a load which itself hangs on a thread. A steady pull on the lower thread breaks the upper thread but a sudden snatch on the lower thread breaks the lower one.



To make the underlying paradox specially clear, use the same kind of thread throughout, but have a single upper thread and two or three strands in parallel for the lower thread.

e. *Breaking a thread* A very small mass (1 gram) is tied to the end of a long loose thread and placed on the table. Although the breaking strength of that thread is many hundreds of grams and it carries only one gram loose on the end, it can be broken by a *very sudden* jerk of the other end. (Strong sewing thread needs 5 or 10 grams for this to succeed.)



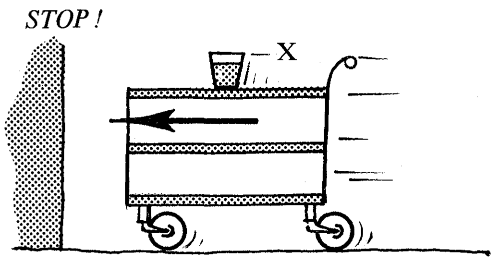
INERTIA

†**27.** A fat boy is sitting on a toboggan (a small sled) on smooth icy ground which slopes *slightly* downhill. The slope is just sufficient for him to slide at a steady slow speed; (that is just sufficient to compensate for friction). Suppose another boy comes up behind and pushes steadily for a few seconds.

I. His uncle says, 'the slope already "overcomes friction", so the slightest extra force will immediately produce a *very large increase of speed*.'

II. The boy agrees that the slope has already compensated for friction; 'but,' he says, 'that only means that any extra force will make no difference.'

Is either comment I or II right? If not, what do *you* say would happen?



†**28.** The sketch shows a tea-trolley or dinner-wagon with a tumbler of water (shown here larger than actual size) standing on it. The trolley is moving to the left when it suddenly hits a wall and stops.

a. If the tumbler slides, which way does it slide, to the left or right?

b. If the tumbler topples over, which way does it topple over? (Answer by a sketch.)

c. If the water slops out, without the tumbler falling, which way does it slop out? (Answer by a sketch.)

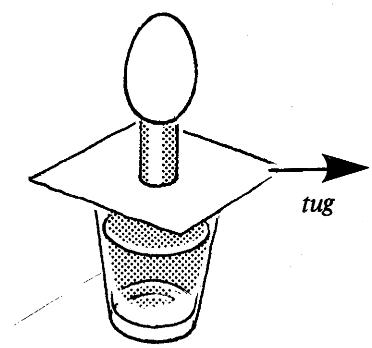
d. Now suppose the tea-trolley is at rest and you want to make the water slop out of the tumbler towards X (without tilting the trolley). What should you do to the trolley?

†**29.** A man's hat blew on to a path. A boy who was passing gave it a good kick, and ran away.

The man knew the boy would come back soon, and decided to 'get his own back'. He put the hat on the path with a large brick underneath. The boy came back and kicked the hat. He squealed because he hurt his foot.

The boy's brother said it served the boy right. His brother tried pushing the hat and brick with his foot; it moved quite easily along the smooth ground. Why was it that the boy hurt his foot and his brother did not?

30. An egg stands on a piece of metal tubing. The tubing stands on cardboard placed over a tumbler containing water. The conjuror jerks out the cardboard.



a. What happens to the egg, and why?

b. There are two reasons for having water in the tumbler. What are they?

31. You have used something called a wig-wag machine or an 'inertia balance'. Its time for one wig-wag depends on the inertia or mass of an object put on it, and not at all on the weight of the object. So it works in just the same way in the laboratory as in a spaceship.

a. How would you show, without taking it out of the laboratory, that it does compare *masses* of objects, and not *weights*?

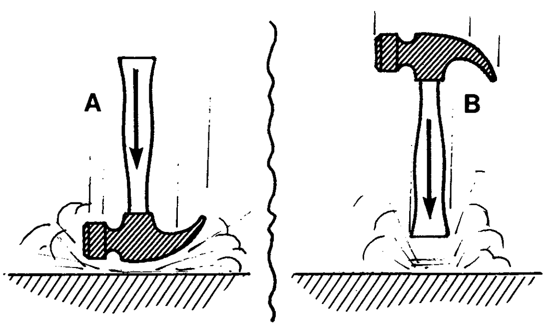
b. If you put a larger lump on it, it waggles more slowly. Give a reason why this happens—that is, a reason in terms of inertia and force. ('The larger lump has the larger inertia, therefore .....')

c. What else do you think has a controlling effect on its rate of waggle? (Choose your answer from: resistance of the air, weight of the springs, springiness of the springs, tightness of fastening to the bench, whether or not it is exactly level.)

32. You have masses of $\frac{1}{2}$ kg, 1 kg, and 2 kg. How would you use a wig-wag machine to find the mass of a lump which is 'somewhere about $1\frac{1}{2}$ kg'?

(Remember that the time for one wig-wag is *not* directly proportional to the mass you put on the platform; in fact, *you do not know* how time varies with mass. *Hint:* Graph paper may be needed.)

33. The iron head of a carpenter's hammer has grown loose on the wooden handle. Two people, A and B, give advice on jamming the head tighter on the handle. A says, 'Hold the hammer upright with the head downward and bring the hammer down with a bang on a strong table.' B says, 'Hold the hammer upright, with the head upward and bring the hammer down with a bang on a strong table.'



(i) Which method is better?
(ii) Explain why.

34. Consider the following: *(see sketch below)*.

A. a *TIN CAN* hung on a long string from the ceiling. It could be filled with sand.

B. a *PIECE OF WOOD* floating on water. It could have small loads put in it or on it.

C. carbon dioxide or compressed air *PUCKS* on horizontal glass.

D. a flat, heavy *PIECE OF METAL*—perhaps a weight—resting on steel balls on a smooth surface.

E. a compensated runway and a *TROLLEY*.

Question: What have all these in common?

Answer: They are attempts to avoid the effects of gravity and friction, so that we can test how things behave when those confusing forces are not acting—that is, they are attempts to simplify things.

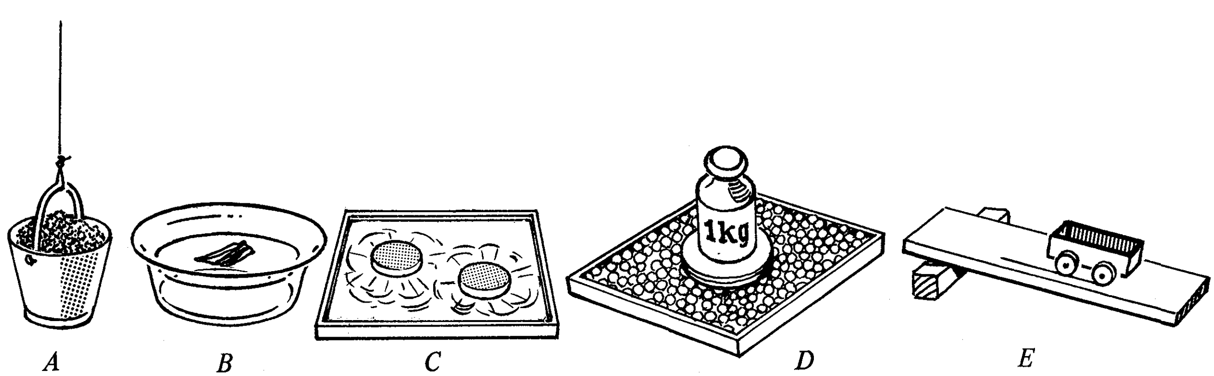
Of course they are not very successful attempts; at best we only get rid of gravity and friction for things moving horizontally or nearly horizontally. There are other snags: A. works only as long as the can moves just a small distance, otherwise the weight of the can becomes important, and E. works only in one direction. If we try to push the trolley any way except *down* the runway, it suffers forces due to weight and friction. Nevertheless, these are the best we can do, short of a voyage in some space craft!

You have tried pushing or pulling the can, the wood, the puck, the trolley, a kilogram rolling on small balls.

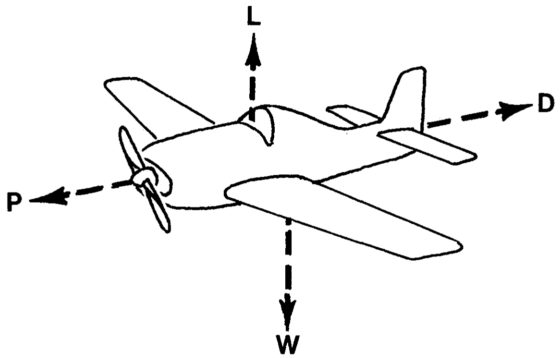
a. Describe what you feel when you give 'it' (the thing in *CAPITALS* in A to E above) a sudden increase of speed.

b. Compare that with increasing its speed slowly or stopping it slowly. That is, describe the difference in feel for large and small accelerations.

c. Describe the difference in feel when you try different quantities of matter, for example two pucks or a pair of trolleys, one on top of the other, instead of just one; or the can filled with sand compared with the can empty.



FORCES IN FLIGHT



† **35.** A small aircraft is flying 'straight and level' and at a constant speed. The propeller pushes air backward as it spins. That air, therefore, pushes the propeller forward. The forces acting on it can be represented by four vectors (lines drawn to scale in the proper directions). These are:
P, the forward push of air on the propeller;
W, the weight of the aircraft (downward pull of the Earth on it);
D, the 'drag' or friction resistance due to the air;
L, the 'lift' provided by air pressures on the wings.

a. The aircraft is flying horizontally with constant speed. You can make *two* separate statements, each using two of those four forces. Write those two statements (or write equations if you prefer).

b. *(ADVANCED, OPTIONAL)* As the. forces are drawn in the diagram, which two might seem to be trying to turn the aircraft's nose upwards or downwards? If the aircraft continues to fly straight and level, what can you say about those two forces?

CHAPTER 4

MOMENTUM CONSERVATION OF MOMENTUM

NEWTON'S SECOND LAW: MOMENTUM FORM

Newton's Second Law in the form $F = ma$ is useful in calculating forces, in estimating the effect of car brakes, in measuring electrons in flight, and in making a theory of astronomy—which was Newton's own reason for writing it.

We can put the same knowledge in another form: we change from:
(A) FORCE = MASS × ACCELERATION, which is the form you know, to
(B) FORCE × TIME = gain (or loss) of MASS × VELOCITY.

The new form *(B)* deals quickly and clearly with crashes, jumps, rocket propulsion, air molecules . . . and it becomes specially valuable when we arrive at Conservation of Momentum. So you should learn to use it. You need not remember the details of the shift from *(A)* to *(B)*; yet you should see the shift made for the sake of your general understanding of science. Here are two versions: a quick piece of algebra and a simpler discussion of common-sense experimental knowledge. Choose the version you prefer.

The algebra version Remember that acceleration, a, is:
(CHANGE OF VELOCITY)/(TIME TAKEN FOR THAT CHANGE)
$a = (v-u)/t$
Then $F = ma = m(v-u)/t$
$\therefore Ft = mv - mu.$

Ft, (FORCE* multiplied by TIME), is a useful thing in physics, so we give it a name. We call it IMPULSE. And mv is a very useful thing, so we give it a name. We call it MOMENTUM. The moving object had velocity u before the force F started acting and it finished with velocity v after F has been acting for time t. So mv is its final momentum and mu is the momentum it had before. Therefore $mv-mu$ is its gain of momentum or change of momentum. Therefore impulse Ft = *change of momentum*, $mv - mu$.

That is an alternative form of Newton's Second Law of Motion. It is a useful form for calculating a force, when we know the time for which it acts and the momentum change.

The common-sense version Instead of using algebra to change Law II from form *(A)* to *(B)* try some common-sense thinking about forces like this:

You have seen that a force makes things go faster, or slower. When we say this, we do not mean just one force that is pulling in one direction while other forces are pulling back. We have to add up all the forces acting on an object—forward and backward and even sideways—to find the total 'resultant' force in one direction. That is the single force which can take the place of all the others together. IF there is any resultant force the object accelerates in the direction of that force.

We call the *resultant* of all the pulls and pushes on an object '*THE* force'. When *THE* force is there, the object it acts on moves faster and faster, gaining velocity. The bigger the force, the more velocity the object gains in each second. And the longer the time during which *THE* force acts, the more velocity the object gains. So you might say the total GAIN IN VELOCITY goes up in proportion

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* We assume, for simplicity, a constant force F. If the force is *not* constant, use its *average* value for F.

to FORCE and to TIME, or to FORCE × TIME combined.

But suppose you have several trolleys all piled on top of each other, a lot of stuff to be accelerated. Then you will not have such a big gain in velocity as with just one trolley being pulled by the same force. So FORCE × TIME does not tell us just the gain in VELOCITY.

Experiments show that when you have twice the mass, you get only half the gain in velocity. So when you look at FORCE × TIME and ask what you get from it, you have to think about how much velocity is gained, also how much mass is there to gain velocity.

Example Suppose you push 1 kilogram for a certain time and it gains 10 metre/second in velocity. You could push a 2-kilogram object with the same force for just as long a time but it would gain only 5 metre/second. Or you could push 5 kilograms for the same time with the same force, and that would gain in velocity only 2 metre/second.

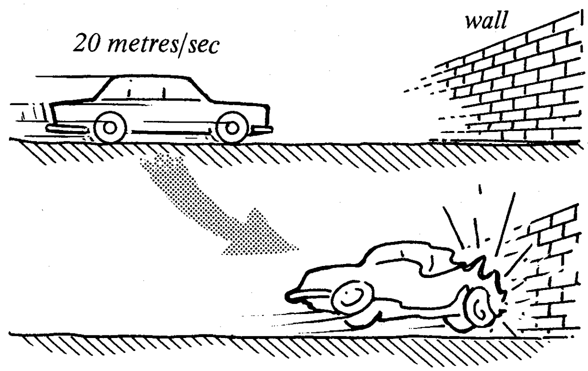
For the same force, acting for the same length of time, we get the same gain of MASS × VELOCITY in every case. That seems a useful product, so we give it a name 'momentum'.

Then gain of MOMENTUM, gain of *mv*, is poportional to FORCE × TIME. You can do experiments to illustrate this, to show that it fits with what trolleys and other things do—of course you could not do enough experiments to prove that it is completely true.

We chose our units for force, newtons, for use in $F = ma$. The same choice applies here; for that 1 newton acting for 1 second will produce a change of momentum of 1 kilogram gaining 1 metre/second of velocity.

(WARNING If you have heard about *kinetic energy*, which is $\frac{1}{2}mv^2$, be careful not to confuse that with *momentum*. Each of these gives some idea of the 'effect' of a force. Momentum is FORCE × TIME while kinetic energy is FORCE × DISTANCE MOVED. You will meet kinetic energy in the next chapter.)

Another example A 1000-kilogram car, moving 20 metres per second (about 45 miles per hour), hits a brick wall head-on and comes to a stop. Suppose the front bumpers are very squashy,



specially built for safety, so that the crash of the car coming to a stop takes 0.10 second. Calculate the force the wall exerts to bring the car to a stop in that time.

The momentum of the car before the crash is (1000 kilograms) × (20 metre/second), and its momentum afterwards is zero. Its change of momentum, *mv*, is −20 000 kg·metre/second. That change of momentum was produced by the force exerted by the wall acting for 0.1 second.

$\therefore$ $F \times 0.1$ *second* = 1000×20 (*kilograms* × *metre/second*).

Those units are the same as newtons × seconds.

$$\therefore \text{Force, } F, = \frac{20\,000 \text{ newton·seconds}}{0.10 \text{ second}}$$

$$= 200\,000 \text{ newtons}$$

If you want to describe the size of that force, ask how much material, of any kind, is pulled by the Earth with 200 000 newtons? *Answer:* 20 tonnes.

That seems an enormous force. And if you calculate the distance the car must travel while the crash is happening (using the *average* speed during the crash, (20 + 0)/2, or 10 metre/second) you will find that 1 metre of the front of the car must crumple up—a lot of that would have to be in the special squashy bumpers.

A greater smash Now suppose the bumpers are very strong and firm, so that the crash takes only 0.01 second. Carry out a similar calculation for yourself and find the huge force involved in the crash. *That is the real force that would act in such a crash—it is not just the answer to a physics problem.*

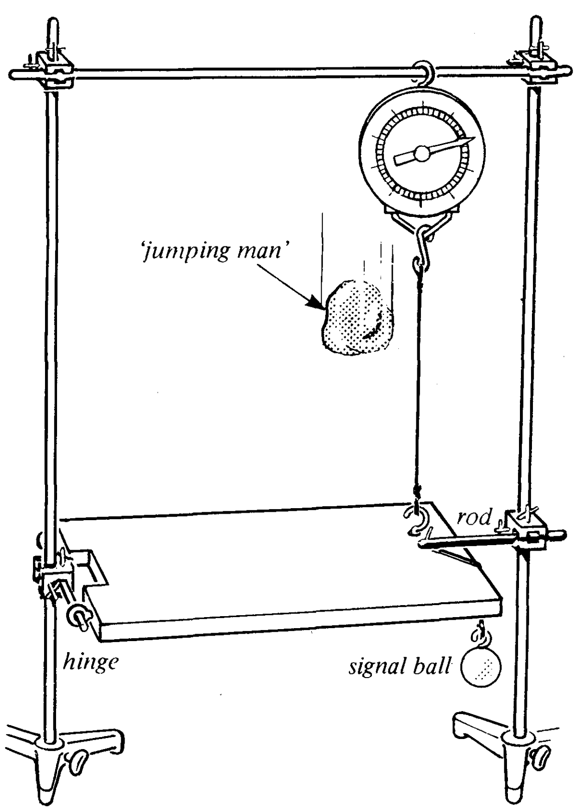
The car would move forward only about 10 centimetres during the crash; no wonder the force is so huge and the crash so bad. Unless the wall is very strong, the crash would probably break the wall down.

Landing after a jump Just before you land on the ground after a high jump you are falling with a lot of momentum downward. You have no momentum after landing so you get rid of a lot of momentum while you are coming to rest. That change of momentum is equal to FORCE × TIME where FORCE is the push that the ground must give to bring you to a stop. If you want to make that FORCE smaller, so that you are not hurt so much, you must make the TIME longer. What do you yourself always do, by common sense, when you are landing after a jump? Does this make your landing time longer?

A dangerous jump Question 51 in Chapter 2 gives an example of a clumsy jump. Try that question now if you missed it before, but use Ft = *change of* (mv).

Demonstration 22
The jumping man

This was offered in Chapter 2 to illustrate the danger. If you missed this experiment before, now is a good time to see it.

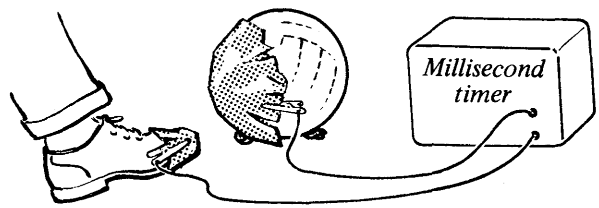


What force do you use when you kick a ball? Question 51 in Chapter 2 asks you to calculate the force. If you missed it before, try it now, using $Ft = \triangle mv$.

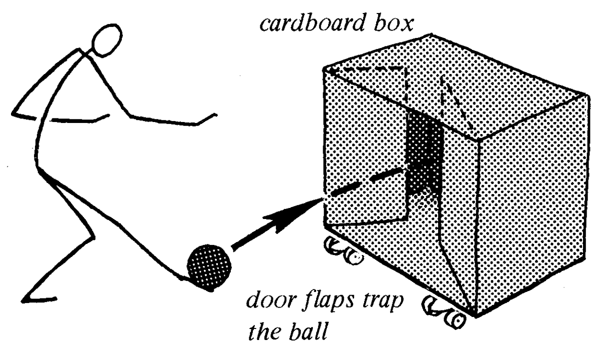
Much better than working through an artificial problem, make measurements on a real soccer ball being kicked. This was offered in Chapter 2. If you did not see this before, this is a good time for it.

Demonstration 23
Kicking a football

Now you have a choice of ways to measure the speed of the ball after the kick:



(i) As suggested in Chapter 2 Demonstration 23, stand on a table 1.25 metres above the floor and kick the ball horizontally. Measure the distance the ball travels before it hits the floor. Calculate the time taken for the vertical fall of 1.25 metres with acceleration g approximately 10 metre/second in each second. Then you know the time for the ball's horizontal travel and can calculate its speed.
(ii) Standing on a table, kick the ball and take a multiflash photo of it in motion. Include a scale of centimetres in the picture, and calculate the speed of the ball from the photograph.
(iii) Kick the ball into a cardboard box on roller skates or a skate board on the floor. (Or place the box on a platform of wood resting on three trolleys.) Arrange cardboard flaps to stop the ball bouncing out of the box again. Then all the



momentum the ball had after your kick is shared with the box. This assumes 'Conservation of Momentum' which you will meet soon.

Make the box massive, by adding some loads, so that it moves slowly enough, with the momentum it has acquired, for you to time its motion.

Ask your teacher for help in working out the ball's speed. This method is similar to the way in which we measure the speed of a rifle bullet.

Progress Questions

DON'T GET HURT

1. When a force accelerates something, or slows something down, it changes the thing's momentum. Remember that you need a big force to change momentum quickly, and a small force to change momentum slowly.

a. *(i)* Bill falls into a pile of straw and Ben falls—from the same height—onto the pavement. Who comes to rest in the shorter time?
(ii) Who gets hurt most? Write a sentence or two, using the words 'force' and 'momentum' to explain your answer.

b. Jill says her hands always hurt when she catches a fast cricket ball, but Jack says that he lets his hands 'give' with the ball, so it doesn't hurt at all.
(i) What is Jill doing wrong?
(ii) Explain why it is wrong. Use the words 'force' and 'momentum' in your explanation.

c. *(i)* When you jump off a table onto the ground, why is it wise to bend your knees during your 'collision'?
(ii) What you are doing is to make your collision with the floor last longer than if your legs were held stiffly. What effect does this have on the size of the force that the floor exerts on you?

BANGS AND CRASHES

2. Suppose you are an engineer, and you have to design barriers to stop each of the following.
(i) a lorry of mass 4000 kilograms travelling at 30 metre/second (about 65 mph);
(ii) a bicycle (plus rider) of mass 80 kilograms altogether travelling at 10 metre/second (about 20 mph);
(iii) a charging elephant of mass 4000 kilograms travelling at 10 metre/second.

a. Two of these have the same speed (velocity). One would be easier to stop than the other. Which one?

b. Two of these have the same mass. One would be easier to stop than the other. Which one?

3. Question 2 reminds you that both the MASS and the VELOCITY of a moving thing matter.

We use the word [MOMENTUM] to mean [MASS × VELOCITY]. The MOMENTUM of the lorry in Question 2*(i)* is
4000 kg × 30 metre/second = 120 000 kg metre/second.

a. What is the momentum of the bicycle in Question 2*(ii)*?

b. What is the momentum of the elephant in Question 2*(iii)*?

c. What is the momentum of a 30-kg child running at 2 metre/second?

d. What is the momentum of a $\frac{1}{4}$-kg ball moving at 40 metre/second?

4. When something is stationary, its momentum is ZERO ($m \times v = m \times$ zero, which is zero). So when something starts from rest, and speeds up it *gains* momentum. And when something stops moving, it *loses* momentum.

a. A 3000-kg elephant moving at 3 metre/second bumps into a wall and stops.
(i) What is its momentum when it is moving?
(ii) What is its momentum when it has stopped?
(iii) So how much momentum does it lose?

b. A $\frac{1}{2}$-kg bag of sugar is allowed to fall. When it is moving at 40 metre/second it hits the ground and it stops. How much momentum does it lose?

c. A 1000-kg car starts from rest and accelerates to 10 metre/second.
(i) What is its momentum when it is at rest?
(ii) What is its momentum when it is moving?
(iii) So how much momentum does it gain?

d. The car in (c) then accelerates to 30 metre/second. How much *extra* momentum does it gain? Explain how you work out your answer.

e. The 1000-kg car moving at 30 metre/second stops.
(i) How much momentum does it lose?
(ii) The car could be stopped in several ways. Write down any you can think of.

5a. Which of the following do you think, from common sense, would need the larger force?
(i) To get a car from rest to 50 km/h in 1 minute?
(ii) To get the same car from rest to 50 km/h in 10 seconds?

b. And which of the next two would need the larger force?
(i) To stop a heavy lorry, travelling at 80 km/h, in 1 minute?
(ii) To stop the same lorry, travelling at 80 km/h, in 10 seconds?

c. Which of the following needs the greatest force?
(i) To stop in 10 seconds a lorry of mass 4000 kg going at 40 km/h.
(ii) To stop this same lorry in 20 seconds.
(iii) To stop in 10 seconds a car of mass 1000 kg going at 40 km/h.

d. Which of the examples in (c) needs *least* force?

6. There are two ways of stopping a moving car. It can be slowed down gently, by its brakes, *or* it can be slowed down very suddenly, by hitting a barrier.

a. Which force is bigger, the force due to the brakes, or the force of the barrier?

b. A car of mass 1500 kg is travelling at 15 metre/second. It is slowed down gently to zero speed, taking 5 seconds to stop.
(i) How much does its speed drop, *in each second*? (That is, what is its backward acceleration?)
(ii) How much backward force is needed?

c. A car of mass 1500 kg is travelling at 15 metre/second. It hits a barrier and is slowed down suddenly, taking only $\frac{1}{5}$ second to drop its speed from 15 metre/second to zero.
(i) Its speed drops 15 metre/second in $\frac{1}{5}$ second. At that rate of slowing down, how much would its speed drop (if it could!) in one whole second?
(ii) How big is the backward force on the car?
(iii) This is the force with which the barrier meets the car. Can you say how big is the force with which the car meets the barrier?

Questions

DAMAGE

7. The rule $F \times t$ = change of mv can tell you something about the dangers of damage when a moving thing lands with a bang. Any object falling freely has an acceleration 9.8 metre/second^2. Its weight (the pull of the Earth on it) is the force that gives it that acceleration. But when a falling object lands on the floor, the floor gives it a large deceleration (negative acceleration) to bring it to a stop.

a. What size of force would be needed to give it a deceleration 10 times g? How big would that force be, compared with the weight of the body?

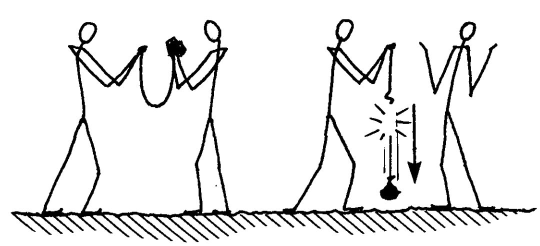
b. What size of force would give the falling body an acceleration 100 times g?

c. Hold a book 20 cm above the table and let it drop. Listen to it landing, and guess how long that crash takes. Then say whether you think its deceleration is about 10 g, 100 g, 1000 g.

d. If you have a valuable stop-watch or calculator or ammeter, what damage may happen to it if you put it down on the table sharply? What are the risks for a baby falling off a sofa and landing on a hard floor?

CHANGES OF MOMENTUM

8a. A stone hangs on a cotton thread, while you hold the top of the thread firmly. The thread is strong enough to support several stones of that size. Someone else takes hold of the stone, lifts it up about $\frac{1}{2}$ metre (letting the thread hang slack) and then lets the stone drop. The thread breaks. Explain why the thread breaks.



b. Suppose the thread is no stronger, but stretches much more easily. Would that make any difference? Give a clear reason for your answer.

c. Can you see now why climbers use nylon ropes?

9. A newspaper report says: 'In order to make a soft landing on the Moon's surface, retro-rockets must be used.'

a. What are 'retro-rockets'? (Retro = backwards, as in 'retrogress', 'retrograde', 'retroactive', and 'retrospect'.)

b. How would the use of retro-rockets lead to a soft landing?

10. This question follows from Question 9. Would the force which the retro-rockets must exert in order to ensure a soft landing need to be 'increased', 'decreased', or 'unchanged', if

a. they are to be switched on for 10 minutes instead of 5?

b. the space-ship is travelling at twice the speed?

c. the space-ship contains two men instead of one?

11. You can easily arrive at
[IMPULSE, Ft] = [change of MOMENTUM, $\triangle mv$]
by two lines of algebra, instead of working out one particular example. Try it:

Start by writing $F = ma$. Then:

a. The acceleration a is the increase of speed from u to v in time t. What can you substitute for a?

b. Multiply both sides of the equation by t and what do you get?

12. *(Advanced, but important for doing calculations about molecules soon)* A toy machine-gun shoots steel balls, each 2 grams (= 0.002 kg), at the rate of 3 balls per second. They emerge with a horizontal velocity 11 metre per second and hit a vertical steel plate. The balls rebound from the plate with almost the same speed as the speed with which they hit it.

a. What is the MOMENTUM of a ball on impact?

b. What is the MOMENTUM of a ball as it rebounds (Remember the velocity is reversed, so it is changed from $+v$ to $-v$.)

c. What is the *change* of MOMENTUM of one ball on impact?

d. What is the *change* of MOMENTUM of all the balls meeting the plate in 10 seconds (at 3 per second)?

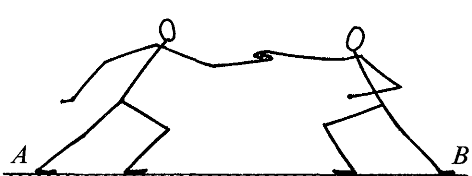
e. To find the average force on the plate use

$$F = \frac{\text{change of momentum}}{\text{time (10 seconds)}}$$

NEWTON'S THIRD LAW OF MOMENTUM AND CONSERVATION OF MOMENTUM

Demonstration 38
'If I pull you, you pull me; if I push you, you push me'

Try the experiment sketched.

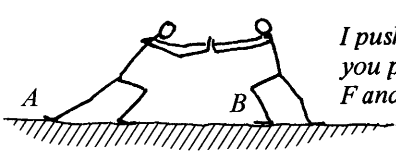


Action = −Reaction The sketch shows one person, A, pulling another, B, with his hand.

Which way is A pulling B, to the left or to the right? Which way is B pulling A?

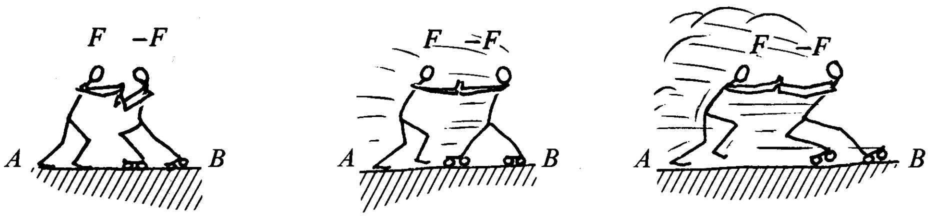
You cannot have one of those two pulls without the other. But those two pulls do not cancel out and come to no pull at all. B feels only one pull, the pull exerted on him by A. And A feels only one pull, the pull exerted by B.

Now look at the sketch of one person, A, *pushing* another person, B.



The reason why B does not accelerate towards the right when A pushes him is because there is *also* another, quite different, force shoving B, to the left. His rough shoes on the floor stop him moving. The floor pushes him away to the left with a friction-force which just balances the push of A.

If A pushed much harder, friction could not match his push and B would start accelerating to the right.



If B wore roller skates, he would accelerate at once when A pushed him and A would have to run away to the right to keep up that push. Even then, with A and B both running faster and faster, A's push on B would still be just matched by B's push on A.

The fact that A pushes B to the right constitutes a force on B. The fact that B pushes A to the left does not constitute a force on B—that is only the force which he is exerting on someone else. So when you are considering B you do not have both forces acting on him, but only the push of A.

Of course if you are considering the combined group A and B together, you should add those two forces making a total of zero.

If A and B stand on a platform on frictionless wheels (or in a boat on water with little friction) it does not matter how strongly they push each other, such pushes will cancel out and not help them to move the platform or boat.

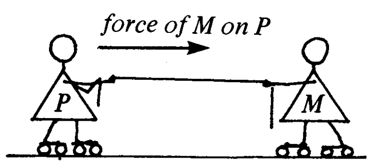
Newton's Third Law We state a general rule: When *any* two objects A and B exert *any* kind of forces on each other the force A exerts on B and the force B exerts on A are *always* equal and opposite.

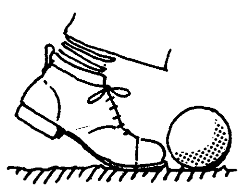
$$ {}_{A}F_{B} = -{}_{B}F_{A} $$

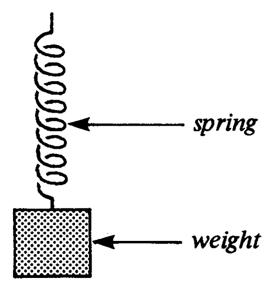
This is called Newton's Third Law. We use it as a general accounting rule.

Progress Questions

PAIRS OF FORCES







13. Copy and complete:

a. Molly exerts a force on Polly to the right. Polly moves to the (/*right*/*left*/). At the same time, Polly exerts a force on Molly to the (/*right*/*left*/) and Molly moves to the (/*right*/*left*/).

b. When the boy kicks the ball, the boot exerts a force on the ball to the (/*right*/*left*/) and the ball moves to the (/*right*/*left*/). At the same time, the ball exerts a force on the boot to the (/*right*/*left*/).

c. The spring exerts a force on the load (/*upwards*/*downwards*/). At the same time the weight exerts a force on the spring (/*upwards*/*downwards*/).

ALSO Copy the sketches and put in labelled arrows to show the forces sensibly.

14a. What stops the boot in (13b) moving to the left?

b. What stops the spring in (13c) moving downwards?

c. What stops the load in (13c) moving upwards?

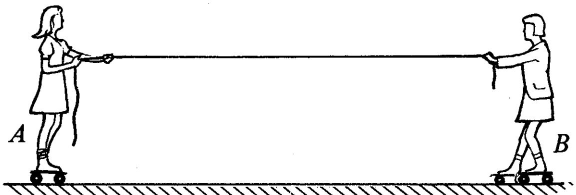
15. A boy and a girl, both sliding on some ice, bump into each other, and both stop dead.

a. What force stops the girl?

b. What force stops the boy?

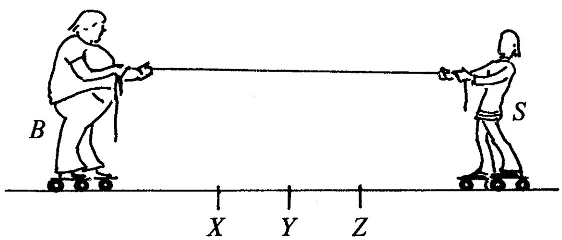
c. Draw a diagram of the collision, and put in labelled arrows to show the two forces sensibly.

16a. Two girls, A and B, weigh about the same. They stand 8 metres apart on roller skates. They hold a rope just taught between them. A starts pulling and draws in the rope hand over hand. B coasts towards A. What else happens?



b. If B pulled as well, what difference would it make?

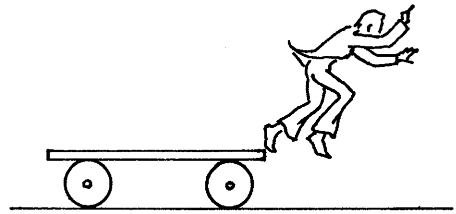
c. A boy, C, who is much heavier than either of the girls, takes B's place. C and A hold the rope just taut. Then A starts pulling again. What happens this time?



17. B and S are two boys on roller skates. Copy and complete:

a. The force of big B on small S is (*/bigger than/the same as/smaller than/*) the force of S on B. So B's change in MOMENTUM is (*/bigger than/the same as/smaller than/*) S's change in MOMENTUM. B's mass is big, so he gets a (*/big/small/*) velocity.

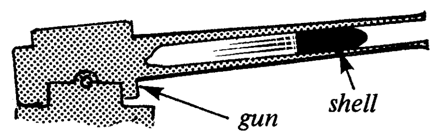
b. B and S meet near (*/X/Y/Z/*).



18. The boy jumps forward off the trolley in the sketch. He moves to the right. During his jump he is kicking the trolley backwards; so the trolley exerts a force *on the boy* to the (*/right/left/*).

Since the boy kicks the trolley backwards the trolley must move to the (*/right/left/*).

RECOIL



19.

(i) The shell is pushed forward by explosive gases. Which way is the gun pushed?

(ii) Which has the smaller mass?

(iii) So which has the bigger velocity?

(iv) Why does the gun stop moving long before the shell?

20a. A jet plane works by squirting hot air out behind it.

(i) The plane pushes the air out backwards. Which way does the air push the plane?

(ii) Which has the smaller mass?

(iii) So which has the bigger velocity?

b. Write as fully as you can about what happens when you blow up a balloon, then let it loose.

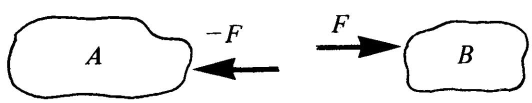
CONSERVATION OF MOMENTUM

We can argue from Newton's Third Law to a very useful general rule which tells us how to make calculations and predictions about all kinds of collisions. It is the rule of Conservation of Momentum.

What does 'conservation' mean? Here is an example, conservation of cash. Suppose you start out for a shopping trip with some pocket money. After buying several things, you return home and feel worried because you are not sure whether some of your money has disappeared without your knowing it. But you say to yourself, 'Calm down. Money does not disappear, nor does it suddenly appear from nowhere. If I add up the money I have brought home in my pocket and each lot of money I spent on buying things, the total will come to just what I started with.' Then you remember the things you bought and do the adding and feel reassured. You have assumed two things: that cash is conserved (does not disappear to nowhere, does not appear suddenly from nowhere) and that you had a 'closed system' which means that it was just you and the shops that dealt with your money. If you gave some of the money to a friend while you were shopping, you must include him in your adding up, or you do not have a complete closed system. Of course, if you have a hole in your pocket that lets coins leak out, you do not have a closed system.

When banks and shops check their cash at the end of the day, they do so with firm and useful trust in conservation of cash.

Conservation of Momentum Suppose two objects or people, A and B, exert forces on each other. We are sure that those forces are equal in size; if A pulls B with a force F then B pulls A with a force $-F$. We shall take that for granted as a general accounting rule for forces in the universe. That rule is called Newton's Third Law of Motion, which states, '*when two bodies interact, action and reaction are equal and opposite.*'



$-F$ = force exerted on A by B

F = force exerted on B by A

Now think what the force F does to B while it acts on it for a time t.
Effect on B: $F \times t$ = change of momentum of B

And for the force $-F$ acting on A,
Effect on A $-F \times t$ = change of momentum of A

Add up those two equations
$(Ft) + (-Ft)$ = [change of momentum for A] + [change of momentum for B]
0 = change of [momentum for A + change of momentum for B].

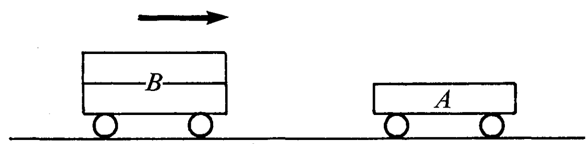
That means the total change of momentum, adding up the changes for A and B is zero. We did not say this was any special kind of force or collision. The forces may be of any kind, and the collision can last for any time. We only assumed the forces were equal and opposite and that F and $-$F act for the same amount of time. (You could hardly imagine A pulling B for a longer or shorter time than B pulls A!)

So this is a completely general rule that applies to ALL collisions, attractions and other interactions: *THE TOTAL MOMENTUM AFTER ANY EVENT IS THE SAME AS THE TOTAL MOMENTUM BEFORE.*

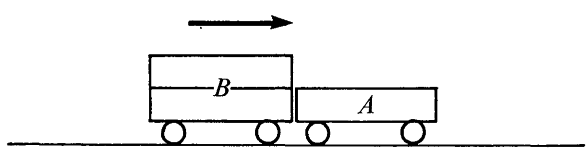
The only restriction is that we must deal with a closed system. If A and B are also interacting with another object C during the collision we must include C's changes of momentum before we say the total change is zero.

Progress Questions

CONSERVATION OF MOMENTUM



before collision



after collision

21. Trolley A has a mass of 1 kg and is at rest, to begin with.
Trolley B has a mass of 2 kg and is moving with speed of 3 metre/second.
Trolley B crashes into A. They both stick together and move along with speed of 2 metre/second. (The runway is compensated for friction.)

a. What was A's MOMENTUM before they collided?

b. What was B's MOMENTUM before they collided?

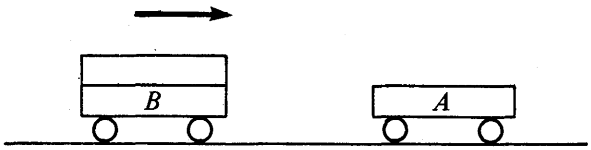
c. What was the total MOMENTUM before they collided? (*HINT:* Add your answers (a) and (b).)

d. What was A's MOMENTUM after they collided?

e. What was B's MOMENTUM after they collided?

f. What was the total momentum after they collided? (*HINT:* Add your answers for (d) and (e).)

g. Look at your answers to (c) and (f), then copy and complete:
The total momentum after collision is . . ? . ., the total momentum before collision.



22. Trolley A has a mass of 1 kg and is at rest to begin with.

Trolley B has a mass of 2 kg and is moving with speed 8 metre/second.

Trolley B crashes into trolley A, but this time they do *not* stick together. Trolley A moves off with speed 6 metre/second, B goes on moving, but more slowly, at 5 metre/second.

a. What was A's MOMENTUM before they collided?

b. What was B's MOMENTUM before they collided?

c. What was the total MOMENTUM before they collided? (*HINT:* Add (a) and (b).)

d. What was A's MOMENTUM after they collided?

e. What was B's MOMENTUM after they collided?

f. What was the total MOMENTUM after they collided? (*HINT:* Add (d) and (e).)

g. Look at your answers to (c) and (f), then copy and complete:
The total momentum after collision is . . ? . ., the total momentum before collision.

EXPERIMENTS TO ILLUSTRATE CONSERVATION OF MOMENTUM

Try some of the collision experiments here with trolleys and tape. In each case calculate the momentum, mv, before the collision and the momentum after; and see how nearly the total momentum stays the same. You need to make sure that all the trolleys you use in any one experiment have the same mass. And where you tilt the runway to compensate for friction you should do so with the tape in use, because this contributes some friction.

Class Experiment or Demonstration 39
Elastic collision of trolleys

Set up a runway and compensate it for friction.

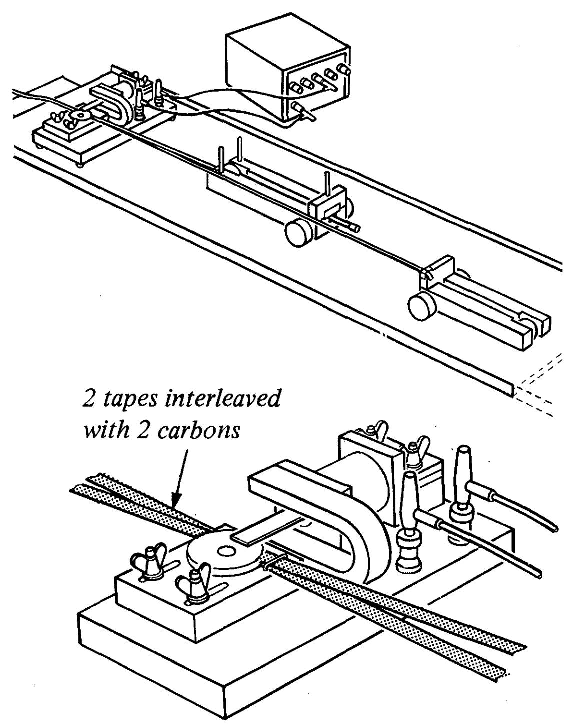
Place two trolleys on the board, each with a tape attached. Run both tapes through the same vibrator with *two* carbon paper discs one for each tape. Compensate the runway for friction with both tapes running through the timer.

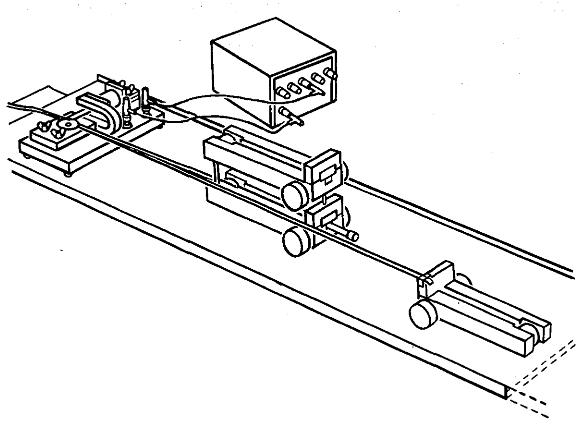
Start with one trolley at rest about half-way down the runway. It should have its spring-loaded piston out, to act as a buffer in a collision. Hold the second trolley at the beginning of the runway, give it a push with your hand, then leave it to run with constant speed until it collides with the first trolley.

Your tapes will give you records from which you can read three steady speeds:
SPEED of the moving trolley before the collision
SPEED of the moving trolley after the collision
SPEED of the other trolley after collision.

Then you can calculate the total forward momentum before and after the collision. You may take the mass of a trolley to be 1 kilogram in this experiment.

There is no need to make tape-charts. Just read the steady speed of a trolley by measuring the length of 5 tenticks on its tape. Then to calculate the trolley's MOMENTUM multiply by its MASS.





Collision of UNEQUAL masses Give the second trolley (the 'projectile') double mass by piling another trolley on top. Watch what happens when it hits the stationary trolley.

Repeat the collision, with tapes to measure speeds.

Each partner should obtain a set of tapes for a collision.

Calculate the momentum, *mv*, of

(i) the projectile trolley, before collision.

(ii) the stationary trolley, before collision (zero).

(iii) the projectile trolley, after collision.

(iv) the stationary trolley after collision.

How does the total *mv* after collision compare with the total *mv* before?

Collision of EQUAL masses Repeat the experiment with a single projectile trolley hitting a single stationary trolley head-on.

Elastic and inelastic collisions *Elastic* has a special meaning in science. When we say a spring is *elastic* we mean that when we stretch it and then release it the spring goes back in exactly the same way and to exactly the same length as it was originally—it shows no sign of fatigue or of permanent stretch. Springs of good hardened steel are elastic over a large range of stretches.

(Rubber cords, such as those you use to pull trolleys, are not perfectly elastic; they show a little fatigue and after-effects, so it is unfortunate that we call them *elastics*.)

Some people like to describe 'elastic' by a slang name, 'snappable-backable'.

In a collision, the colliding objects approach each other, losing motion energy, come to rest momentarily, then move apart. If they end up with the same total of motion energy as they started with we call the collision *perfectly elastic*.

We call the collision *inelastic* if the total motion energy is much less after collision than before. (Then some of the original motion energy has disappeared into other forms.)

Example: Throw two lumps of sticky clay towards each other. Suppose they hit head-on and stick together. Then we call the collision *completely inelastic*. If the two masses were equal and speeds were equal, the combined lump will be at rest; all the motion energy will have changed to some other form—so that is a very *inelastic* collision. But momentum is a vector and the two equal and opposite lots of momentum add up to the same total afterwards as before, *ZERO*—Conservation of Momentum holds as always.

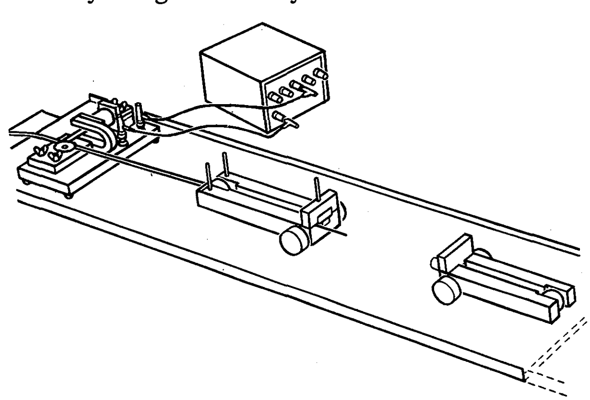
Class Experiment or Demonstration 40
Sticky collisions

Let one trolley run into another on a runway and arrange for them to stick together on collision. Make tape measurements to find out what happens to momentum when the collision occurs. One trolley has a sharp pin on it and the other a soft cork to make them stick together.

You will be measuring constant speeds in this case, not acceleration—though of course, there are violent accelerations in the very short time of the collision itself.

a. Equal masses Set up a runway with a timer at one end and tilt the runway to compensate for friction with a trolley pulling the tape.

Place the other trolley without tape about halfway along the runway. Make sure it is at rest.

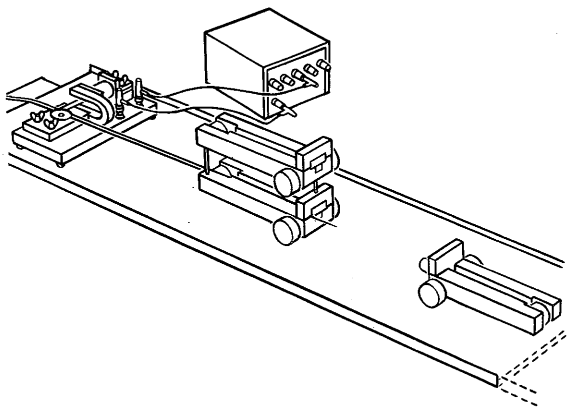


Start the trolley with the tape near the beginning of the runway. Give it a quick push and let go, so that it runs at constant speed. Its motion will be recorded on the tape. After the collision, the tape will show the motion of the two trolleys which are locked together.

Each member of the group should make his own tape record of that collision.

Measure your own tape and find the first trolley's initial speed, in centimetres per tentick. And measure the speed of the two trolleys after collision, in centimetres per tentick.

Call the mass of one trolley M—or else just 1 kg, if you like. Calculate the total momentum before collision and total momentum after collision.



b. Unequal masses 2:1 Repeat the experiment, starting with twice as much moving material. For this, pile an extra trolley on top of the first trolley and anchor it with tape. Run a collision. Measure the tape and calculate the momentum before and after collision.

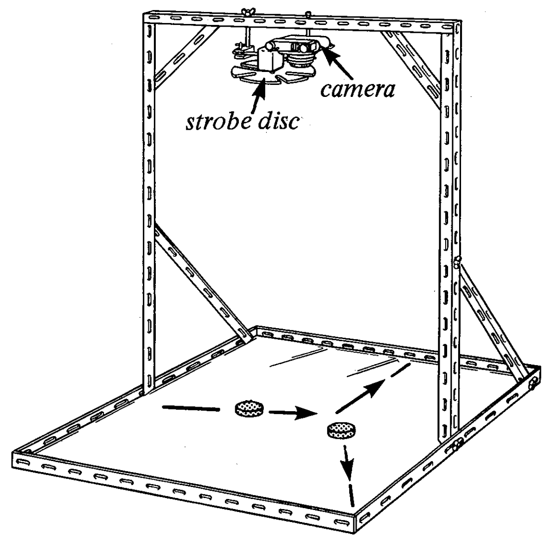
Demonstration 41
Multiflash photos of momentum interchanges

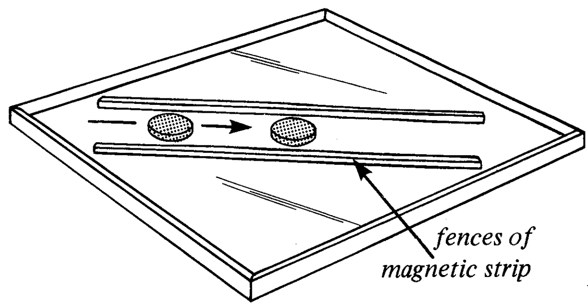
You may see photos taken of pucks colliding as they slide on a glass sheet. If so, take a copy of each picture.

a. One puck sliding alone. What does the picture tell you?

b. One puck makes a head-on collision with an equal puck at rest. What happens to the first puck's momentum?

c. A sliding puck makes a head-on collision with a



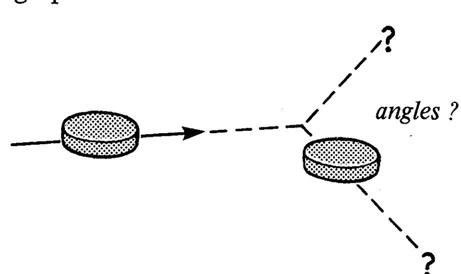


puck of double mass at rest. On your copy of the photo, mark the successive positions of the pucks and make measurements. Record the momentum of each puck *before* and *after* the collision. (Call the mass of a single puck M.) Was momentum conserved?

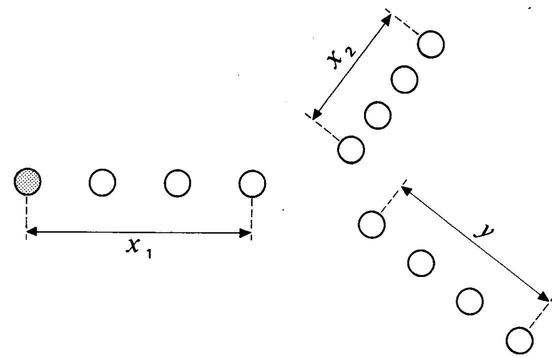
d. A sliding puck makes a glancing collision with an equal puck at rest.

(i) First just watch the event, in daylight. Do you see something special?

(ii) Look at the tracks on a multiflash photo. What interesting fact do you see on the pattern? If you succeed in finding an important scientific fact about this pattern, you should ask for the photograph of a nuclear event.



(iii) *(Advanced)* Mark successive positions of pucks on your photo as in the diagram, make measurements and record the momentum of each puck *before* and *after* collision. After collision there are two lots of momentum, because both pucks are moving. Each momentum is a vector (see the explanation ahead). So you should not add those two by arithmetic: you must use geometrical addition as in the diagram. Does the *resultant* momentum agree with the original momentum?



x_1, x_2, y, are distances travelled in three camera-ticks

NOTE ABOUT VECTORS

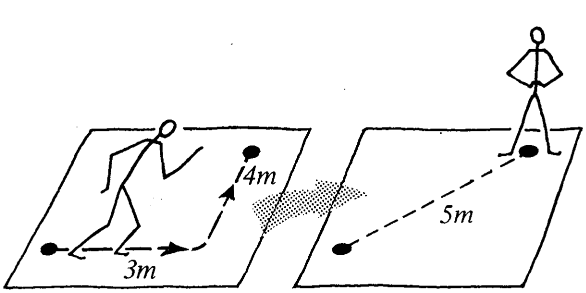
If you walk 3 metres due east on the floor, turn towards the north and walk 4 metres due north, what single trip would carry you straight from start to finish? If you know Pythagoras' Theorem, you can see from the diagram that the single trip is 5 metres. We call that the *resultant* of the two trips. And we call the trips themselves vectors (from the Latin to carry or draw). A vector is a measured quantity which has direction as well as size. You cannot combine trips of 3 metres and 4 metres and find a resultant unless you know their directions.

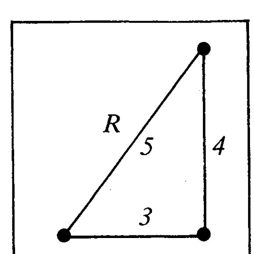
Experiments show that forces are vectors. If several forces of different sizes act on a body, pulling in different directions, we can find a single *resultant* force which will have the same general effect on the body, by combining the forces just as we combined the two trips.

Velocity is a vector. To know the velocity of something fully, you must know how fast it is moving *and* in what direction. SPEED tells us just how fast a thing is moving, without any statement about direction. So speed is not a vector (we call it a *scalar*). VELOCITY is a vector and we combine velocities in the same way as we combine trips to find a resultant. Because we often deal with velocities rather than speeds, we use the letter v for velocity or speed.

MOMENTUM is a vector. MASS does not have a direction but VELOCITY does, so mv is a vector with direction as well as size. To add together two lots of momentum you need to draw straight lines to represent them, of suitable size and with correct directions. Then you can join the start to finish and find a RESULTANT MOMENTUM.

If a collision is not head-on, then the colliding bodies move off afterwards in different directions. To use the Conservation of Momentum, you must remember each lot of momentum is a vector. Then if only one object is moving before the collision its momentum is a vector; and the momentum vectors of the objects after collision must add up by the geometry adding method to equal the original vector. This is an important matter in analysing cloud chamber-pictures of nuclear collisions.

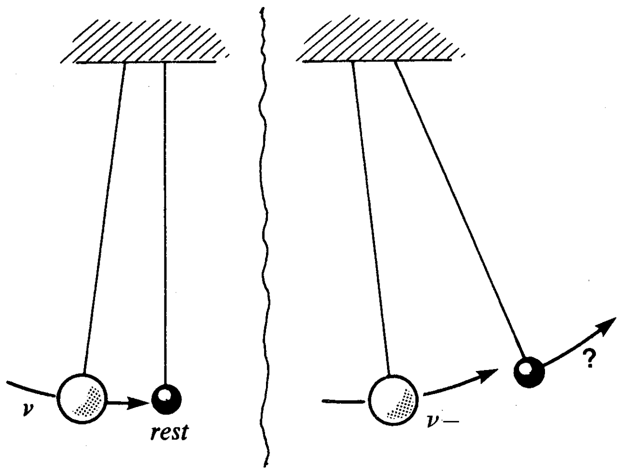




Pythagoras
$3^2 + 4^2 = 5^2$

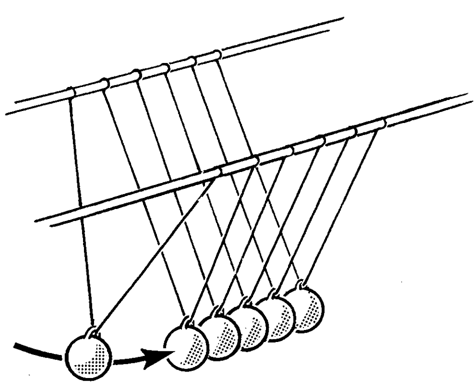
Demonstration 42
Collision between long pendulums
(OPTIONAL)

You may see the bobs of two pendulums colliding. These offer a quick review of the experiments with pucks.



Demonstration 43
A line of colliding balls

You may see this as a toy or in the lab. You could try several good experiments with it.



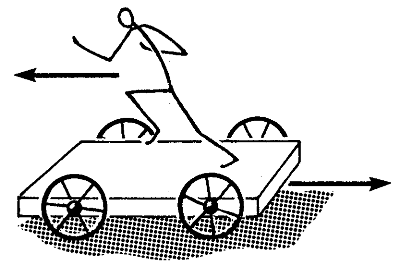
MANUFACTURING MOMENTUM

It is easy to produce momentum, you do so every time you start to walk or run. At rest you have none, in motion you have a lot. But that change is always at the expense of producing an equal amount of momentum the opposite way.

Think of a rocket: the exhaust gases come out with backwards momentum and the rocket gains forwards momentum.

If you start running, suddenly gaining momentum, it *seems* as if nothing gains any opposite momentum. Yet we believe the whole Earth does gain an equal amount backwards—but its M is so huge that the gain of v is too small to notice.

You can test this if you stand on a movable floor and start to run. (See the sketch.)



Does momentum ever appear from nowhere, or is it always created in equal and opposite amounts? We believe Conservation of Momentum is universal: momentum is *ALWAYS* produced in equal and opposite quantities.

Explosions give good illustrations.

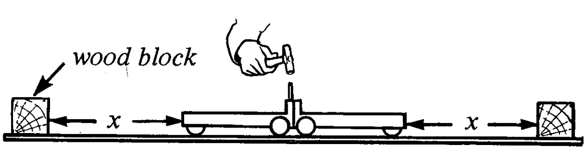
Try one or both of the following experiments.

Class Experiment 44
Explosion between two trolleys

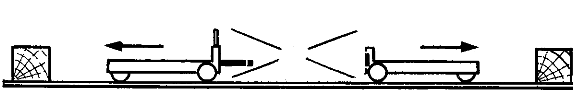
Start with two trolleys locked together at rest. Let a concealed spring push them apart. Compare their speeds. (The runway must be level, not compensated for friction, because one trolley runs each way.)

Instead of a timer and tape, place blocks of wood at suitable distances and watch the arrivals of trolleys. To prepare for the explosion push the buffer rod in against the built-in compression spring.

You can release the buffer rod by a smart tap on the vertical release post. Then there is an 'explosion' and the trolleys fly apart.



x, x, equal recoil distances



Start with the two trolleys in contact, half-way along the table or runway. Place a block of wood at each end of the table to act as a stop or marker.

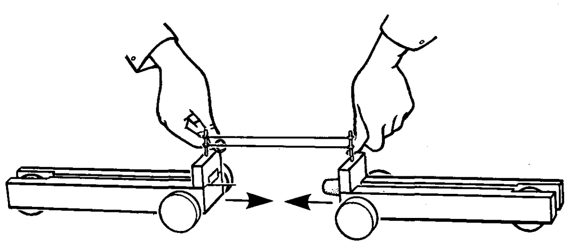
(i) Try an explosion with trolleys of *equal masses*. Place the blocks so that each trolley moves the *same distance* after the explosion, before hitting its stop. Watch to see if your prediction of *simultaneous arrival* is fulfilled.

(ii) Explosion with unequal masses, 2:1 Double one mass by borrowing an extra trolley and putting it on top of one trolley. Then repeat the experiment.

Decide for yourself how to rearrange the stops so that you expect the trolleys to hit their stops simultaneously.

Then guess at an answer to this question: 'Does momentum ever appear from nowhere, or is it always created in equal and opposite amounts?'

Class Experiment or Demonstration 45
'Inside-out' explosion with trolleys



Let stretched elastic pull two trolleys towards each other till they meet with a bang.

Arrange a *level* runway. (It must be level, not tilted to compensate for friction, because one trolley runs each way.)

Place two trolleys on the runway. Hold them some distance apart, with two elastic cords stretched between them, trying to pull them together. Release both trolleys at the same instant.

Install a large pin on one trolley and a cork on the other. Then the trolleys will stick together when they collide. So it will be an *inelastic* collision. Watch what happens.

Try the experiment again with one of the trolleys doubled by piling another one across the top.

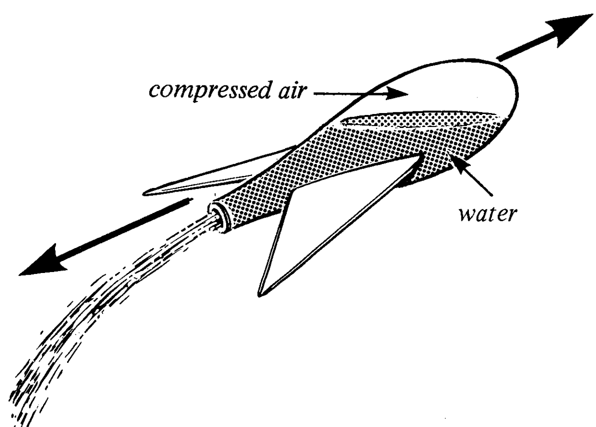
Recoil When a gun fires a bullet, the explosion drives the bullet out with large momentum, and the gun recoils with equally large momentum, moving the opposite way: momentum is not created, except in equal and opposite amounts. The recoiling gun soon comes to rest. Its momentum has not really been destroyed but only shared with the Earth.

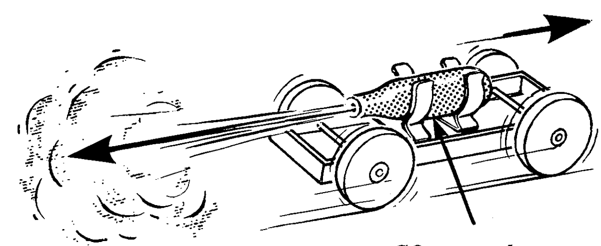
Rockets How is a rocket propelled? See a demonstration of a toy rocket if you missed it earlier.

Demonstration 16
Rocket

The toy rocket is partly filled with water, partly with air which is pumped in and compressed. Or, you may see a model driven by carbon dioxide from a capsule. The water or gas that shoots out of the hind end of the rocket carries away backwards momentum, so the rest of the rocket gains forwards momentum.

Discuss with your teacher the way in which gas molecules give a rocket momentum before they leave it.

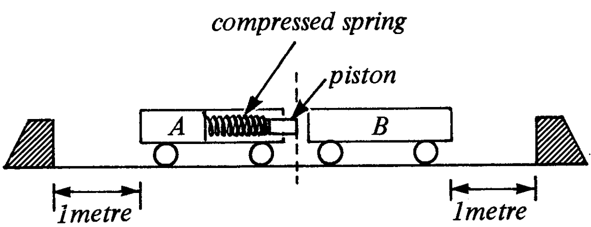




Progress Question

MOMENTUM IN EXPLOSIONS

23a. Suppose A and B have the same mass. They are both at rest.

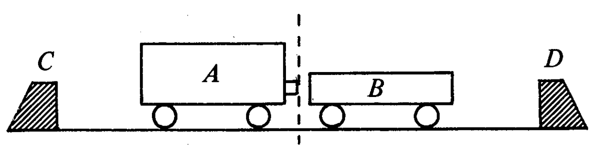


(i) Suppose you release the spring inside A. What do you see (and hear)?
(ii) Copy and complete:
Before the explosion the momentum of both trolleys is . . ? . . so the total momentum is . . ? . . .

After the explosion A has momentum to the (*/left/right/*) and B has momentum to the (*/left/right/*).

A's momentum is (*/bigger than/the same size as/smaller than/*) B's momentum, so A's momentum balances B's momentum, and we can say that the total momentum is still . . ? . . .

b. Now suppose A's mass is twice B's mass.

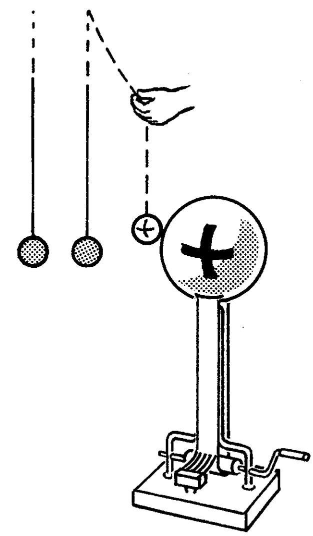


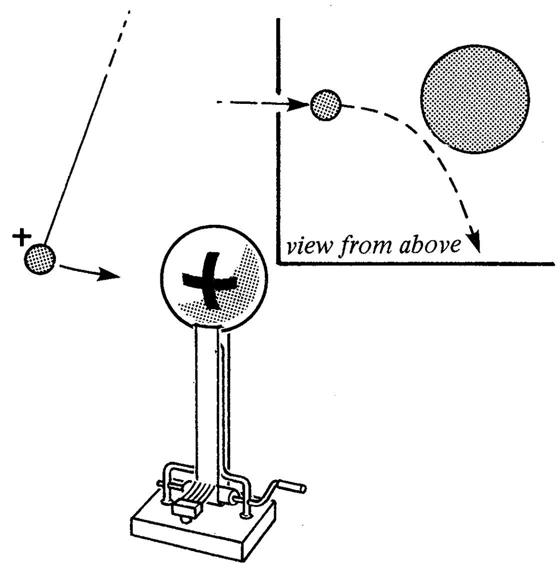
(i) When you release the spring, what do you see (and hear)?
(ii) How can you arrange A and B and the stopping buffers C and D at the beginning to show that, after the explosion, A's momentum balances B's momentum?

Demonstration 46
Collisions controlled by electric charges
(OPTIONAL)

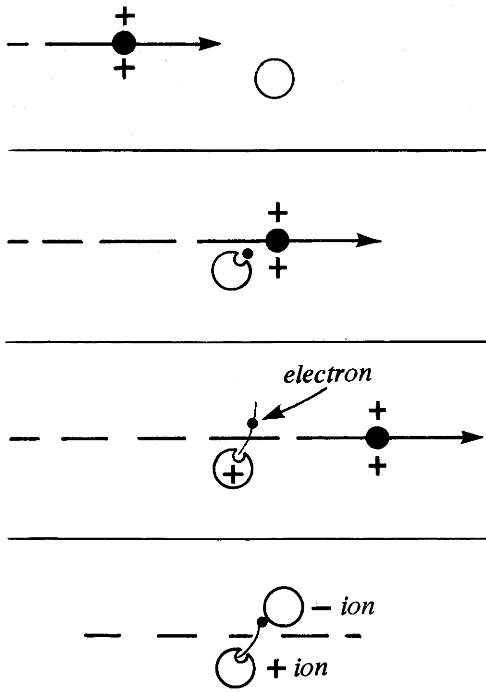
Run a Van de Graaff machine until the large ball has a large electric charge. Hang a table-tennis ball (coated to make it conducting) near the large ball, on a long nylon thread. Charge the small ball, by letting it touch the big one. Pull it to one side and throw it towards the big ball. Watch its motion.

This is a good model of a nuclear collision. The large ball might represent the nucleus of an atom of gold in a thin sheet of gold leaf. The small ball might represent a high-speed alpha-particle from some radioactive atom.





Nuclear collisions We look deep into the inner structure of atoms by sending in alpha-particles as probing bullets and watching how they are bounced off their path in rare nuclear collisions. Alpha-particles whizzing through gold leaf (illustrated by Demonstration 46) can tell us about atomic structure. (See *Pupils' Text 5*.)

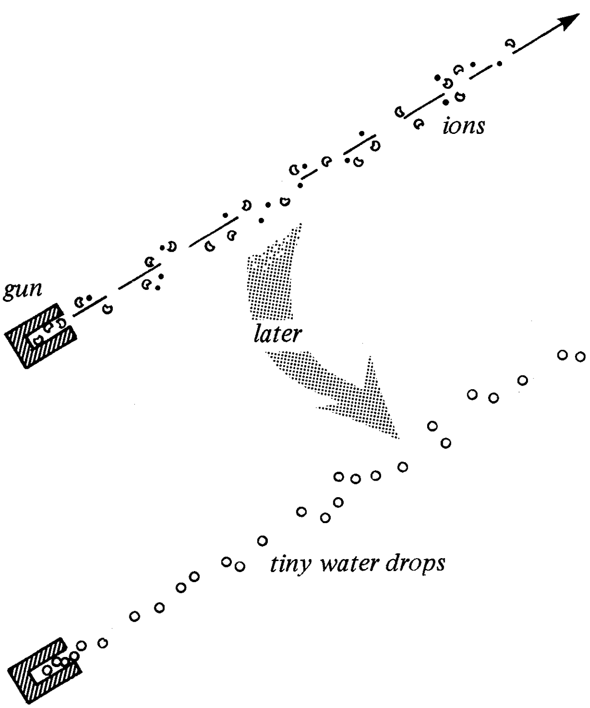


alpha – particle approaches atom

alpha particle, (He $^{++}$) pulls electron off an atom as it passes by

another atom catches the electron

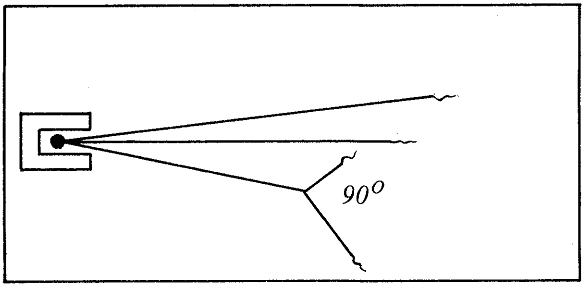
two ions (one +, one –) are left and water drops form on them



Alpha-particles whizzing through wet air in a cloud-chamber leave tracks of damaged air molecules on which tiny drops of water collect. You can see or photograph the line of water drops that shows the alpha-particles' track. Most of the tracks are straight but sometimes—very rarely—you see the result of a violent collision between an alpha-particle (itself a helium nucleus) and the nucleus of some other atom in the wet air. So two tracks continue from that collision, making a fork.

Measurements of the picture can tell you the momentum of the alpha-particle before the collision and of each nucleus after. Assuming the collision is elastic so that kinetic energy is conserved, we analyse a forked track—with momentum conserved as always—and we thus compare nuclear masses.

Look at some cloud-chamber pictures. You will see that the forks which show close nuclear collisions are rare. In fact, they are far more rare than that, because the pictures are lucky shots chosen from a long series of snapshots mostly without a fork.



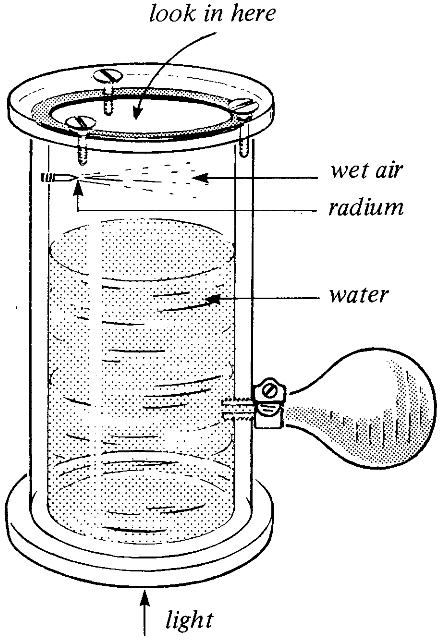
In one cloud-chamber picture, you will see the track of an alpha-particle make a 90° fork. The alpha-particle and the target nucleus that it hit bounce away after collision in directions that make a right angle.

This gives us a special piece of information, when we know that such 90° forks only happen when the alpha-particle is shot through wet *helium* gas. See the demonstration with two long pendulums carrying steel balls that collide; or discuss the algebra and geometry of this collision. This is an advanced problem for discussion with your teacher.

Exhibit 47
Cloud-chamber pictures

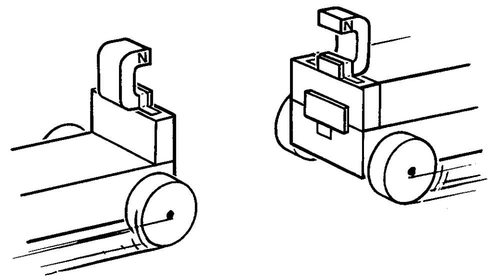
See these posted up on the wall, or look at them in *Pupils' Text 5*.

Demonstration 48
Expansion cloud-chamber



Watch closely and see the straight tracks. If they look crooked, that is because small air currents dragged them out of shape before you had time to look.

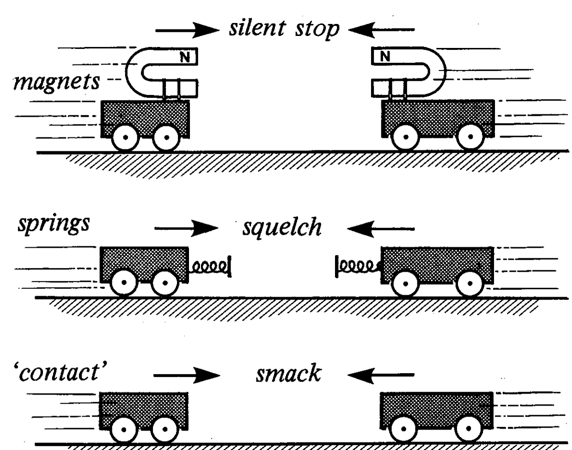
Demonstration 49
Silent collision with magnets: head on impact of trolleys

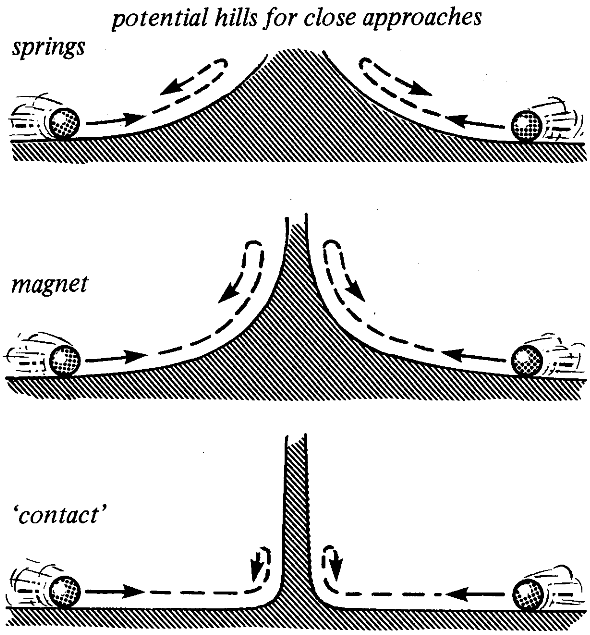


Two toy wagons on a model railway are equipped with strong horseshoe magnets in such a way that they repel. Watch a collision. This is like a collision between individual molecules or atoms.

FORCES IN COLLISIONS: WHAT IS 'CONTACT'? *(OPTIONAL NOW)*

In collisions between magnets on wagons, the colliding bodies do not seem to touch each other, but they are brought to rest and then pushed away by strong magnetic forces when they are very close. You can see this happening with spring buffers. In common collisions, such as two hard wagons colliding or a bat hitting a ball, you can see them hit and hear the noise of 'contact'; but is that really different from the quiet pushing of magnets?





When atoms (or molecules) are far apart (as molecules in ordinary air are) they exert practically no forces on each other. As they approach they attract a little. When they are much closer they repel. When closer still they repel strongly.

If you had 'super microscope' spectacles and could watch the atoms of the colliding bodies, you would see opposing atoms being moved closer and closer to others, being repelled more and more strongly, until the colliding bodies were at rest, and then the same repulsions pushing the colliding bodies apart.

What you see with two magnetic pucks is not an accurate model of atoms repelling but it does show the way in which atoms and molecules collide. There is no such thing as atoms actually *touching* each other—not even when you think you are pushing your finger and thumb together until the atoms touch. All that is really happening is stronger and stronger repulsions are building up as you push them closer and closer together. The repulsions produce pressures on nerves in your finger and thumb, and the nerves send messages which you call 'touching'.

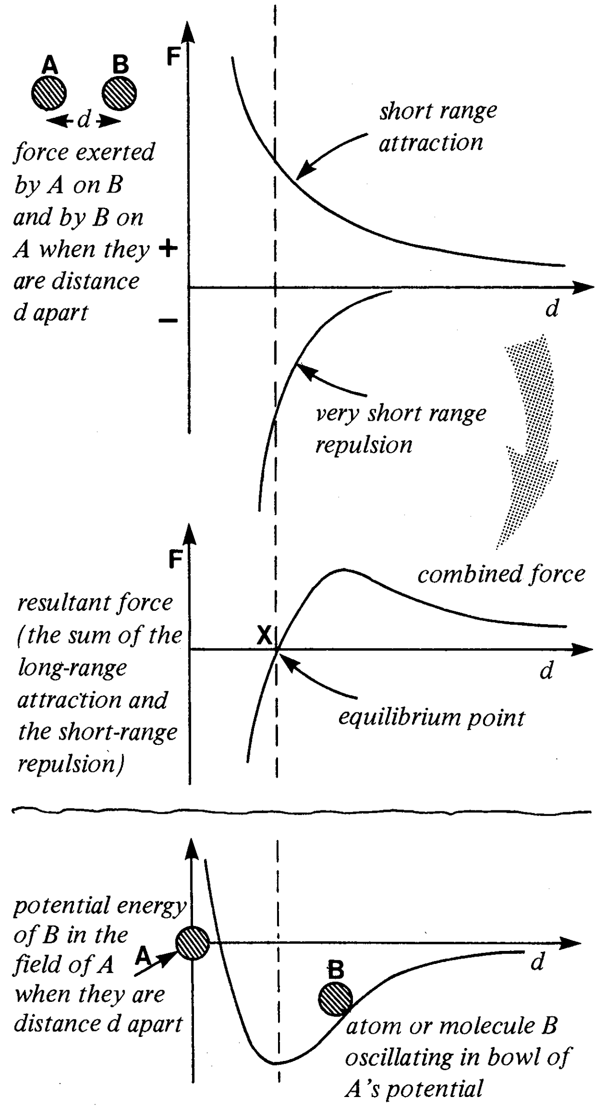
To illustrate collisions in a different way, imagine the wagons replaced by rolling balls. And, instead of mysterious repulsive forces, let the balls roll up a hill of suitable profile. Note that for the contact smack the hill is very sudden and steep; but it is *not* a *vertical* wall.

(These are called potential hill diagrams because the heights on the hill represent the potential energy stored during the collision in the spring—or in magnetic fields or in the force-fields of atoms.)

Such potential hills are useful in discussing collisions in nuclear physics.

We may sketch graphs of the forces.

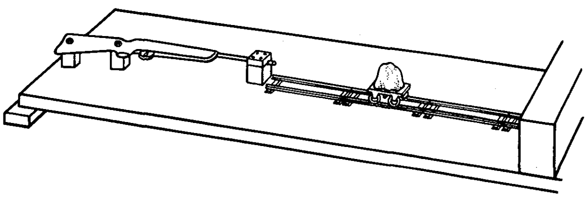
ATOMS OR MOLECULES EXERT FORCES



USING MOMENTUM CONSERVATION

Rifle bullet The speed of a rifle bullet may be measured by firing it into a target so that the bullet's momentum is shared out among target and bullet together. We assume that Conservation of Momentum holds for this event; then we can calculate the original speed of the bullet from a measurement of the target's slow motion afterwards. See such a measurement made with a bullet from an air rifle.

Demonstration 50
Speed of rifle bullet measured by momentum-exchange



Fire a bullet into a small railway wagon on friction-compensated rails. Load the wagon with clay. The bullet stays inside the clay and does not go right through.

Then trust Conservation of Momentum for this collision.

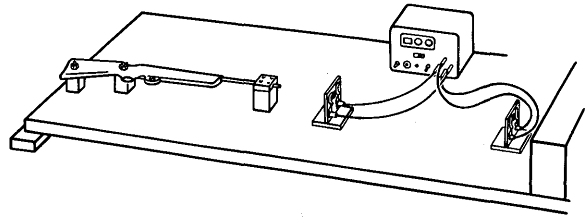
Before the bullet hits the wagon it has a lot of momentum because it is moving fast; and the wagon at rest has none. After the smash, the bullet and wagon continue as a single object with much smaller speed because there is a much bigger mass. But you may assume that the total momentum must be the same as before. (That is, unless the Earth has stolen some momentum—we can avoid this by friction compensation of the track).

Suppose the bullet of mass m was fired with muzzle velocity V and the bullet entered the wagon of mass M and the wagon and bullet then continued with constant speed v.

Assuming Conservation of Momentum is true, $mV+0 = (M+m)\times v$. That is an equation which enables you to measure the speed of a bullet without ever timing anything moving so fast. You only need to time the slow motion of the wagon (containing the bullet) afterwards.

Demonstration 51
Another way to measure a bullet's speed

Instead of sharing out the bullet's momentum and assuming conservation, we can measure the bullet's speed directly by timing its flight over a known distance. See the sketch.

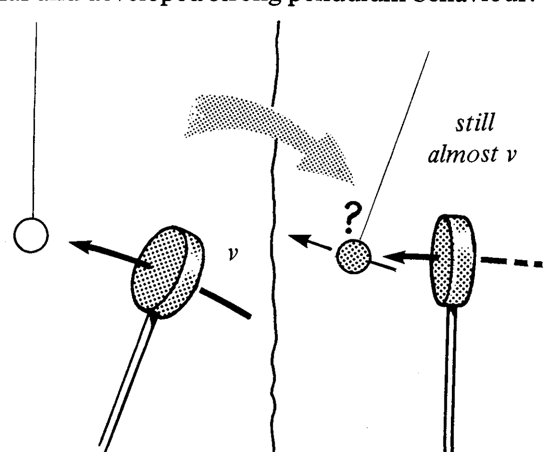


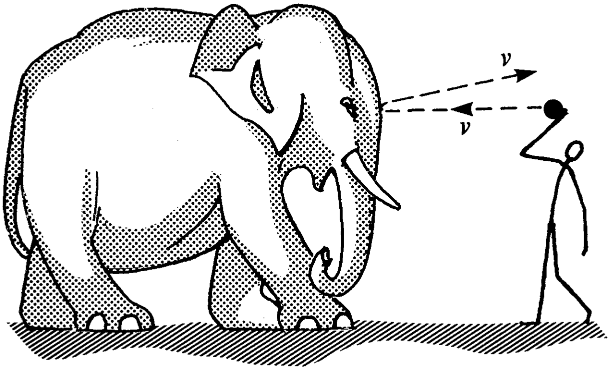
The results of the two experiments may agree quite closely. If they do, that gives some support to the principle of Conservation of Momentum.

SPECIAL ADVANCED PROBLEM (OPTIONAL)

When a massive bat hits a ball, how fast does the ball move? If a moving object—ball, puck, trolley—makes an elastic collision head on with a stationary object of the *same* mass, it stops, and the target object moves ahead with the speed that the missile had. But when a moving bat hits a stationary ball of *much smaller* mass, things are quite different. *The ball flies ahead just twice as fast as the bat.* Is this statement true? There are two ways of finding out:

(1) *Arrange an experiment* Hit a stationary table-tennis ball with a massive bat and examine the motions by taking a multiflash photo. Hang the ball by a long thread from the ceiling and photograph the motion before the ball has swung far and developed strong pendulum behaviour.

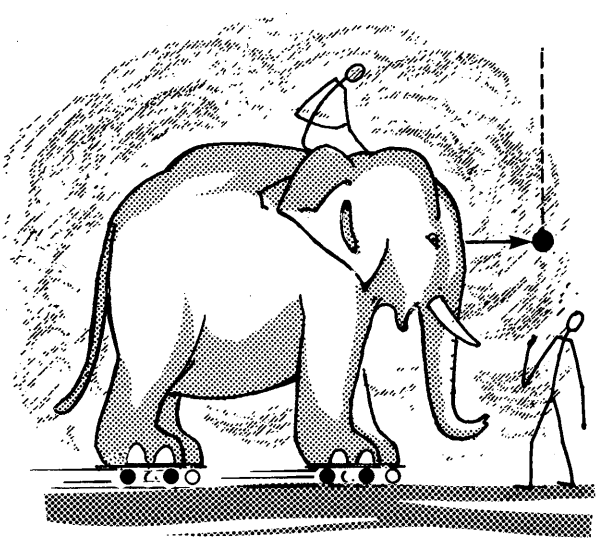




(2) *By a theoretical argument* Imagine a collision between a table-tennis ball and an elephant. First throw the ball straight at the stationary elephant's forehead at 5 metre/second. The ball will bounce back with speed almost 5 metre/second (common-sense knowledge). If the elephant has ideal roller skates on his feet, he will recoil very, very slowly, barely noticeably.

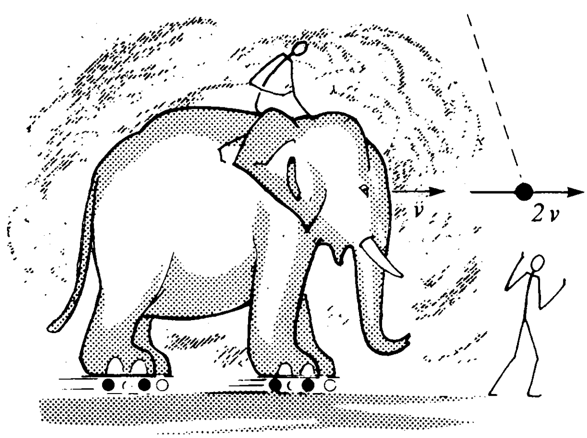
Now let the elephant move and hit a stationary ball. Suspend the ball in mid-air by an imaginary thread from the sky and let the elephant glide on roller skates towards it at 5 metre/second. When the elephant's forehead hits the ball, what motion will the ball take? This is the problem we are trying to solve. It seems difficult to answer this until we try the following trick.

Imagine the elephant surrounded by fog, so that you, who are riding on his back, have no idea how fast he is moving along the road. (Pretend the elephant is moving so smoothly on his roller skates that you know nothing at all about his motion.)



Then in the fog you see a table-tennis ball. You think the ball is moving straight towards you, at 5 metre/second. You still do not know that you and the elephant are gliding along. So, thinking the ball is rushing towards you at 5 metre/second to hit the elephant's forehead, you know what it will do. It will bounce away forwards at speed 5 metre/second from the front of the elephant.

Now forget about the fog and imagine your partner standing on the ground watches the same event from outside. He sees the ball at rest until the elephant hits it. Then the ball bounces away from the elephant's forehead at 5 metre/second *relative to the elephant*. But he also sees the elephant himself moving 5 metre/second. How fast will your partner see the ball move, from his standpoint on the ground?



This is what we call a 'thought experiment' a useful method in physics theory. Of course you cannot predict the facts of real nature just by arguing with nothing to help you but logic; but our argument contains a concealed piece of experimental information, the general rule that Newton's Laws of Motion—and all mechanical events that they describe—have the same form to a moving observer (you on the elephant) as to a stationary one (your partner on the ground). This is the first form of relativity; and you know it is reasonable because you know that experiments in a smoothly running railway train happen the same way as in a train that has stopped.

This result, that the ball moves away twice as fast as the bat, is true of table-tennis balls, roughly true of cricket balls, tennis balls and golf balls, and of a railway engine shunting a light wagon.

When gas molecules hit a *stationary* piston head on they bounce back, on the average, with equal speed in the opposite direction. But when they hit a *moving* piston that is approaching them they bounce back faster in the opposite direction with a *gain of speed* twice the speed of the piston. Think what that means for the air in a bicycle pump as you push the piston in.

CHAPTER 5

KINETIC ENERGY

Conservation of P.E. + K.E.

MOTION ENERGY: ITS MEASUREMENT, CALCULATION, AND USES

Supplies of energy and uses of energy are very important. You will hear much discussion of energy in business, in government planning, in world politics.

Many people nowadays ask for fuller knowledge of energy. This chapter, together with Chapter 9, will help you to gain such knowledge for the future.

This is a chapter about *motion energy*, with its professional name KINETIC ENERGY. You will see how the kinetic energy of a moving object can be calculated from the object's mass and speed. Then you can use that to answer questions such as these:

How far will a car travel while the brakes are bringing it to a stop?

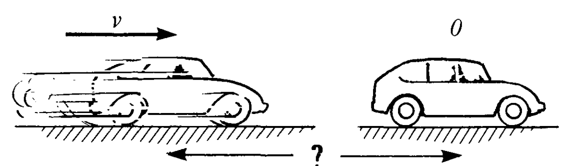
How high will the pendulum swing after being given a push?

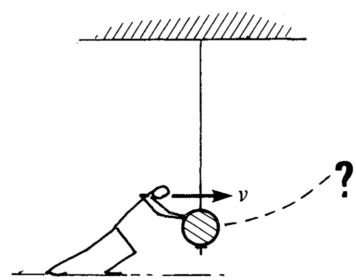
How much of its energy does the bullet lose when it hits a target?

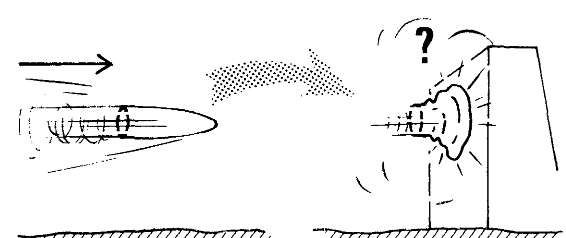
When air is made hotter, what happens to its molecules?

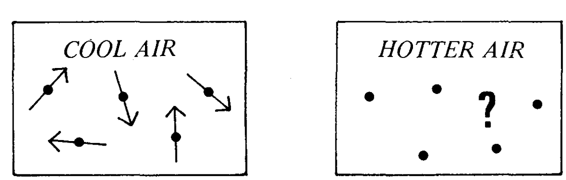
When electrons are driven out of an electron-gun powered by a 200-volt battery, how fast are they moving?

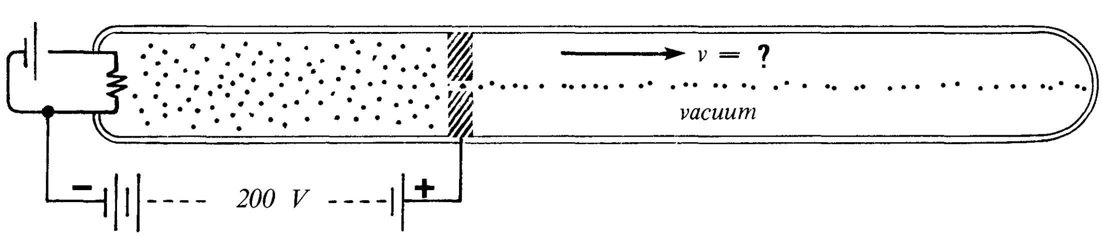
And you will use your new knowledge of kinetic energy when you read Chapter 9 on Energy in general.









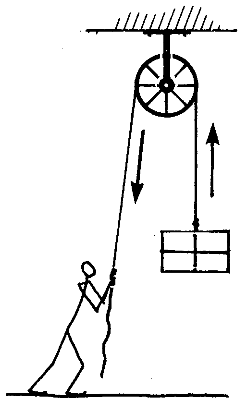


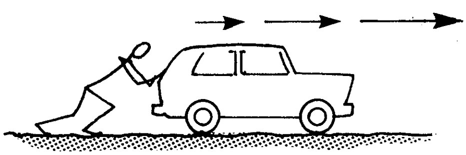
†DISCUSSION FOR CATCHING UP: DESCRIBING ENERGY

†Fuel and useful jobs If you learnt about energy in an earlier year, you found it described as something which we get from fuels, including food. It seems to be stored in fuels.

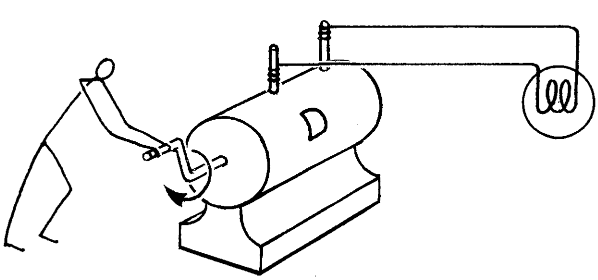
Energy does useful jobs for us when it changes to some other form. 'Useful jobs' are jobs which need some fuel. At first sight, that looks like a stupid description, talking in a circle! Yet you will find it helpful in learning about energy.

Useful jobs that need fuel

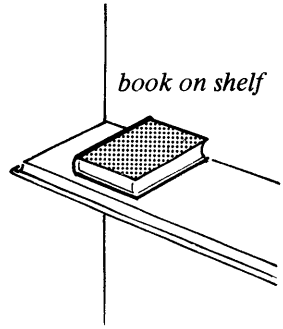


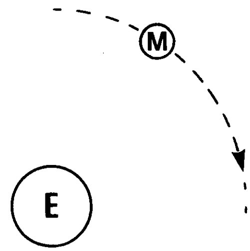


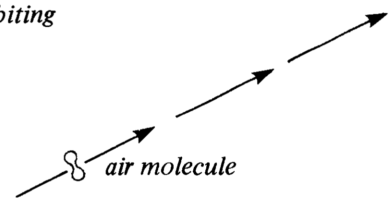
Hauling up a heavy load against gravity is a useful job. So is pushing a car and making it move faster. And so is driving a dynamo to light electric lamps. All these need fuel for an engine, or food for a person or an animal.



Jobs that do not need fuel



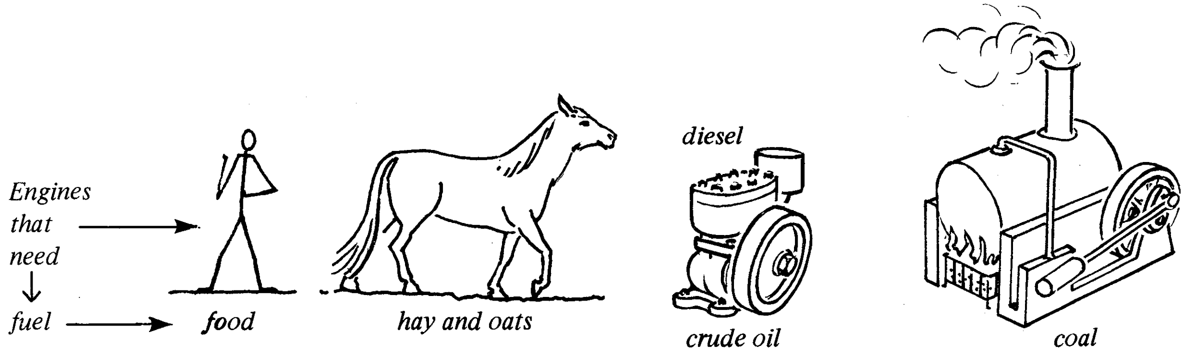




When a shelf supports a load of heavy books, it needs no fuel; it does not draw upon a supply of energy. A gas molecule, flying along far out in space needs no fuel to keep moving at constant velocity. The Moon needs no continuing supply of energy to keep it orbiting round the Earth. Yet each of these things already has some energy: the bookshelf and books are high above the floor, so they have an extra store of gravitational potential energy (up-hill energy). The flying molecule has some kinetic energy *(motion energy)*. The Moon has kinetic energy of its orbital motion and some potential energy on account of the Earth's gravitational field.

† Forms of energy Here are names for some forms of energy (with simple unofficial names in brackets):

GRAVITATIONAL POTENTIAL ENERGY, P.E. (up-hill energy)
KINETIC ENERGY, K.E. (motion energy)
STRAIN ENERGY, P.E. (springs-energy)
RADIATION ENERGY (light energy), which is known to be the energy of electromagnetic waves of every kind—X-rays, ultraviolet, visible light, infra-red and radio waves.

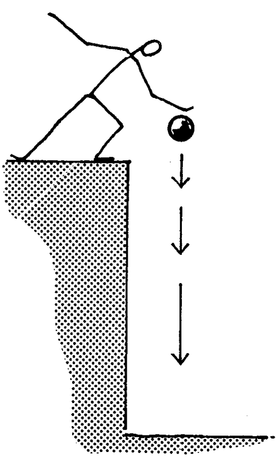


ELECTRICAL ENERGY, stored between the plates of a charged capacitor; carried by electric and magnetic fields surrounding a circuit; or stored in the magnetic field of a magnet . . .

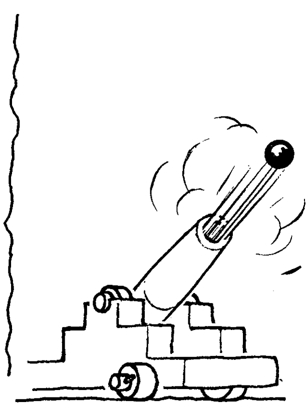
CHEMICAL ENERGY, stored in a firework, in a battery, or in food—and thence in our muscles.

MOLECULAR ENERGY, in the force-fields between molecules—involved in melting and evaporation.

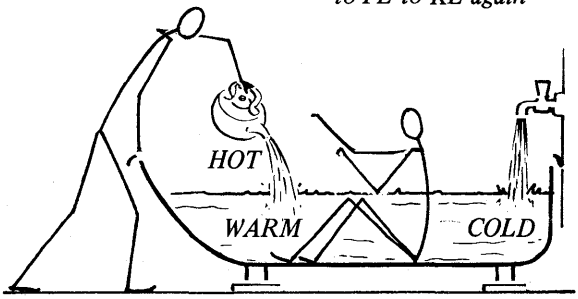
NUCLEAR ENERGY, involved in radio-active changes.



gravitational PE to KE



chemical energy to heat to KE, to PE to KE again



heat energy is shared out

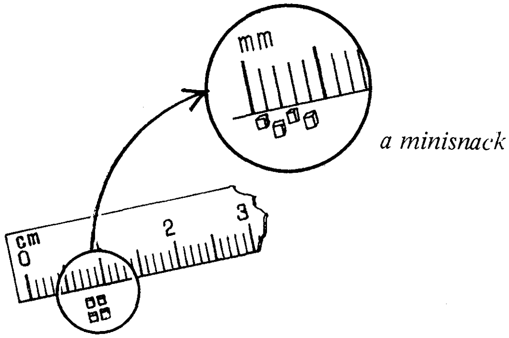
One of the commonest and most important of all forms of energy is:

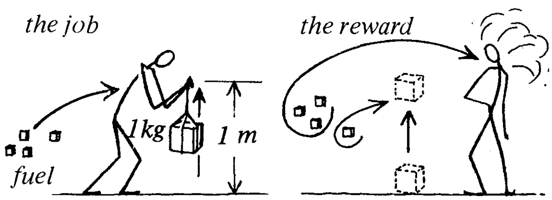
HEAT OR THERMAL ENERGY. We are soon going to discuss heat as a form of energy. That is the very important story in Chapter 9.

†**Energy-changes and useful jobs** Energy does not disappear when a useful job is done: it only changes from one form to another; or, sometimes, it just moves from one place to another. When you let a stone fall, its gravitational potential energy changes into kinetic energy. When a bullet is fired in a gun, chemical energy of the explosive turns into heat energy of gases that are formed and some of that is then re-organised into kinetic energy of the bullet. When you pour in a kettleful of boiling water to warm up a cold bath, you must move some heat energy from the water in the kettle to the larger amount of cold water in the bath. (But could you move the heat energy back again?)

A simple job at a simple cost: one 'minisnack' Lift a heavy book from the floor to a window ledge. Suppose you have thus raised 1 kilogram through 1 metre. You have used a little of your own store of 'fuel', drawing on chemical energy—or breakfast energy as we might call it. Even though you do not notice it, you are then a little tired: and you will need a tiny bit more food presently, to make up for the fuel you have used.

How much food do you need to re-fuel you after you have hauled 1 kilogram up 1 metre? Put a pinch of granulated sugar on the table. Select four crystals of average size. That will be about $2\frac{1}{2}$ milligrams of sugar altogether; and they will give you the food energy you need for re-fuelling. We give that a nickname, a *minisnack*.





One of the four grains of sugar provides enough energy to pay for raising the kilogram one metre; but your muscles are only about 25% efficient for rapid movements. The rest of the food energy you use appears as waste heat in muscles. You convert energy that the other three grains replace into waste heat.

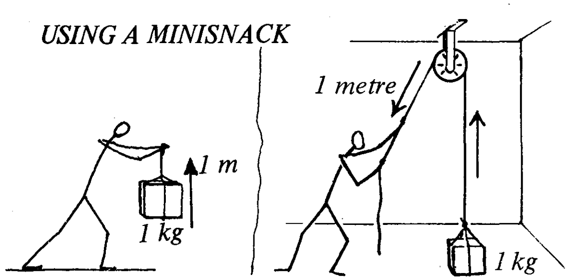
Question

1. A 50-kilogram pupil climbs a staircase to the top floor of a house, 4 metres higher up altogether.

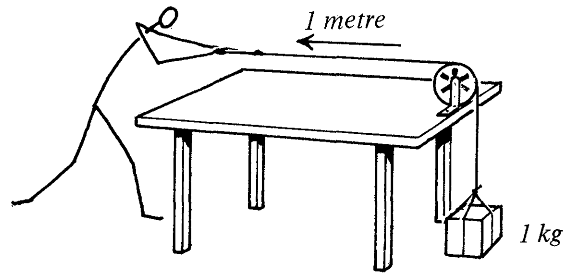
a. How many minisnacks does he or she need for re-fuelling?

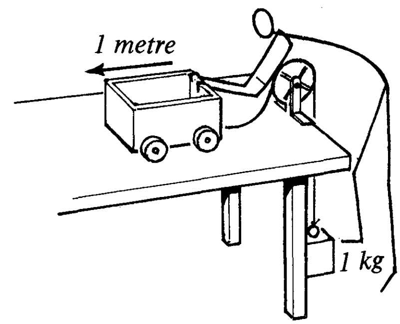
b. Taking one minisnack to be $2\frac{1}{2}$ milligrams of sugar (0.0025 gram) calculate how much sugar, in grams, that re-fuelling needs.

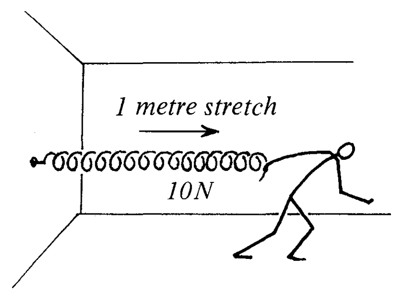
c. Small cubes of lump sugar are about $2\frac{1}{2}$ grams. How many climbs like this climb could one lump provide for?

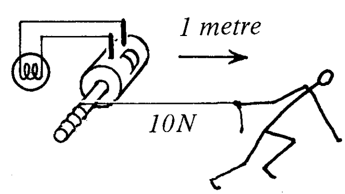


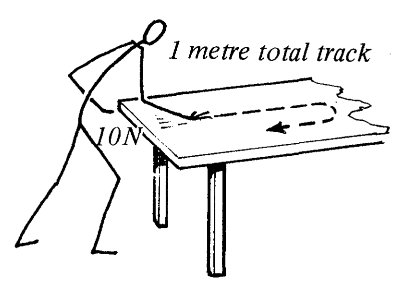
USING A MINISNACK



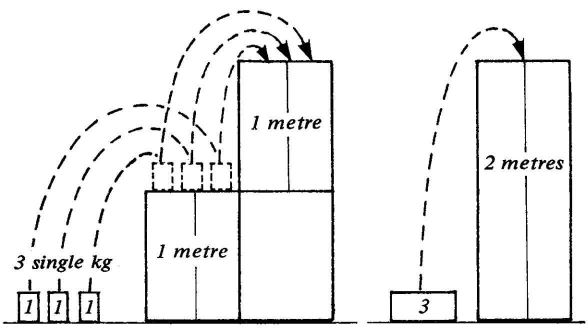








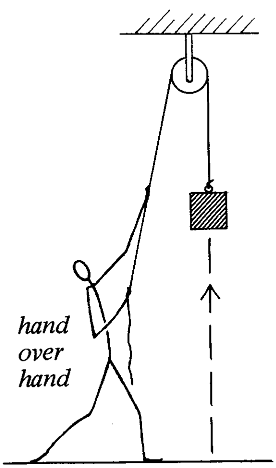
†**Counting energy-changes** Watch a useful job being done by an energetic man. He pulls a load of three kilograms from the floor to a shelf two metres higher up. He uses a little of his own store of chemical energy. He will need a tiny bit more food to make up for the fuel he has used. Six minisnacks would do—a chip of sugar the size of a grain of wheat or rice.



Suppose the man does the job in stages: one kilogram from floor to shelf, then another kilogram from floor to shelf, and one more kilogram from floor to shelf. Will that cost him the same amount of food energy in the end? People have tried experiments on this and find that it does take the same energy if it is done in stages by a man (or by an engine). The man needs just as much extra food or fuel if he does the job in three stages.

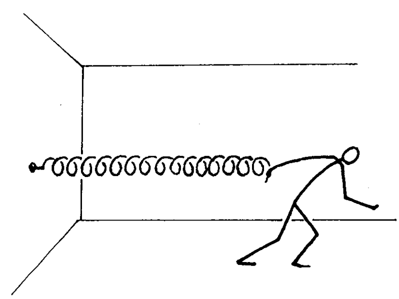
He could do each of those three lifting jobs in two stages, raising each kilogram one metre, then another metre higher.

His use of food would be the same whether he does the job in 6 stages* or all in one move—six minisnacks altogether either way.



We may call each of these six jobs of one-kilogram-hauled-up-one-metre by a temporary name, one kg · metre job. That is *NOT* a modern unit of energy change: it is not even universally constant in size and you will have a better unit soon. But for the moment it will serve to show how we can measure energy-changes.

Then to raise the 3-kilogram load from floor to shelf two metres above, the man must take 6 kg · metre jobs from chemical energy in his muscles, across to some energy stored up by the raised load. We say he has transferred that energy *FROM* chemical energy *TO* gravitational potential energy.



Instead of using his muscles to lift a load, the energetic man could use them to stretch a spring. There you could see quite clearly where the energy goes. It goes into the stretched spring which stores it. The spring could give it back, to haul up some load for him and thus do a useful job in turn.

We talk of energy being stored up by the lifted load**, or in the stretched spring. In each case it is a store of this marvellous thing, energy, which enables us to do jobs.

* He might waste still more food energy in working extra muscles if he bends down several times; and it might cost him more to stretch up for the higher half of the raising. However, we can give him a simple pulley and rope so that he can pull hand-over-hand in many short pulls with his arms always in the same position.

** In the case of the lifted load, the energy it gains is somehow stored by the gravitational field; but it is difficult to say where the store is. In the case of the stretched spring, the energy is stored in the electrical force fields of the atoms of the spring. In the case of explosives and fuels and foods, energy is stored in electrical force-fields of atoms and molecules.

MEASURING ENERGY-CHANGES: WORK

Energy-transfer It is the *transfer* of energy that is the important thing; so we need a way of measuring it. You have just seen a rough way of measuring a transfer in unit jobs, each of one kilogram raised one metre; but we need a more general scheme.

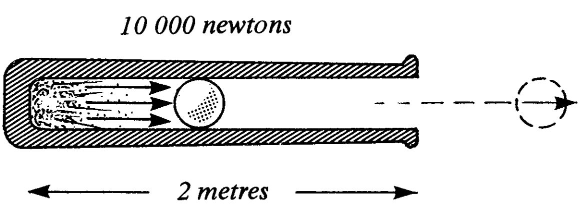
When we counted those 6 unit jobs we were multiplying 3 kilograms by 2 metres. But we really meant the *pull of the Earth on 3 kilograms* multiplied by *2 metres*. We were really calculating the energy-cost by:

FORCE OF MAN'S PULL ×
VERTICAL DISTANCE MOVED BY MAN'S HAND

Proper units for energy-transfer It would be better to measure the pull, in proper units for force: that is, in *newtons*. Then, the energy-transfer will be expressed in *newton · metres*.

These are much better units because they have the same value everywhere in the universe. We shall use these units for every form of energy.

Work When we move some energy from chemical energy in muscles to potential energy for a raised load, or to strain energy stored in a spring, we calculate the shift or *transfer* of energy by multiplying FORCE by DISTANCE MOVED. We call the result WORK.



WORK = energy transfer
= 2 × 10 000 newton·metres
= 20 000 joules

You will find it easier if you avoid using the word 'work' as a name for some particular kind of energy (as some scientists prefer to do). Use it only as a way of stating *how much energy is transferred*. The transfer must be *FROM* one form *TO* another. Therefore we talk about energy changes like this:

> 'The explosive in a cannon drives a bullet with FORCE 10000 *newtons* along a barrel of LENGTH 2 *metres*. The WORK is 10000 *newtons* × 2 *metres*, a transfer *FROM* chemical energy *TO* kinetic energy.'

If you always say *FROM* and *TO* like that in describing energy-changes you will be quite safe. You will not make mistakes about + and − signs. You will never have to label the WORK + or −. In fact, when you treat WORK in this way, it should not have a + or − sign because it is an energy-change which is positive for one kind of energy and negative for the other.

That is rather like a postal order for 50p which Jones sends to Brown. It is not money itself but it makes a money transfer *FROM* Jones *TO* Brown. It is not + or − itself but its effect on Brown's money is +50p and on Jones' money −50p. And so with WORK: we do not say + or − but always say what the energy comes *FROM* and what it goes *TO*.

†**Calculating work** Wherever there is a force that pushes or pulls something along through a distance, we calculate the WORK by multiplying FORCE (measured in *newtons*) by DISTANCE (measured in *metres*). Then the result is measured in *newton · metres*; and we give them a short name *joules*.

Sometimes there is an energy-change for which you cannot find a measured force and distance. Then you may have to use roundabout methods, converting to another form in a measured change. And then you should trust our idea that energy never gets created or lost, never appears from nowhere and never vanishes unaccountably.

CONVERSION EXPERIMENTS WITH KINETIC ENERGY

You can learn how to calculate the kinetic energy of a moving object from measurements of its mass and speed. But before that you should see some illustrations of kinetic energy changing to or from other forms of energy. These are qualitative experiments without any measurements, to give you a feeling for kinetic energy. See them as demonstrations, or try them yourself.

Demonstration 53
Kinetic energy: qualitative demonstrations

See some of the demonstrations sketched.

a. *Kinetic energy from chemical energy in muscles.* Put a trolley on the table and give it a push.

b. *Kinetic energy from the potential energy of a falling load.* Place a trolley on a runway and pull it with a thread that runs over a pulley to a small load.

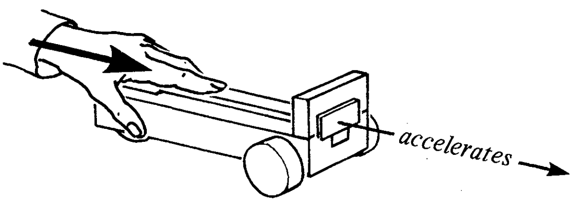
c. *Elastic potential energy changing to kinetic energy*. Make a catapult for the trolley as in the sketch. Load it. Let it push a trolley.

d. *P.E. to K.E. to P.E., etc.* Arrange two catapults, one at each end of a level runway and watch them sling a trolley to and fro.

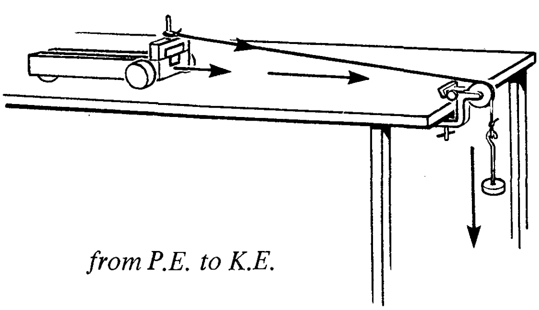
e. *Collision with magnets*. Equip two trolleys with magnets arranged to repel. Give them kinetic energy, running towards each other. Watch the changes of energy.

Experiment 54
Qualitative experiments on kinetic energy
(OPTIONAL)

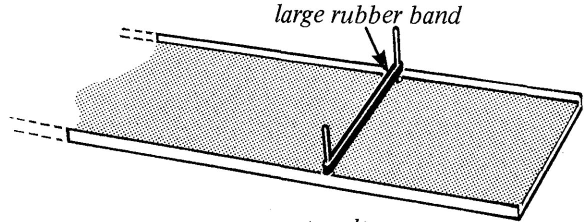
If you like, try some of the experiments of Demonstration 53 yourself.



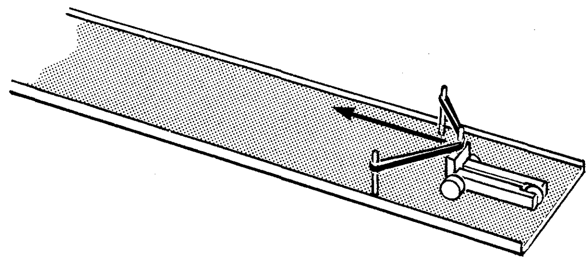
from chemical (food) energy to K.E.

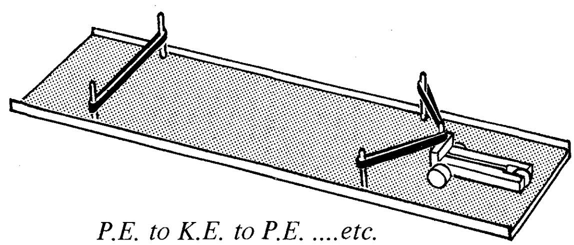


from P.E. to K.E.

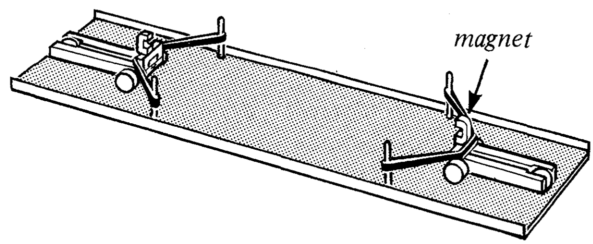


catapult





P.E. to K.E. to P.E. ....etc.



Progress Questions

ENERGY TRANSFERS

2. Describe in a few words, or by a sketch, an experiment you have done or seen in which:
(i) strain energy (springs-energy) changes to motion energy;
(ii) motion energy changes to strain energy and back to motion energy;
(iii) strain energy changes to motion energy and back to strain energy.

ENERGY-TRANSFERS: WORK

When you lift a load of books, energy is transferred from chemical (food) energy to up-hill energy. This energy-transfer happens when a force (your lifting force in this case) moves an object up through a distance.

In cases like this, where a force pushes or pulls through a distance, you can work out the amount of energy transfer by multiplying FORCE by DISTANCE.

The product FORCE × DISTANCE is very useful, because it measures energy-transfer: so we give it a name 'WORK'.

3a. Copy and complete:

When you lift a load, you transfer energy *FROM* . . ? . . energy in . . ? . . *TO* . . ? . . energy.

b. You lift a load of 2 kg through 3 metres. The Earth pulls 10 newtons in every kilogram, so it pulls 20 newtons on the load.
(i) What is the FORCE you lift with?
(ii) What is the DISTANCE the force moves?
(iii) So how much is the WORK?

c. Now copy and complete:

When you lift a load of 2 kg up through 3 metres, the WORK is . . ? . . newton·metres (joules) and the load gets . . ? . . joules extra up-hill-energy.

d. You then let the load fall. How much motion energy does it have just before it hits the floor?

e. What happens to that energy next?

WORK

4. A load of 50 kg is lifted through 2 metres.

a. What FORCE is used to lift it? (The Earth pulls 10 newtons on each kg.)

b. How much is the WORK?

c. How much ENERGY is transferred to up-hill-energy (P.E.)?

d. Suggest where this energy could come from.

5. A 70-kg man is hauled up 10 metres in a lift.

a. What FORCE is needed to haul him up? (The Earth pulls 10 newtons on each kg.)

b. How much is the WORK in lifting him?

c. How much extra up-hill-energy does he get?

d. Where does this extra up-hill-energy come from?

6a. How much is the WORK when a 2-newton force moves an object a distance of 2 metres?

b. How much is the WORK when a 4-newton force moves an object a distance of 2 metres?

c. How much is the WORK when a 50-newton force moves an object a distance of 3 metres?

7. The engine in a car is working full tilt. And the driving force on the car is 20000 newtons. The car travels 100 metres.

a. How much is the WORK?

b. How much energy is transferred for this, from the car's fuel?

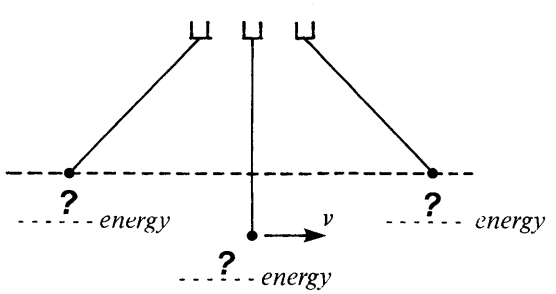
c. Suppose all of that energy is transferred to motion energy of the car. How much motion energy is given to the car?

USEFUL JOBS AND FUEL

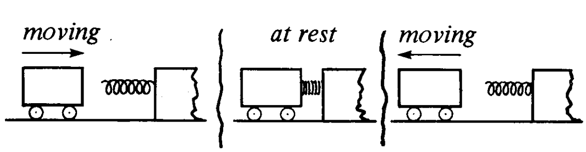
††**8.** Here is a list of ten 'jobs' done by living and non-living things. Which of these is a 'fuel-using' job, and which requires no fuel? (For your answer, write two lists: a list marked 'use fuel', and a list marked 'no fuel'. Just use the small letters that are printed before each job.)

a. A man hoisting a sack of potatoes off the ground onto his back.
b. Stone pillars holding up a roof.
c. Air molecules in motion, in a room at constant temperature.
d. A piston being driven in and compressing a gas.
e. A man winding up the spring of a clock.
f. A carpenter's clamp tightly holding two pieces of wood together.
g. A refrigerator keeping things cold all through a hot day.
h. Water keeping a boat afloat.
i. A bus moving along a level road on a windy day.
j. A man, or an electronic computer, doing arithmetic sums.

ENERGY-CHANGES



†† **9.** The figures show three positions of a swinging pendulum bob, the extreme positions on either side, and the central position where it is moving fastest, with speed v. Each figure is drawn to represent either *kinetic* energy or *potential* energy. Copy the figures and write in the correct word in each case.



10a. Copy each of the three figures above and label the energy either *kinetic* (motion) energy or *strain* energy (springs-energy).

b. Then write two or three sentences describing the energy-changes that take place when 'truck hits buffers, and rebounds'.

CONSERVATION OF (P.E.+K.E.)

11a. A 5-kilogram load, situated in the Earth's gravitational field, is raised a vertical height of 3 metres.

(i) What is the energy-transfer (WORK) in joules?
(ii) How much potential energy, in joules, is gained?
(iii) The load is then allowed to fall back through the distance of 3 metres. How much kinetic energy, in joules, does it gain?
Formulae:

$$\text{kinetic energy} = \tfrac{1}{2}mv^2 \qquad v^2 = u^2 + 2as$$

Here u will be zero, since the load starts from rest, and $a = g$, the acceleration of free fall (10 metre/second^2). The gravitational field strength, g, is 10 newton per kilogram.
(iv) In *(iii)* potential energy has transferred to kinetic. Is the P.E. lost equal to the K.E. gained?

b. Repeat part (a) but instead of using the numbers, use algebra shorthand with height h, mass m, and g. Thus you can show that in all similar cases (and not just that of part (a)) K.E. gained = P.E. lost.

K.E. AND P.E. (Assume K.E.+P.E. constant. No need to use K.E. $= \frac{1}{2}mv^2$.)

†† **12.** A brick having weight (Earth pull) 40 newtons is lying on the ground. A man picks it up and raises it to 2 metres above the ground. He then allows it to fall.

a. What is the energy-transfer, or work (in joules) when the man raises the brick?

b. What is the increase of potential energy of the brick when it is lifted 2 metres above the ground?

c. What is its kinetic energy on its return just before it hits the ground?

d. What happens to this energy after it hits the ground?

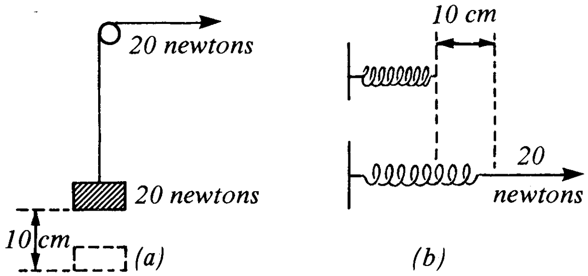
†† **13.** Suppose, in the last question, that the brick, instead of hitting the ground, has fallen into a hole 3 metres deep.

†† From *Pupils' Texts 1 and 2.*

a. What is its kinetic energy just before it hits the bottom of the hole?

b. How do you account for the fact that it seems to have acquired more kinetic energy than is equivalent to the energy originally supplied by the man?

P.E. IN A SPRING



†† **14a.** A man lifts a load which the Earth pulls with a force 20 *newtons*. He raises the load through a height of 0.10 metre (=10 cm). How much gravitational potential energy does he thereby give to the load?

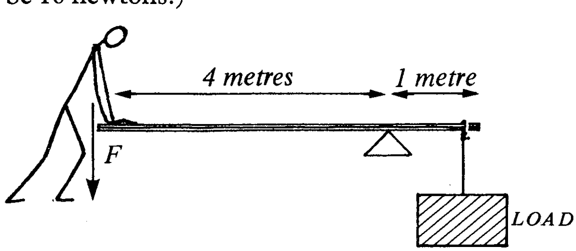
b. A man extends a spring through a distance of 0.10 metre. The force he finally needs to hold the spring stretched is 20 *newtons*. While he is stretching the spring up to that point he uses no more force than is necessary at each stage. That is, the first centimetre of stretch is accomplished with a force that is practically zero; for the next centimetre, more force, and so on. Only at the end does he exert 20 *newtons*.

Why, in doing this, does he store less potential energy in the spring than was stored with the load of (a) when it was lifted 0.10 metre?

c. Make a guess at the actual amount of potential energy likely to be stored in the spring in Question (b). (The obvious guess is the correct answer, provided that the spring obeys Hooke's law.)

MACHINES AND WORK

(In this section take the weight of 1 kilogram to be 10 newtons.)



†† **15.** A man uses a long plank to lift a heavy load. He arranges the plank on a pivot as shown in the diagram. By pushing downwards with an effort, F, he can just lift a 100-kg load.

a. What is the pull of the Earth on the load (its weight), in *newtons*?

b. How big must the effort F be in *newtons*?

c. The load is . . ? . . times as big as the effort.

d. If the plank swings on the pivot so that the effort moves down 0.4 metre (40 cm), how much energy is transferred from the man to the plank?

e. How far is the load raised?

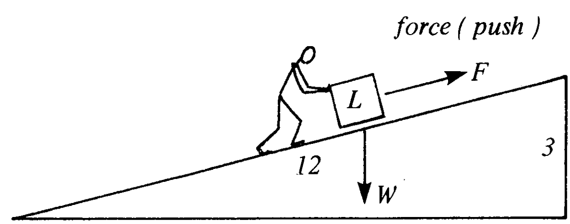
f. How much energy is transferred from the plank to the load?

g. Is there any gain or loss in energy corresponding to the gain in force found in (c)?

16a. If the pivot of the plank in Question 15 above were a rather rusty steel rod fixed to the plank and the rod fitted in holes in two rusty steel plates, what difference would it make to your answers, for (a) to (f) above? Take each answer in turn and guess some suitable figures.

b. What is now your answer to (g) above?

17. A man pushes a 30-kilogram load a distance of 12 metres up a slope of 1 in 4 (1 up in 4 along the slope). Assume the friction is negligible.



a. Through what vertical height does the load rise?

b. Calculate the amount of potential energy (in joules) the load has gained.

c. This gain of potential energy is given by the WORK when the man moves a force F over a distance of 12 metres. How much is that WORK, in terms of F and the DISTANCE?

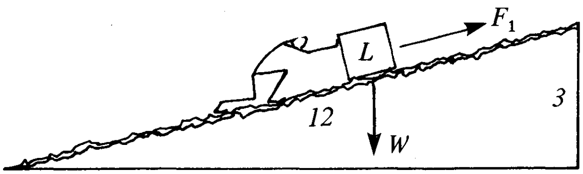
d. Write an equation stating that the P.E. gained (calculated in [b]) is equal to the energy the man transfers from chemical energy (the work from [c]).

From that calculate the value of F (in newtons).

e. What is the ratio of the man's push to the pull of the Earth on the load? (That means: is

$$\frac{\text{man's push}}{\text{Earth's pull on load}}$$

2 or 4 or $\frac{1}{2}$ or $\frac{1}{4}$ or what?)



18. A frictionless slope like that of Question 17 is, of course, unobtainable. The sketch shows a rough slope, also 1 in 4. Now the man exerts a force, F_1, pushing a 30-kg load up the slope.

a. Is F_1 bigger or smaller than F (Q. 17)? Why?

b. If F_1 is 125 *newtons*, how much is the work that measures the energy-transfer when the man pushes the load 12 metres up the slope?

c. How much potential energy is gained by the load?

d. How much of the energy the man provided with his push has *NOT* been transferred to potential energy?

e. What has happened to it?

f. How much is the frictional force that the man has to push against as he pushes the load up the rough slope? Whereabouts does this frictional force act?

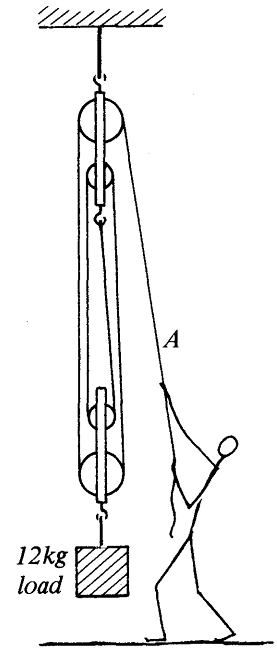
19. The figure shows a set of pulleys being used for raising a 12-kilogram load (top right).

a. If the load is to be raised one metre, how much rope must be pulled down at A? (Think of the length of slack produced when the load is raised.)

b. In fact, an engineer using some real pulleys finds that the least pull at A which will keep the load moving upwards is 40 *newtons* not 30. Give two reasons for this difference.

c. How much energy is transferred by the man's effort in raising the load one metre vertically higher?

d. How much potential energy is transferred to the load?



e. The 'efficiency' of a machine may be defined as the percentage,

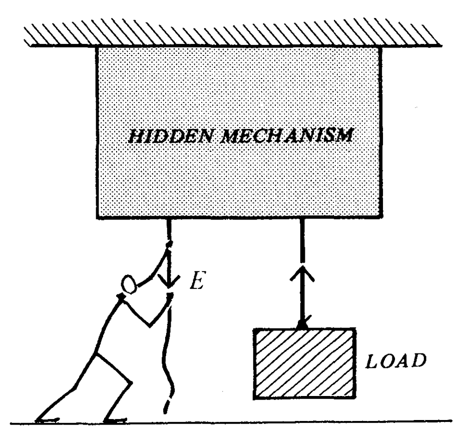
$$\frac{\text{energy transferred from machine to load}}{\text{energy transferred from effort to machine}} \times 100\%$$

What is the efficiency of this pulley system?

Note: The figure is drawn so that you can see the pulley arrangement clearly. In fact, the pulleys in each block would be side by side on the same axle, though free to turn separately.

20. The figure shows a machine whose mechanism is hidden (it might be a set of gears). When the rope labelled E, for 'effort', is pulled down 7 metres the load rises 1 metre.

a. Suppose there is no friction. If the effort is 20 *newtons*, what is the load that can be raised?



b. What can you say about energy input and energy output under these conditions?

21. A 'screwjack' is used for lifting a car when a wheel has to be changed. All such screwjacks are so inefficient that more than half of the effort exerted is used to oppose friction in the jack. However, this inefficiency is a help to the user; why?

HOW TO CALCULATE KINETIC ENERGY FROM MEASUREMENTS

Suppose an object of mass m is moving with speed v. We shall show that the object's kinetic energy is $\frac{1}{2}mv^2$. The statement:

$$\text{K.E.} = \tfrac{1}{2}mv^2$$

comes from our definition of work, as a measure of energy-transfer combined with Newton's Law II in the momentum-form Ft = change of mv. You may call K.E. $= \frac{1}{2}mv^2$ a 'formula'; and then you can use that formula for some interesting calculations. But you should first see how that formula is arrived at—so that it is neither a mystery nor guesswork.

FINDING A FORMULA FOR KINETIC ENERGY

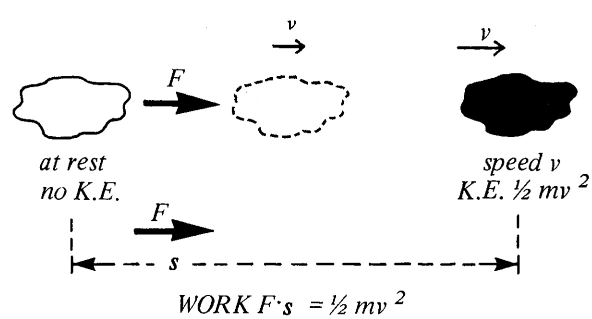
Algebra method Find how much kinetic energy a moving object has got when it has speed v. Start with the object at rest and push it until it has speed v. Suppose that there is no friction, no other force, so that all your push F is used to accelerate the object. The WORK which is the transfer *FROM* chemical energy *TO* the kinetic energy of the object is

FORCE, $F \times$ DISTANCE, s, *OBJECT MOVES ALONG*

Then $F = ma$.

$\therefore$ WORK $= F \times s = mas$.

That is the transfer of energy to the object's kinetic energy. We would like to calculate that kinetic energy from the object's mass and velocity, instead of having to worry about the acceleration it had while it was acquiring that energy. So we put together two of our earlier formulae to calculate the value of as. On the left in the box below is the full working for speed v at the end and speed u at the start. On the right is the simpler form (which you can use in this case because we started with the object at rest, so $u = 0$).



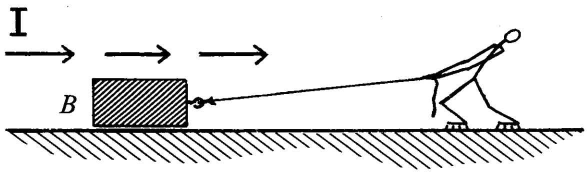
Definition of acceleration $a = \dfrac{v-u}{t}$	Definition of acceleration $a = \dfrac{v}{t}$
Distance travelled $s = \dfrac{v+u}{2} \times t$	Distance travelled $s = \dfrac{v}{2} \times t$
$\therefore as = \dfrac{v-u}{t} \times \dfrac{v+u}{2} \times t$	$\therefore as = \dfrac{v}{t} \times \dfrac{v}{2} \times t$
$\therefore as = \frac{1}{2}v^2 - \frac{1}{2}u^2$	$\therefore as = \frac{1}{2}v^2$
Then WORK $= Fs = mas = \frac{1}{2}mv^2 - \frac{1}{2}mu^2$	Then WORK $= Fs = mas = \frac{1}{2}mv^2$
Then GAIN OF KINETIC ENERGY $= \frac{1}{2}mv^2 - \frac{1}{2}mu^2$	Then KINETIC ENERGY $= \frac{1}{2}mv^2$

Either version leads to KINETIC ENERGY, K.E. $= \frac{1}{2}mv^2$

Geometry method This method uses a graph. It is a much better method because it does not have to pretend the acceleration is constant. It shows that the kinetic energy of a mass m, is $\frac{1}{2}mv^2$ when it has speed v, whether it arrived at that speed through a constant acceleration or through any other type of motion.

We shall explain the argument in several parts, (1), (2) etc.

(1) In this story, we shall talk about *tiny* changes—like putting one more $\frac{1}{2}$p into a piggy bank that is already half full.

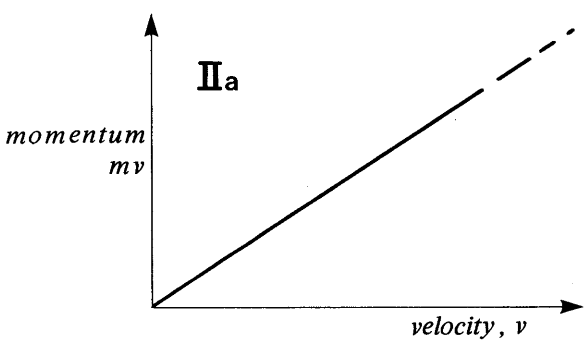


Sketch I shows a box B on a slippery floor. A man ties a cord to it and pulls. This makes the box move faster and faster. It gains more and more momentum.

See what happens in a TINY BIT OF TIME, t. *The man's pull, F,* acting for that TINY BIT OF TIME, gives the box a TINY GAIN OF SPEED, v so it makes a TINY CHANGE (GAIN) OF MOMENTUM, mv.

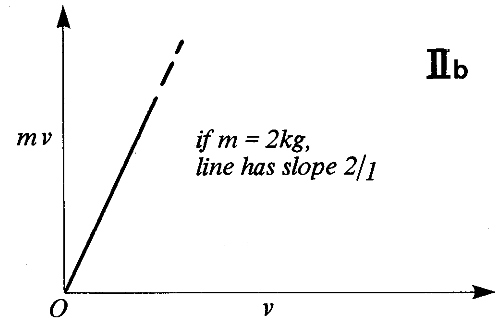
Remember that FORCE $\times$ TIME $=$ CHANGE OF MOMENTUM. Then, here: FORCE $\times$ TINY BIT OF TIME $=$ TINY CHANGE OF MOMENTUM.

(2) Now plot a strange kind of graph* for an object like that box. Plot speed v along, and momentum mv up. (See sketch IIa.)



The mass of the box, m, stays the same while the box moves faster and faster. So for each point on the graph, the distance up from the axis is just m times the distance along from the other axis.

Suppose the mass of the box is 2 kilograms. Then each point on the graph is twice as far up as it is along. (See sketch IIb.)



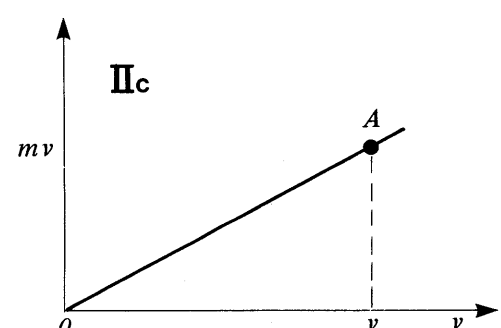
Then the graph *MUST BE* a slanting straight line, passing through the origin 0. Discuss this peculiarity with your teacher.

Suppose you have plotted such a graph, all the way from 0 (starting at rest) up to A when the box has speed v. The graph is a straight line for every kind of motion between 0 and A. (Sketch IIc.)

Now that you know what this special graph looks like, think about a single point on it. That point shows just one value of the moving object's speed and momentum. If the object moves faster and faster, that point moves up the line 0A. Or, the object might go faster and faster for a while, then go slower and slower, then go faster and faster: the point would move forwards up the line, then backwards downhill, then forwards.

When the point is at 0 (zero speed, zero momentum) the object is at rest. When the point is at some point A above a value v_1 on the speed scale, the object is moving with speed v_1 and has momentum mv_1 at that instant.

If all you see of the graph is just a straight line from 0 to A (as in sketch IIc), that shows the object



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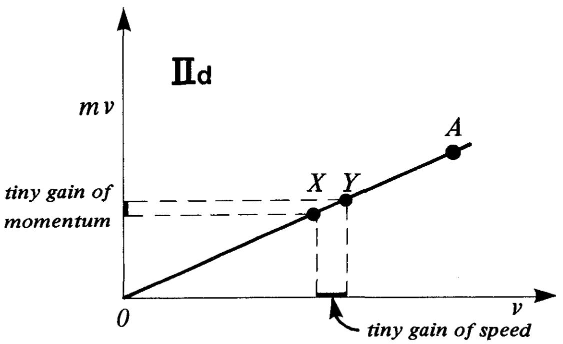
* For other examples to illustrate the idea, see the boxed description on a later page.

has speeded up from rest to v_1. (But you cannot tell what kind of motion if had, from 0 to A—and it does not matter in this story.)



(3) Now we start the main explanation. Mark two points, X and Y, on the line 0A, very close together. From the stage shown by X to the stage shown by Y, the moving object makes:

A TINY GAIN OF SPEED v
(see this marked on the v-axis)

and

A TINY GAIN OF MOMENTUM mv
(see this marked on the momentum-axis)

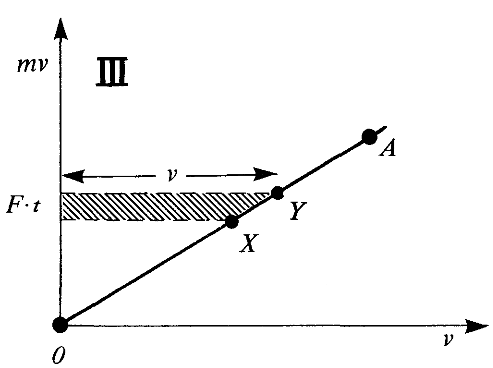
Remember that

CHANGE OF MOMENTUM = FORCE × TIME

Then, here

TINY GAIN OF MOMENTUM mv = FORCE × TINY BIT OF TIME, t

(That tiny bit of time is the time taken by the object to move from the stage shown by X to the stage shown by Y. Since X and Y are *VERY* close, the time between them is likely to be tiny.)



Look at the narrow horizontal pillar that is shaded on diagram III:

its height is FORCE × TINY BIT OF TIME, t

its length is the speed in the X-Y region. We call that v.

The shaded area is:

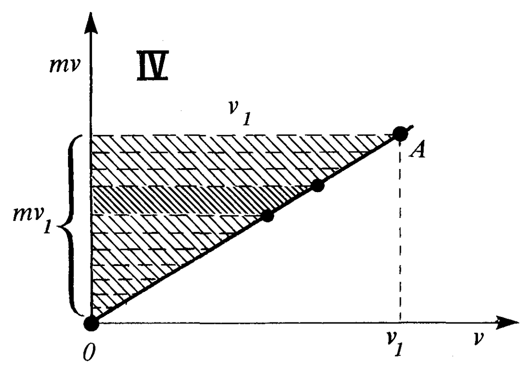
FORCE × TINY BIT OF TIME, t × SPEED, v

= FORCE × TINY DISTANCE travelled between stage X and stage Y

But FORCE × DISTANCE is WORK, which tells us the transfer of ENERGY. So the shaded area tells us the tiny bit of ENERGY gained by the moving object.

(4) Draw in more and more pillars like that, to meet the whole line from 0 to A. Then the total work (the total energy-transfer) is shown by the total area of all the pillars shaded in diagram IV. If v_1 is the final speed at A, the area of that shaded triangle is:

$$\tfrac{1}{2}(mv_1) \times (v_1) \text{ or } \tfrac{1}{2}mv_1{}^2$$



All that has happened to the object between 0 and A is that it has speeded up from rest to final speed v_1. So all the energy-transfer is *TO* kinetic energy of motion; and the kinetic energy at A is $\tfrac{1}{2}mv_1{}^2$.

In ordinary use, we just call the object's final speed v. (We do not need to label it specially v_1.) So we say:

AN OBJECT MOVING WITH SPEED v HAS KINETIC ENERGY $\tfrac{1}{2}mv^2$.

Notes?, questions?, learning? Now that you have seen that explained, you can relax. Tests and examinations would not ask you to write out the algebra story or the geometry one. So you need not copy either of them out and learn them. Yet examiners might be glad to know that you have watched the explanation, so that you understand that K.E. $= \tfrac{1}{2}mv^2$ is a sensible rule to use, and not a mysterious 'formula'.

The automatically straight-line graph: examples of uses to find a formula

1. To show that πR^2 *gives area of a circle.*

For any circle π is the number 3.14... in circumference = $2\pi \times$ RADIUS or $\pi \times$ DIAMETER.

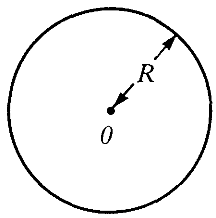
So π is $\dfrac{\text{CIRCUMFERENCE}}{\text{DIAMETER}}$

Starting from that (as a definition of π) we can show that the area of a circle is πR^2.

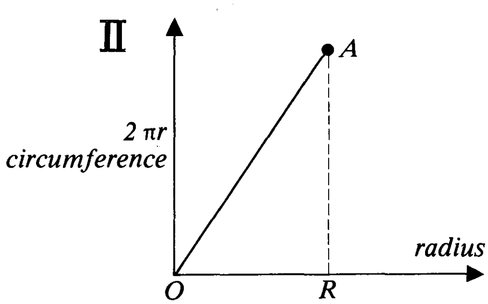
Draw a large circle with centre O and radius R. Plot a graph of $2\pi r$ upwards against r along.

Then the graph *MUST* be a straight line and its slope will be 2π.

I



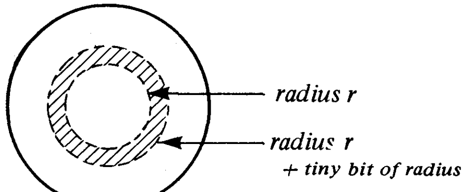
II



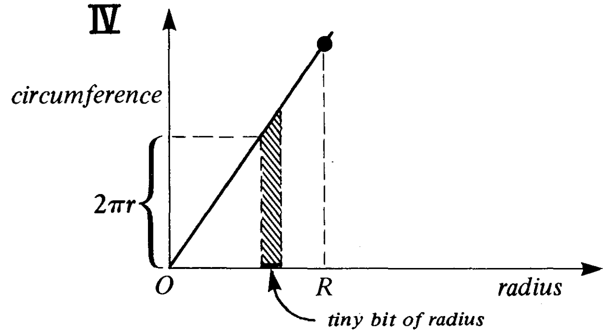
The end-point A, of the graph belongs to a big circle of radius R. Each other point of the graph-line OA belongs to a smaller circle, of radius r.

Sketch III shows two small circles close together with radii (r) and (r + TINY BIT OF RADIUS). What is the *area* of the shaded ring between them? The ring has width (TINY BIT OF RADIUS) and LENGTH $2\pi r$ (its circumference). Its area is $2\pi r \times$ (TINY BIT OF RADIUS).

III



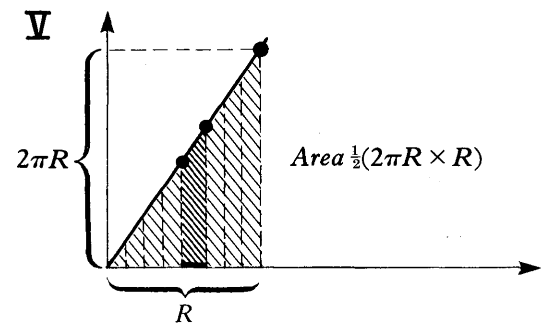
IV



On the Graph IV the shaded pillar shows just that same area, $2\pi r \times$ (TINY BIT OF RADIUS).

Now ask about all such rings from the centre O out to radius R. Their total area is the same as the area of all the pillars in Graph V. That is the triangle of height $2\pi R$ and base R.

V

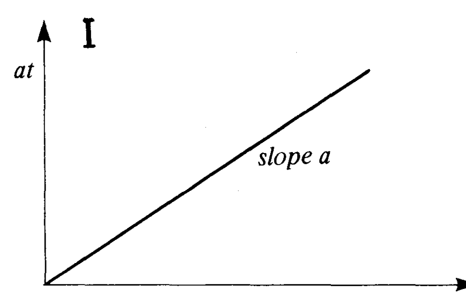


AREA = $\frac{1}{2}(2\pi R \times R) = \pi R^2$

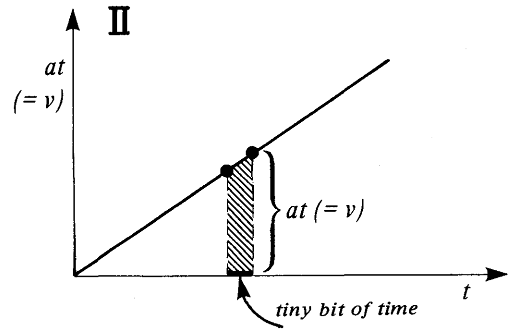
Therefore area of circle is πR^2.

2. To show that $s = \frac{1}{2}at^2$ *for constant acceleration from rest.*

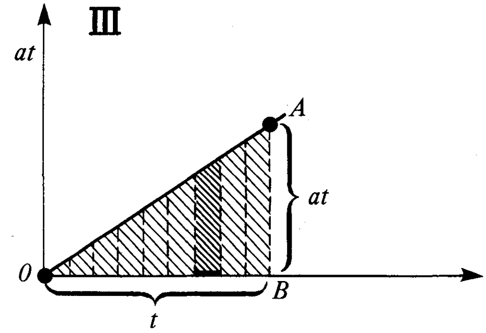
I



Plot a graph of *at* upwards against *t* along. Then with *a* constant the graph MUST be a straight line; and its slope will be *a* (Graph I).



Choose a TINY BIT OF TIME on the t-axis and draw a pillar up to the line (Graph II).
The area of the pillar is: height × width,
$(at) \times$ (TINY BIT OF TIME)
and that is $(v) \times$ (TINY BIT OF TIME),
since ACCELERATION × TIME *IS* SPEED.



And that is (TINY BIT OF DISTANCE TRAVELLED).
Then total distance travelled, s, is given by the total area of all such pillars (Graph III).

s = area of triangle OAB

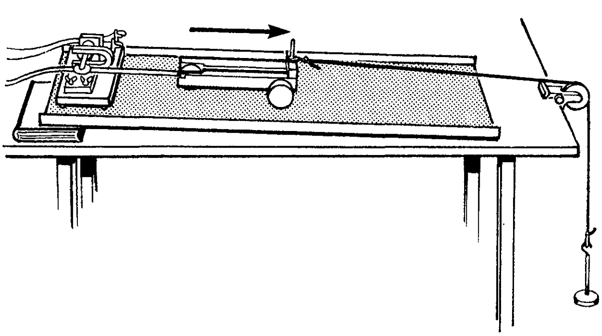
$= \frac{1}{2}at \times t = \frac{1}{2}at^2$.

EXPERIMENTS WITH MEASUREMENTS OF KINETIC ENERGY

Try some of these experiments yourself—or watch demonstrations, but the more you do yourself the better.

Experiment 55
Potential energy changing to K.E.
Measurements with P.E. changing to K.E.

Let a small load hanging on a thread pull a trolley and give it some K.E.



Calculate the gravitational potential energy lost by the load; and compare that with the kinetic energy gained by the trolley.

Compensate the runway for friction. The friction compensation must be arranged with the ticker-tape in use, otherwise the drag by the tape may be comparable with the pull of the small load.

Fasten a pulley to the edge of the table at the end of the runway; and run a thread over it from the trolley to a 100-gram load.

Attach tape to the other end of the trolley. Pass the tape through a vibrator.

Release the trolley. The falling weight accelerates it until it hits the ground. After that the thread is slack and the trolley moves with a constant *velocity*, v. Estimate the value of v from the tape. Measure the mass of the trolley in kilograms by weighing on a balance.

Calculate $\frac{1}{2}mv^2$, that is the trolley's K.E. in newton · metres or joules.

To calculate the potential energy lost by the load multiply thus:

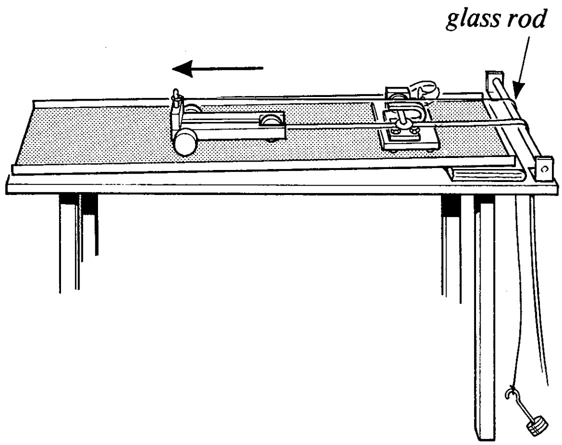
MASS OF THE LOAD × FIELD STRENGTH × HEIGHT FALLEN BY LOAD

Compare your calculated results for kinetic energy gained by the trolley, and potential energy lost by the load.

Would you expect this experiment to give close agreement? Although you would like to see energy conserved, you must remember there are some unaccounted-for losses: friction of the pulley, kinetic energy of the load itself that is wasted at the floor, as well as the errors you make in these measurements.

Experiment 56
K.E. to P.E. Reverse of Experiment 55
(OPTIONAL BUFFER EXPERIMENT)

Compensate the trolley board for motion in the opposite direction and use the trolley to *raise* a load.



Arrange the trolley, thread and load as before; but start the experiment with the trolley near the edge of the table, with the thread slack and some of it lying near the floor. Since the thread is slack, a pulley cannot be used, but a glass tube or a knitting needle will serve as a roller instead. (Or arrange a second pulley very *close* to the first to prevent the thread leaving the groove.) The tape runs out behind the trolley and passes through the vibrator.

Give the trolley a push, with the vibrator switched on. The trolley travels down the compensated runway with constant velocity until half-way along; then the thread goes taut and the load is raised a distance d as the trolley comes to rest. Measure d.

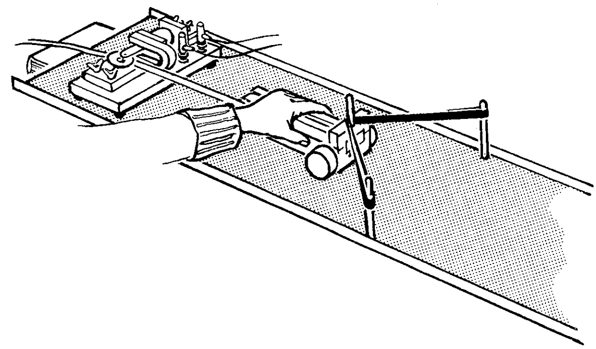
Calculate the K.E. lost and the P.E. gained, and compare them.

Demonstration or Experiment 57
Energy measurements with a catapult and a trolley: strain energy to K.E.

This is an important advanced experiment. Watch it carefully.

The runway is compensated for friction, with tape on the trolley. Near the starting end, two upright posts hold a rubber band which acts as a catapult to sling the trolley along the runway.

Measure the strain energy released by the



catapult and the kinetic energy gained by the trolley. Compare those two lots of energy. This experiment is not easy; so you should be content with rough agreement.

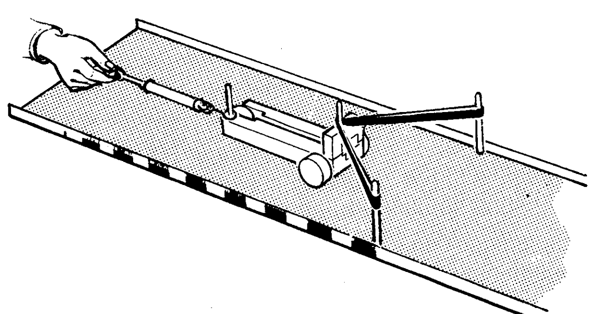
Here are instructions for you or your teacher to follow:

Pull the trolley back so that it stretches the rubber band. Then energy is stored in the catapult.

When the trolley is released the rubber band hurls it along the runway. Take the tape record to measure the trolley's constant speed after the rubber band has finished driving it. Look at the tape record to see what has happened. The strain energy (spring-energy) stored in the rubber band is changed to kinetic energy (motion energy) of the trolley.

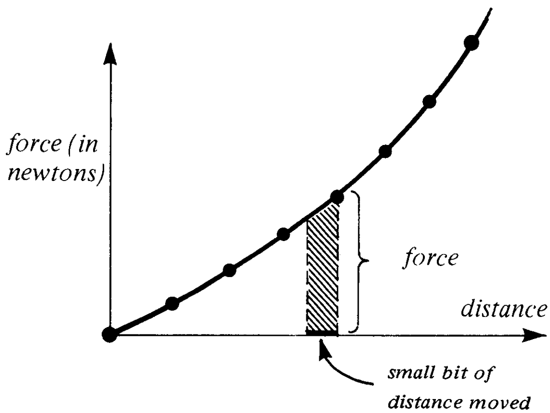
Make careful measurements of energy as follows:

(i) Measuring the strain energy stored in the catapult. We must measure the WORK which tells us the energy put into storage in the catapult. That WORK is FORCE × DISTANCE measured as we drag the catapult back. *But the force is not constant:* it changes as the rubber band is stretched more and more. So we must measure the work bit by bit as we load the catapult.



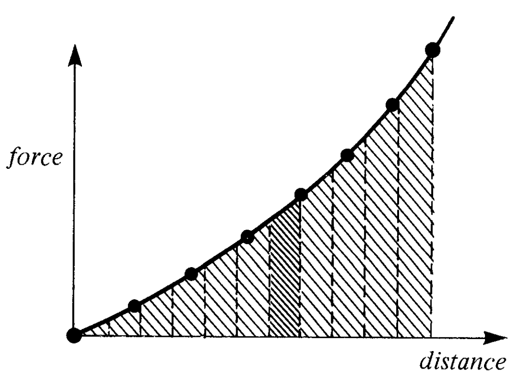
Pull the trolley back with a spring balance marked in newtons and note the reading every centimetre. At each reading of the spring balance also record the *total* distance the trolley has been pulled back from the catapult's zero point. (The zero point is where the trolley's post first touches the catapult.)

Plot a graph of FORCE (upward) against DISTANCE (along).



The area under such a graph represents the WORK which measures the transfer of energy FROM *chemical energy* in our muscles TO *strain energy* in the catapult. To show why that is so, take a small part of the total-distance-pulled-back and draw vertical lines up from that to the curve that has been plotted from measurements. The area of that pillar is the WORK for that small bit of the potential energy stored. It is the FORCE AT THAT STAGE × THAT SMALL DISTANCE MOVED.

Then the total area under the graph—from the beginning of the loading process (when the post on the trolley first touches the catapult) to the position where we hold the trolley ready to launch it—gives the total ENERGY STORED in the catapult before launching.



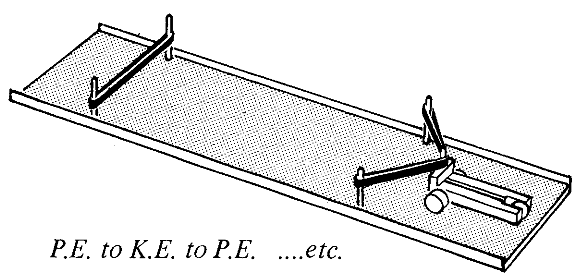
Estimate the energy stored by measuring the area under the graph. Plot your own graph and estimate the area. Then all members of the class can compare notes.

(ii) Measuring the K.E. given to the trolley. Pull the trolley back, *stretching the catapult the same amount as before*. Release the trolley and obtain a tape record of its speed, v, *after it has left the catapult*. Measure the trolley's mass m. Calculate the trolley's K.E. $\frac{1}{2}mv^2$.

(iii) Compare the two forms of energy. Does the K.E. gained agree with the energy given up by the catapult? This experiment is by no means easy: and we should not expect more than rough agreement.

Demonstration 58 or Experiment 59
Table tennis with a trolley started and stopped by catapults *(OPTIONAL)*

Use one catapult to start a trolley and another catapult to bring it to a stop. Compare the strain energy lost at first with the strain energy gained at the other end.



P.E. to K.E. to P.E. ....etc.

Compensate your runway for friction *without* tape. You do not need timer and tape for this.

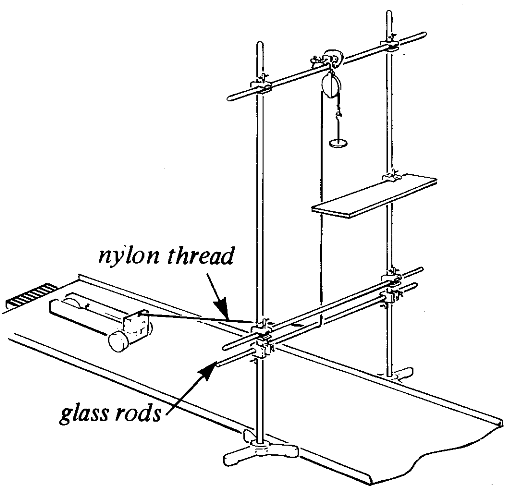
Set up a catapult at each end of the runway. *Make sure your catapults are closely matched.*

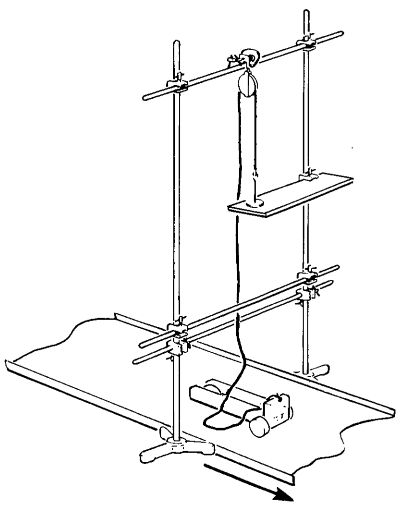
Then you can just measure the total distance the first catapult is pulled back at the starting end and the total distance the other one is pushed back at the finish.

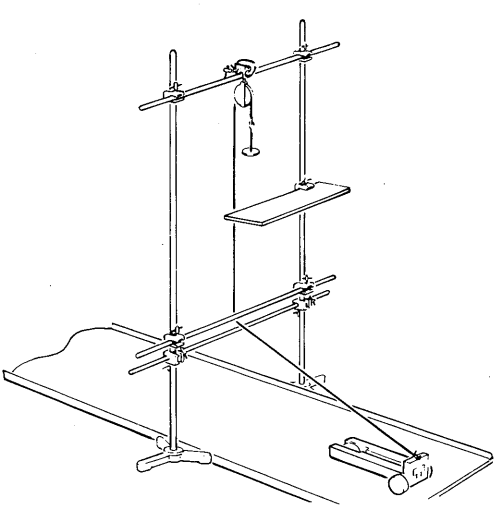
Do these match? Discuss the result with your teacher.

The trolley has neither gained nor lost kinetic energy, so we should expect to make the move without cost. Only our old enemy and friend friction upsets the story.

Demonstration 60
Free transport from here to there along the table by borrowing some K.E.





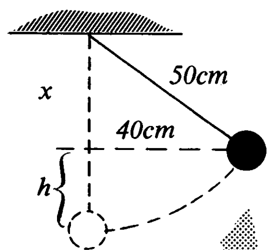


The demonstration illustrates a general idea, but the actual apparatus wastes some energy (in friction-heating of air, strings, etc.), so the result is not very convincing. Watch the demonstration and treat it charitably as an *experiment of principle*, which can teach you an important idea.

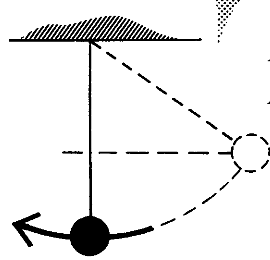
CHANGES OF ENERGY OF A PENDULUM

If you trust the general principle of Conservation of Energy, you can calculate a pendulum's maximum speed from the height at which you started.

Question. The bob of a 50-cm pendulum is pulled aside a horizontal distance 40 cm. How high is the bob above its rest position? (Remember the shape of a 3-4-5 triangle.) As it swings back to its central position, the bob loses gravitational P.E. How much? At its central position, it is moving with kinetic energy $\frac{1}{2}mv^2$. Calculate v.



$$50^2 = 40^2 + 30^2$$
$$\therefore x = 30 \text{ cm}$$
$$\therefore h = 20 \text{ cm}$$
$$= 0.2 \text{ metre}$$



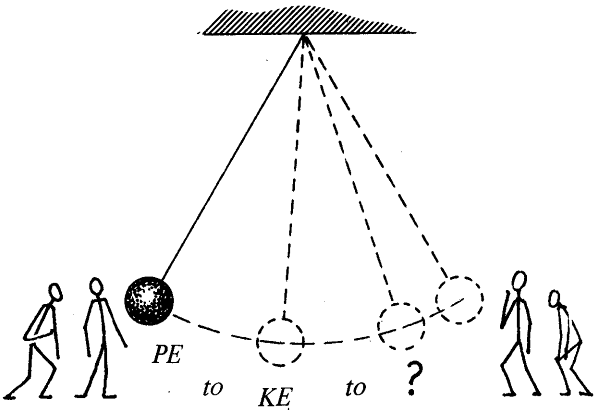
$$\text{K. E. gained} = \tfrac{1}{2} mv^2$$
$$\text{P. E. lost} = m\ g\ h$$
$$= m \times 9.8 \times 0.2$$
$$\tfrac{1}{2} mv^2 = m \times 9.8 \times 0.2$$
$$v^2 = 2 \times 9.8 \times 0.2$$
$$v \approx \sqrt{4} = 2 \text{ metre/s}$$

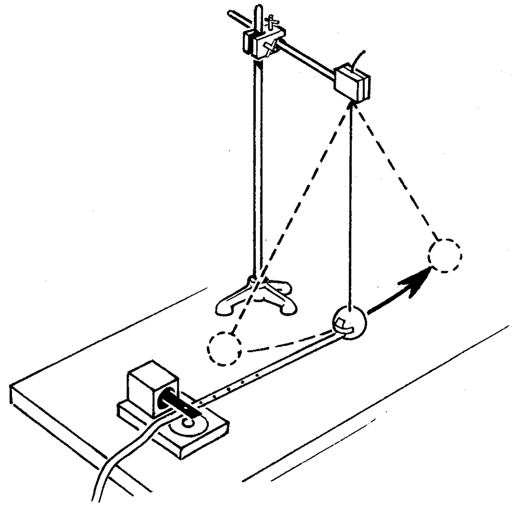
In that calculation, if you wanted to know the mass of the bob you might take it to be 2 kg. If you waited for that before calculating the speed, now work it out.

However, you did not actually need to know the mass. There are two reasons for not needing to know the mass:
(i) a reason connected with the actual calculation.
(ii) a reason from a piece of experimental knowledge.

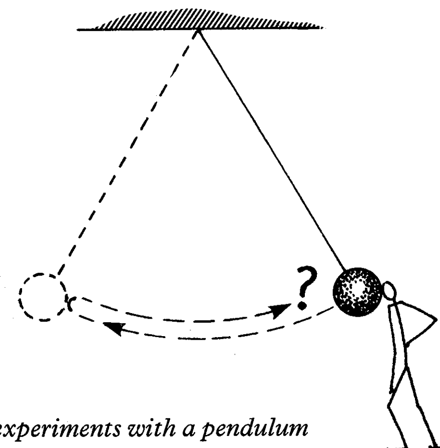
Demonstration 61
Massive pendulum to show energy changes

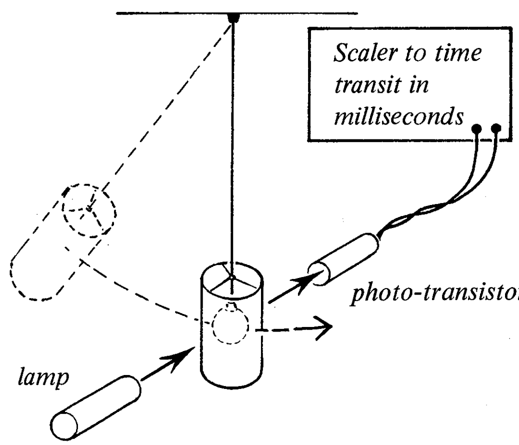
a. Watch the pendulum swinging and think about its changes of energy.





b. Confidence in conservation. See or try the experiment of drawing the bob of a long pendulum aside until it touches your head, and then just let it go and watch its return without flinching.



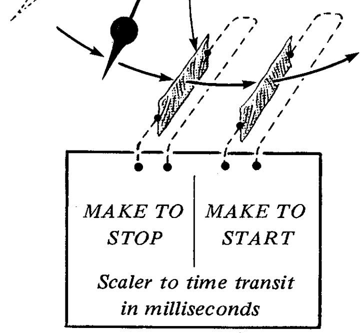


Extra experiments with a pendulum
(ADVANCED OPTIONAL)

c. Measure the speed of the bob at the lowest point of the swing with tape and timer. Compare this with the value you calculate by assuming Conservation of Energy.

d. Measure the maximum speed of the bob with a lamp, photo-diode and millisecond scaler. You need a large cylindrical bob for this or else an ordinary bob surrounded by a cylindrical collar, to act as the obstacle for light.

e. Devise a method for measuring the maximum speed of the pendulum like the time of flight measurement for a rifle bullet. Arrange two strips of metal foil a short distance apart, so that a spike on the pendulum bob breaks each in turn.

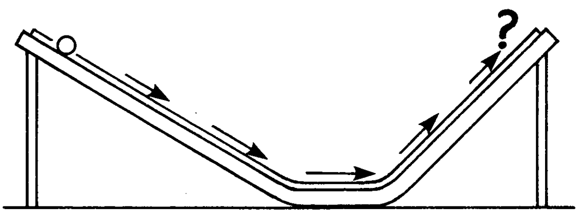


Demonstration 62
Downhill-and-uphill motion: Galileo's guess

If you missed it before, see Galileo's downhill-and-uphill experiment with a ball rolling on a curtain rail. This now throws light on energy-conservation.

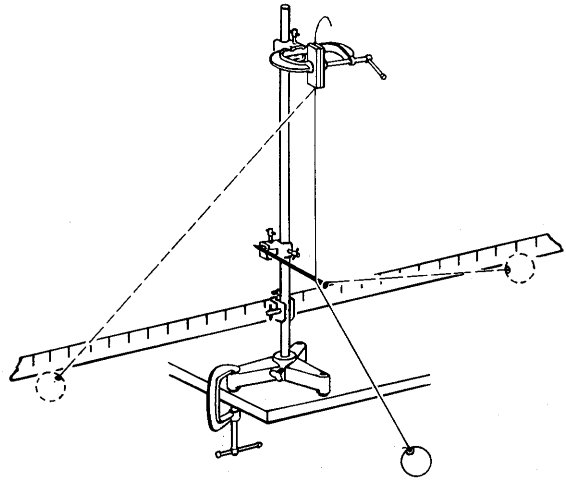
You could elaborate this into a scenic railway.

If you like, build a loop-the-loop experiment with curtain rail and think about the forces on a ball that makes the trip.



Demonstration 63
Galileo's frictionless invention: pin and pendulum experiment

If you did not see Galileo's pin-and-pendulum experiment you should see it now.



Progress Questions

KINETIC ENERGY $\frac{1}{2}mv^2$

22a. Use K.E. $= \frac{1}{2}mv^2$ to work out the K.E. of a 40-kilogram girl moving at 1 metre per second.

b. If she doubles her speed how much K.E. does she have?

c. How much K.E. would a 80-kilogram teacher moving at 1 metre per second have?

USING $K.E. = \frac{1}{2}mv^2$

23. A car of mass 1500 kg is travelling at a speed of 30 metre per second (about 100 km/h).

a. What is its kinetic energy?

b. To stop this car, the brakes must take away that kinetic energy. Suppose the braking force is 7500 newtons.

Calculate the braking distance. (Remember that WORK = FORCE × DISTANCE.)

24. A 1500-kg car is travelling at 15 metre per second. The brakes are applied. Suppose the braking force is 7500 newtons.

a. Calculate the braking distance (see Question 23 for help).

b. Compare your answer with Question 23b.

c. Copy and complete:

When you have double the speed, you need . . ? . . times the braking distance.

ASSUMING CONSERVATION OF [K.E. + P.E.]

25. (In this question, calculate changes of P.E. Assume [P.E. + K.E.] constant, and find K.E. by subtracting P.E. from the total. (No need to use K.E. $= \frac{1}{2}mv^2$ here.)

A cricket ball of mass 0.15 kg is thrown straight upwards. It rises 6 metres vertically in the air.

a. How much P.E. has it gained when it reaches its highest point?

b. How much K.E. has it at its highest point?

c. Half-way back to the ground how much P.E. has it?

d. So how much K.E. has it gained in falling half-way?

e. Just at the instant before it hits the ground, how much P.E. has it?

f. So how much K.E. has it gained in falling the 6 metres?

g. To what form of energy does this K.E. go now?

h. To answer this question you had to ignore air friction. Would the effect of air friction make your answer to (f) smaller or bigger?

CATAPULT EXPERIMENT

26. Give a brief outline of an experiment in which you measured the kinetic energy $\frac{1}{2}mv^2$, gained by a trolley from a catapult (the catapult may have been a rubber band or a steel strip, or a spring). You also measured the strain energy released from the catapult. Describe how you measured *(i)* $\frac{1}{2}mv^2$, *(ii)* the strain energy.

USING K.E. $= \frac{1}{2}mv^2$

27. Use kinetic energy $= \frac{1}{2}mv^2$ to solve the following problem. A long train of goods wagons has a total mass of 800 000 kg. The train is accelerated from rest to a speed of 15 metre per second by a locomotive which exerts a steady pull of 100 000 newtons. Show that the distance covered in reaching this speed is 900 metres (just over $\frac{1}{2}$ mile).

28. A car's brakes can exert a retarding force equal to half the weight of the car (half the pull of the Earth on it). The brakes are applied when the car is travelling at 30 metre per second (= 108 km/hour, 66 miles/hour).

a. If m = MASS of the car in kg, what is its WEIGHT in newtons?

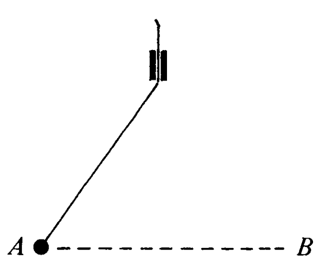
b. What is the retarding force of the brakes in newtons?

c. Use $Fs = \frac{1}{2}mv^2$ (or more correctly, $Fs = -\frac{1}{2}mv^2$ for this case) to find the STOPPING DISTANCE of the car.

d. How much TIME does the car take to stop?

e. Comment on the likely results of fast travel in misty or foggy conditions on a motorway.

PENDULUMS



29. A string with a load on one end is clamped tightly at the top. The load is moved out to A and allowed to swing.

a. How high does it reach at the other end of its first swing?

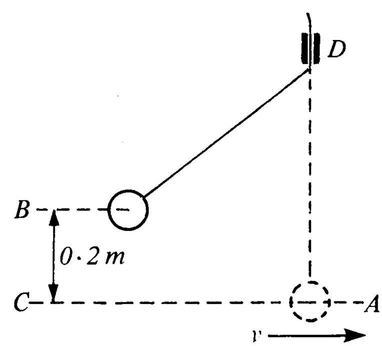
b. After swinging for several minutes does it reach level AB?

c. If there were no friction, and the support didn't move at all, for how long would the load go on swinging?

30. A pendulum bob is given some extra gravitational potential energy by being pulled outward and upward with the string kept taut. It is then released.

a. Describe the energy-changes that occur during a swing to and fro.

b. The bob swings for a long time, but finally comes to rest. Say what has happened to the original energy then.



31a. A pendulum is clamped firmly at D. The bob, which has a mass 2 kg, is raised from A to B. At B it is 0.2 metres higher up than at A. How much energy has it gained?

b. The bob is allowed to swing back. What is its kinetic energy when it passes through A?

c. Use K.E. $= \frac{1}{2}mv^2$ to work out the speed of the bob at A.

d. Suppose you want to measure the speed of the pendulum bob as it passes A to see whether it agrees with your calculation. How would you make such a measurement?

P.E. AND K.E.

32. Taking $g \approx 10$ newton per kilogram, find how far you have to raise one kilogram to give it one extra joule of potential energy.

33. A 0.1-kilogram ball falls vertically from a height of 3 metres on to a horizontal steel plate and rebounds to a height of 2.5 metres.

a. What is the potential energy of the ball before the fall?

b. What is its kinetic energy just before it strikes the plate?

c. What is its kinetic energy just after it leaves the plate on rebound?

d. What happens to the energy which seems to have disappeared between (b) and (c)?

34. A small load of 5.0 grams is arranged to accelerate a 1.0-kilogram trolley along a friction-compensated track. The load falls 1 metre before hitting the floor. After the load has hit the floor the trolley is timed over a distance of 2 metres.

a. What is the potential energy transferred from the falling load?

b. Assuming all the potential energy is transferred to kinetic energy of the trolley, how fast will the trolley be moving? How long will it take to travel the 2-metre distance over which it was timed?

c. The assumption made in (b) is not quite correct: a little bit of potential energy goes somewhere else, not to kinetic energy of the trolley. Where does it go?

d. If we took account of the little bit of energy mentioned in (c), would the estimate in (b) of the speed of the trolley be the same, or greater or less?

35. A 0.030-kilogram bullet travelling horizontally at 600 metre per second enters a bank of earth. It tunnels into the bank to a distance of 3 metres and comes to a stop.

a. What is the kinetic energy of the bullet before impact?

b. Calculate the (average) force acting on the bullet to slow it up as it makes the tunnel.

36. A 0.020-kilogram bullet is fired at 400 metre per second into a block of wood fixed to a trolley running on a friction-compensated runway. The mass of [trolley + wood + bullet] is 2.0 kg. The bullet embeds itself in the block of wood, and the [trolley + wood + bullet] moves down the runway.

Calculate:

a. The speed of the trolley, etc, *after* the impact (remember that the Principle of Conservation of Momentum *always* holds),

b. the kinetic energy of the bullet *before* impact,

c. the kinetic energy of the trolley, etc., *after* impact,

d. the kinetic energy lost during the impact.

e. Express (d) as a percentage of (b). That is,

$$\frac{\text{(K.E. lost)}}{\text{(K.E. of bullet before)}} \times 100\%.$$

f. Into what forms is the lost K.E. transferred?

37. A 1000-kg gun fires a 30-kg shell horizontally with a velocity of 500 metre per second.

a. Calculate the velocity of recoil of the gun. (Remember to conserve momentum.)

b. Calculate the initial kinetic energies of the gun and of the shell.

c. What fraction of the total kinetic energy does the shell carry?

d. Calculate the constant force necessary to remove the recoil of the gun in a distance of 30 cm (0.3 metre).

38. A heavy pendulum had a 0.2-kg bob on a thread 1.0 metre long. A multiflash picture was taken as it swung through its central position, with 50 flashes every second.

A horizontal scale of centimetres was placed close to the swinging pendulum, and it was found that the biggest spacing of the bob between flashes was 6.0 cm (= 0.06 metre).

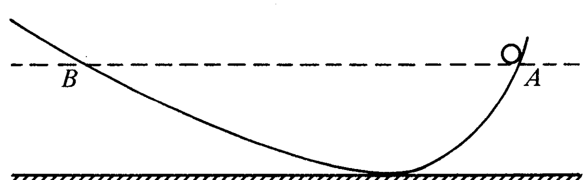
a. Calculate: the maximum velocity of the bob,

b. the maximum kinetic energy of the bob,

c. the height to which the bob rises from its lowest to its highest position,

d. *(Advanced)* the angle of swing of the pendulum (that is, the angle between the central position and an extreme position).

A PUZZLE



39. *(Advanced)* An experimenter bent some curtain rails in the shape shown, and held a steel ball at A. He then released it, but it did not reach B, at the same level as the other side. Close observation showed that it skidded without rolling over the first few centimetres at A, where the slope is steep, then it started to roll. *(Continues)*

Question : Why didn't it reach B?
Answer : Friction. But where was the high frictional loss, and why didn't it occur in other parts of the ball's travel?

USING WORDS TO SHOW K.E. $= \frac{1}{2}mv^2$

40. Each part of this question has an answer which is left unfinished. Copy each answer filling in the [ ] with *WORDS*.

A mass accelerates from rest to a final speed.

a. How do you work out the acceleration, from the SPEED and TIME?

Answer : $\text{ACCELERATION} = \dfrac{[\ ?\ ]}{[\ ?\ ]}$

b. So how do you work out the force?

Answer : $\text{force} = \ ?\ \times \dfrac{[\ ?\ ]}{[\ ?\ ]}$

c. How do you work out the *average* speed, from the final speed?

Answer : $\text{average speed} = \dfrac{[\ ?\ ]}{[\ ?\ ]}$

d. So how do you work out the distance it goes?

Answer : $\text{distance} = \dfrac{[\ ?\ ]}{[\ ?\ ]} \times [\ \ ?\ \ ]$

e. To find out the WORK you use:

$$\text{WORK} = \text{FORCE} \times \text{DISTANCE}.$$

Your answers to (b) and (d) should turn this into

$$\text{WORK} = [\text{MASS}] \times \frac{[\text{SPEED}]}{[\text{TIME}]} \times \frac{[\text{SPEED}]}{[2]} \times [\text{TIME}]$$

Look and see that TIME comes on the top and on the bottom.

Ten seconds on the top and ten seconds on the bottom would cancel; so would 13 seconds on top and 13 seconds on the bottom, and so would *any* number of seconds.

What are you left with when you cancel out TIME?

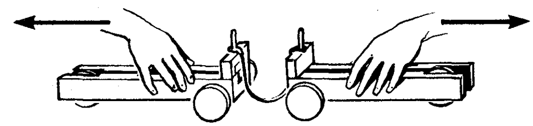
Answer : $\text{work} = [\qquad] \times [\qquad]$
$= \ldots ? \ldots$

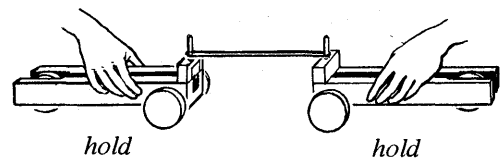
f. This amount of work tells us how much energy is transferred to kinetic energy ('motion energy').

Copy and complete:

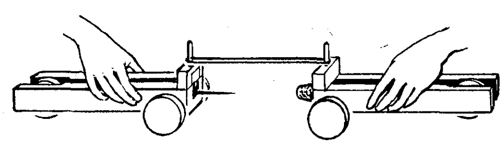
We use $\frac{1}{2}$[mass] × [speed]^2 to calculate . . ? . . energy. The energy is measured in . . ? . . and the mass must be in . . ? . . and the speed in . . ? . .

Demonstration 64
Kinetic energy disappears in collisions that are inelastic





a. Two trolleys, connected by a weak spring or rubber band are given pushes to start them moving apart; but they come to rest. Where has their kinetic energy gone? Can you get it back?



b. Two trolleys connected by a spring or rubber band are held far apart and released. They gain kinetic energy, but this disappears when they stick together on meeting (because they are arranged with sticky buffers or a pin and cork). What has happened to the kinetic energy that the spring gave them?

c. Two trolleys with spring buffers are connected by a spring. They are held apart, with the springs stretched then released. Even when they meet, the spring is still pulling them together. Watch what happens. What has happened to the energy that the connecting spring provided?

All these are things to discuss with your teacher, because they illustrate important questions about energy in engineering.

CHAPTER 6

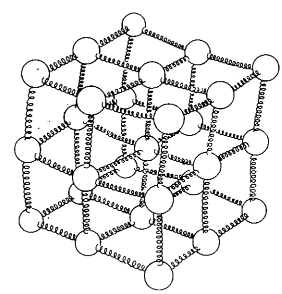
GASES I

Models for catching up; simple molecular picture; a model to suggest Boyle's Law; a simple prediction of molecules' speeds

THINKING ABOUT MOLECULES

MOLECULAR PICTURE OF SOLIDS, LIQUIDS, GASES

Matter comes in three states: *solid, liquid, gas.* In every case we picture it as made up of small particles in continual motion—atoms or molecules (family groups of atoms). But we picture different amounts of orderly arrangement, and different types of motion, according to whether we are describing solid, liquid or gas.



SOLIDS

Our picture of a solid is of atoms (or groups of atoms) arranged in a regular framework or 'lattice'—like the repeating patterns of a wall-paper. But the pattern is spread out in three dimensions in the space of the solid. Atoms are held in this framework by strong forces which give the solid its strength.

Atoms and molecules exert attractions on each other at short distances. Nowadays we know that all those forces are electrical, arising from the electric charges inside atoms. Those are forces exerted by negative electrons and positive nuclei of atoms on each other.

Demonstration 65
Model of atoms in a solid

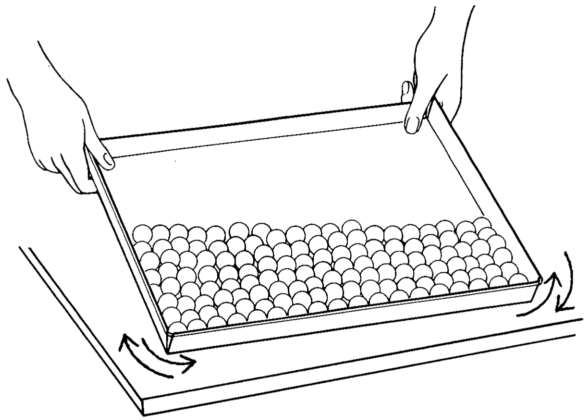
See a model of a crystal, as in the sketch. (That is just a 'teaching model', not a 'thinking model'. The balls represent atoms and the springs represent the forces that tie the 'atoms' together.)

The atoms in a solid are constantly vibrating (moving to and fro) in various directions. The hotter the solid, the wider the to-and-fro motion. If the solid is heated enough, the vibrations may carry some atoms so far from their neighbours that they are held too weakly and cannot stay in the well-ordered crystal arrangement: then the solid melts.

LIQUIDS

Atoms and molecules, crowded but moveable In a liquid, the atoms or molecules (groups of atoms) are not much farther apart; but they are less firmly locked in position by forces of neighbours. A liquid can flow when we pour it—rather like a crowd of people flowing along a street—so molecules must be able to slip past each other.

A molecule often moves out of the strong field of force of a neighbour for a short time, and soon moves into another neighbour's strong field; so the regular crystalline order is not maintained. We picture a liquid as having small patches of well-ordered arrangement, but with molecules easily slipping past each other to move from one patch to join another.



† Experiment 66
'Teaching model' to represent a liquid

Put enough marbles in your tray to fill it at least a quarter full. Keep the tray slightly tilted so that all the marbles run down to one end (without running on top of each other). Agitate the tray gently with one edge on the table top. Watch the motion of the marbles.

Watch a marble 'evaporating' from the 'liquid' of marbles in the tilted tray.

Think about a real molecule evaporating from the surface of a liquid. The molecules of a liquid attract each other: they must do this, or liquids could not hold together in drops.

Also watch the progress of one marked marble in the 'liquid'—we call this *diffusion*.

Liquid to gas: what can you think out? The change of volume from liquid to gas is something like 1 to 1000. Suppose molecules in a liquid are very close, 'touching' or 'rubbing shoulders', with their centres only a little more than one diameter apart. *Then how far apart must they be in gas?* (That is a question for thinking ahead. You have the necessary information. If you are lucky, you may be able to think this out; but if you do, do not 'give the show away' to others. That kind of thinking-out of new knowledge from some given information is good science. It would be a great pity if you believed that '*scientists just tell the answers*'; because that is not what real science is like. Better descriptions of science are: '*Scientists find out*'; '*scientists do some experiments; they do some thinking, then arrive at more knowledge by hard work*'. You are being a good scientist if you worry a bit about questions for thinking ahead.)

GASES

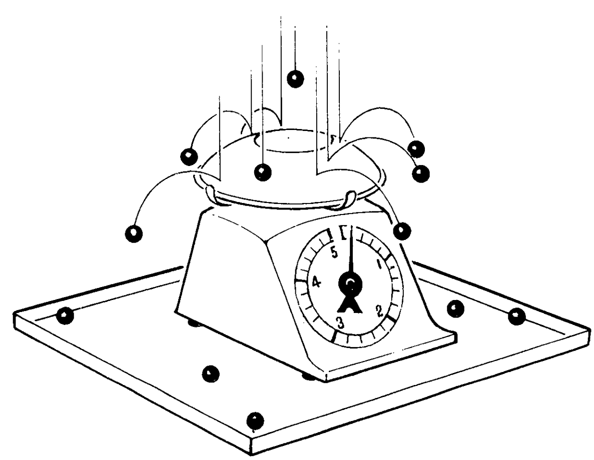
Molecules far apart In gases and vapours, we imagine there are enormous spaces between molecules most of the time. Think of the great change of volume from *liquid* to *gas*. Molecules must have moved far apart (unless they have swelled up enormously during that change which is most unlikely). We believe air molecules hardly exert any force on each other, except very briefly in collisions. We picture them as moving very fast, colliding sharply, and bombarding the walls of their container.

Air pressure We make a bold guess about the *pressure* that air (or any other gas) exerts on surrounding walls. We believe that pressure is simply due to bombardment. Molecules hit the walls and bounce back at full speed. The massive walls smooth out the short sharp impacts into a steady force.

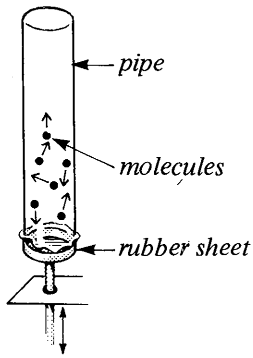
Therefore molecules in gases must be moving very fast. Their energy is energy of motion, individual molecular kinetic energy. How could you put more energy into a gas?

All this is talking about a picture of molecules and their behaviour—a 'thinking' model or theory. If you have not seen 'teaching' models to illustrate these ideas, you should see them now.

Demonstration 67
Model to show bombardment making pressure



See the demonstration sketched. A stream of marbles falls on the top of spring weighing scales.



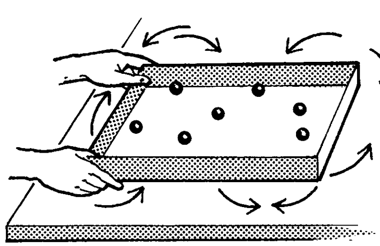
Demonstration 68A
Model of air molecules

Watch the three dimensional model of air molecules again. Small balls are kept in motion by a vibrating piston at the bottom of a tall pipe. This is a model of the atmosphere. *Does the population of 'molecules' in the model stay the same as you go up higher and higher?*

† Experiment 68B
'Teaching model' to represent a gas: marbles in a tray

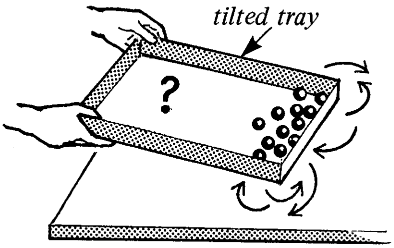
Put a few dozen marbles in a tray, to represent air molecules in the room—or any gas molecules in a box.

(i) Agitate the tray by sliding it about on the table with a rapid irregular shaking motion, to imitate the hot walls of the room.* Watch.

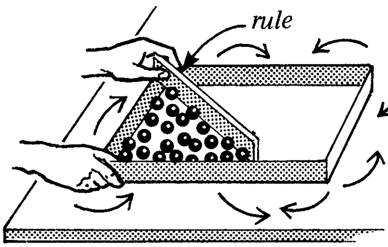


(ii) Illustrate a higher temperature. Agitate the tray more violently.

(iii) Listen to the sounds. Can you hear the different kinds of collision, some on the walls, others between marble and marble?



(iv) You can imitate the atmosphere (with its population thinning out higher up) by giving the tray a *very slight* tilt, and then keeping it tilted while you agitate it.

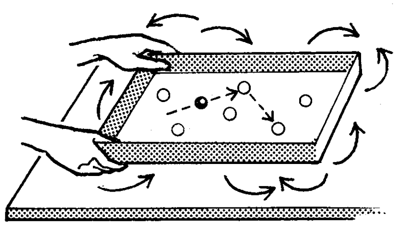


(v) For a model of a compressed gas, add more marbles and agitate the tray. Crowd all the marbles into half the tray, with a ruler. Continue to agitate the tray and see the gas expand when you remove the ruler.

A convenient way to hold the ruler still is to place a small book in the tray and hold the ruler firmly up against it.

What is the effect of reducing the area further still?

(vi) There are still more things you can do, such as watching one particular marble.



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* If the walls of the room were not as warm as the air, but were completely cold with little or no vibrations of their own, air molecules arriving at the walls would give up their kinetic energy and soon fall down to the floor. So, when using the tray of marbles as a good model, you should keep its walls in constant motion.

A question for thinking ahead If you stir up a collection of moving marbles with your fingers, you can make them move faster. Guess what will happen in air (or any other gas) if you stir it up with a rapidly moving fan and wait till the whirlpools of air have calmed down. You will have given the whole gas some motion, but that motion seems to disappear. *Where does it go?*

A question for arguing: *why don't air molecules fall down the floor?* Think of a molecule in the air half way up from floor to ceiling. It does not fall down crash to the floor. Collisions by molecules below it must somehow push it *up* more than the collisions by molecules above push it *down*—and thus balance its weight. Yet the molecules below it are no more violent, no 'hotter'. So there must just be more of them.

You can see that in the model there are many more molecules in the lower regions than in the upper regions of the model gas. So any particular molecule in the middle is more likely to be hit upward from below than downward from above. That is why air does not collapse to the floor.

Are molecules real or is this just a fanciful picture to amuse us? You should see an experiment to support the idea that air is made of invisible particles moving fast, frequently colliding, bombarding, making the Brownian Motion.

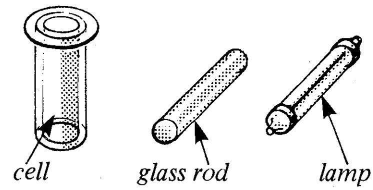
Unless you have seen this before and clearly understood it, you should see it now with a good microscope; and take plenty of time to watch the specks of ash.

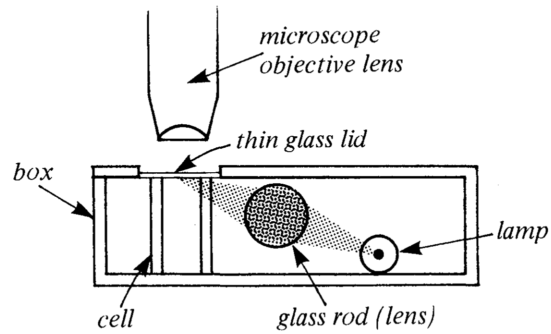
Experiment 69
Brownian Motion of smoke in air

Put some smoke in a small cell. Smoke is made up of tiny specks of white ash. You will see a strange motion; and you may well believe you are seeing the effects of bombardment by air molecules.

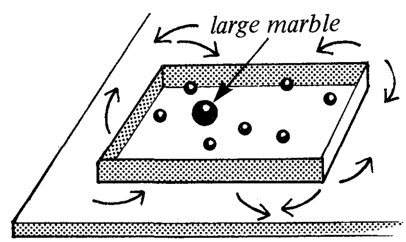
We name this motion after the botanist Brown who discovered it. (He probably thought at first he was seeing living things.)

This is the nearest thing to first-hand evidence of molecules you are likely to meet. *It would be a great pity to take it on trust from a book or only to see it in a film, when you could watch the real thing with a microscope.*





Experiment 68C
'Teaching model' of Brownian Motion



Place a larger object, such as a bigger marble or a matchbox, among the marbles in your tray. Watch what happens to it when you agitate the tray. Compare its motion with that of the smaller marbles.

This suggests what might happen to something much larger than an air molecule, if it is floating in air. You can see this in real life by watching tiny specks of white smoke in air.

Progress Questions

MODELS OF A GAS (Do not answer these questions until you have seen in action the 'teaching' model with balls in a tall tube. Give fully labelled diagrams.)

1a. What do you see when the piston is vibrating steadily?

b. How can you make the balls move faster?

c. What does the disc do when the balls move faster? Why?

d. Draw a sketch to show what you see when you take the disc away, with the piston vibrating.

e. When you *stop* the piston, what do you see? Where does the energy of the balls go to?

f. To keep the model working, you have to keep supplying energy, through the piston. Why?

2. We think molecules in a gas move very much like the little balls in the model in Question 1.

a. The air in the room exerts pressure on the walls of the room. How do you imagine it does this?

b. Perhaps air molecules slow down when they bump into the walls (like the little balls in the model). What would happen in the room if they did?

c. Real air molecules do not need to have a piston to keep them moving. Why not?

3. When you shake a tray of marbles, it is a crude model of air in a room.

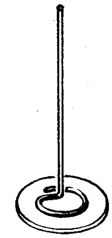
a. How do the marbles make 'pressure' on the sides of the tray.

b. Do all the marbles move at the same speed?

c. When you shake the tray harder, you make the pressure bigger. Why does the pressure get bigger? (Two reasons)

d. Can you think of one or two other ways of making the pressure bigger?

4. The sketch shows a paper disc with a thin wire handle. The disc can be put in the tube to act as a ceiling or piston. First the vibrator is stopped and the balls lie at rest on the rubber. The disc is put in and falls down the tube till it rests on top of the balls.



a. What happens when the vibrator is switched on?

b. What happens if the agitation of the vibrator is made more violent?

c. What happens when a small extra load is put on the disc?

d. The balls in the experiment without the disc, resembled molecules in the atmosphere—in fact, this is a model of the atmosphere. What is this apparatus *with* the disc, a model of?

† **5.** Suppose you use the model with balls in a tube again. You put in one ball which is larger and heavier but still fairly light. The small balls are still there. What happens to this larger ball when the vibrator runs?

MODEL WITH MARBLES IN A TRAY
(Do not answer these questions till you have experimented with the model.)

6. You are given a number of marbles and a suitable metal tray. Describe how you would use them for each of the following:

a. To illustrate what happens when gas molecules are in a box and the *box* is suddenly made twice as big. *Hint:* Imagine you start with all the marbles crowded into one half of the tray and held there by a ruler.

b. To illustrate a tall 'atmosphere' of molecules?

Questions

MODELS OF A GAS (Do not answer these questions until you have seen in action the 'teaching' model with balls in a tall tube.)

7. A lot of small balls are placed in the tube.

a. Sketch the tube, showing the balls inside when the vibrator is in motion.

b. Describe in words the position of the balls in your sketch (in not more than two or three sentences).

c. In what way do the balls in the tube resemble the molecules of air in the atmosphere?

d. Mention some differences between this 'atmosphere model' and the real atmosphere of air.

8. In the 'teaching' model of a gas, many small balls are put in the tube and a light movable ceiling is held above them.

a. Draw a sketch to show what the model looks like when the piston and balls are in motion.

b. Write a few words to explain how this model illustrates air molecules exerting pressure.

c. When a small load is placed on top of the movable ceiling, the ceiling falls a little way and then stays at a new balanced position. Explain in a few words why it behaves like this.

d. Energy has to be fed in by the motor and piston to keep the balls in motion. But no energy has to be supplied to real air molecules to keep them in constant motion. Why is there a difference?

e. If we raise the temperature of air, we believe its molecules move faster. How can we 'raise the temperature' of the balls in the tube?

f. How could we make the model resemble the whole atmosphere vertically above us, instead of a sample stopping at the ceiling?

† **9.** You agitate a tray containing 24 white marbles. There is also one red marble of exactly the same size and mass as the white ones. You continue to agitate the tray.

a. Sketch a tray about 10 cm long (4 inches); and draw a line to show a likely path you might see the red marble following.

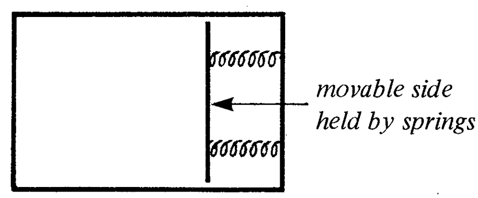
(You need not draw the rest of the marbles nor need you draw the red marble. Just draw a line to show a likely path for it as it flies along among the other marbles sometimes making collisions.

b. Would one of the white marbles follow the same kind of path as the red marble? Or would you expect it to behave differently Give a reason for your answer.

c. *(Advanced)* Suppose you take out the red marble and put in a larger green marble having about twice the mass of a white marble.

(i) Would the path of the green marble *look* different in any way from what you drew for the red marble in (a)?
(ii) If you watched the green marble, and kept track of the time, what difference might you notice?

'THOUGHT-EXPERIMENT' (You are not likely to have done it but you can easily suggest what would happen if you did do it.)



† **10.** The sketch shows a tray with marbles. The marbles are kept in the tray by a 'movable wall' at one end, held in position by two springs. The diagram shows the position of the movable wall when the tray and marbles are agitated.

a. What happens if the agitation is increased by shaking more violently?

b. What happens if the agitation is slowed down? Stopped altogether?

c. What happens to real gas molecules if the gas is made hotter?

d. What happens to the pressure which a gas exerts on the walls of a container if it is made hotter?

e. Did you see an experiment that illustrates your answer to (d)? Either describe or sketch it.

Progress Questions

BROWNIAN MOTION

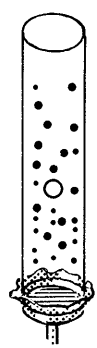
11. You have looked through a microscope at smoke trapped in a tiny glass jar.

a. Describe what you saw.

b. The tiny glass jar is like the model in Question 5. Instead of a big light ball and lots of tiny balls, it has smoke particles and air molecules.

(i) Which behave like the big light ball—the smoke particles or the air molecules?
(ii) Which behave like the tiny balls?
(iii) Which move faster—the smoke particles or the air molecules?

c. Now explain what you see through the microscope.



12a. When you set the piston going, what do you see the big light ball doing?

b. Why does it do this?

c. Which moves faster—the big ball or the tiny ones?

GAS MOLECULES AND HEATING

With smoke in much hotter air the Brownian Motion is faster.* We guess the air molecules are moving faster.

If you heat some air with a Bunsen burner or an electric heater, the molecules move faster. All the energy given to them by heating goes into kinetic energy of individual molecule's motion, in the simplest gases like helium or neon. In other gases, such as oxygen and nitrogen, which have two atoms in each molecule, some of the energy goes into spinning motion, and in some cases into energy of atoms vibrating to-and-fro in a molecule—yet most goes into K.E. of direct motion.

* This is true, but you will have to take it on trust. With any easy heating of air, the increase of motion is small, and much of it is masked by changes of the air friction which opposes the movements.

Questions

BROWNIAN MOTION (Do not answer this question until you have looked at the real Brownian Motion of smoke specks through a microscope.)

13a. Describe the motion of the smoke specks. Illustrate with a sketch the movements of one speck.

b. Explain why the motion of the smoke specks suggests that air molecules are also in motion.

c. If you could watch smoke specks of different sizes carefully, you might notice that they seem to move with different speeds. Which would move faster, a large speck or a small one? Arguing from your answer to that, do you think air molecules move much faster than the smoke specks or much slower, or at about the same speed? (Remember that air molecules are too small to see, even with a powerful microscope.)

† **14.** (Another question on motion of smoke specks.)

a. Particles larger than the smoke specks you looked at would be easier to see. What two disadvantages would there be in using larger particles?

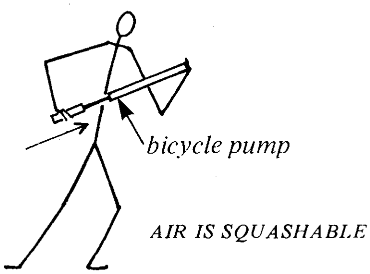
b. Suppose you hang a table tennis ball on a long fine thread in a closed room with no draughts in it. Would the ball remain *completely* at rest?

c. Write a sentence or two explaining your answer to (b).

Now return to that question for thinking ahead. *What do you imagine happens to air when you churn it up by waving your hand or by stirring it with a fan?* You are giving the whole gas some motion, but that motion seems to disappear. *Where does it go?*

There is another way of giving extra motion to gas molecules. Push them with a piston acting like a bulldozer pushing earth. Try this with a bicycle pump. Close the exit with a finger and push the piston in very fast. *What happens?* Feel the side of the pump.

When gas molecules meet any wall that is at rest, they bounce away elastically. They neither gain nor lose motion energy on the average. *But what happens if they hit a RAPIDLY MOVING piston? What happens to the energy of a ball that is hit by a RAPIDLY APPROACHING bat or racquet? Does the ball rebound with the same speed as before, when you hit it with a smash?* Guess what happens to gas molecules and the gas as a whole, when a piston is driven in. Try it with a bicycle pump. Keep the outlet closed with your thumb. Push the piston in.

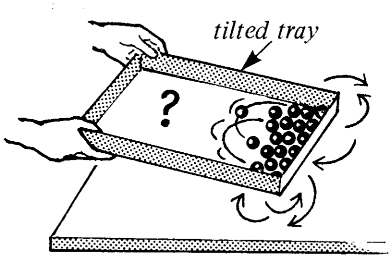


This is how the cylinders of a diesel engine are fired—see Question 19 ahead.

LIQUIDS AND EVAPORATION

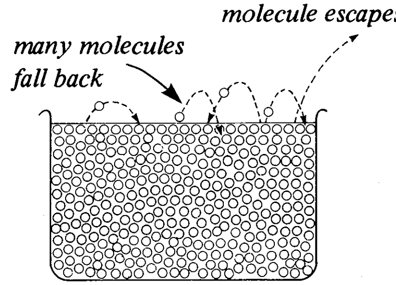
Experiment 66
'Teaching model' to represent a liquid

If you did not try this experiment earlier, try it now. Put more marbles in the tray and tilt it. Watch a marble 'evaporating' from the 'liquid' of marbles in the tilted tray.



Evaporation Think about a real molecule evaporating from the surface of a liquid. The molecules of a liquid attract each other: they must do this or liquids could not hold together in drops.

Is it easy for a molecule to escape from the surface and stay away? As you guess from your model, many a molecule that evaporates will fall back, like a rocket falling back to Earth if it is not given enough speed to start with. Only very fast rockets can escape to outer space; and only *extra fast* molecules can escape from a liquid surface.

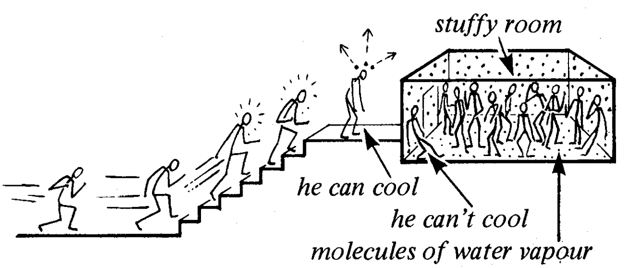


Evaporation

Evaporation Evaporation is the escaping of *extra fast* molecules, the ones that are extra rich in kinetic energy just at that time. (What happens to the average money of each person in a family if the richest members of it go away?) What about the liquid that is left after extra rich molecules have evaporated?

Wet your finger and wave it in the air to let some water evaporate. *What do you feel?*

Evaporation is a cooling process Your body uses evaporation as a thermostat. When you get too hot, some water oozes out through your skin as sweat and evaporates. That is part of your human air-conditioning system to keep you from overheating.



In a very crowded room, the air soon becomes so full of water vapour that people in it cannot keep cool by letting perspiration evaporate. Water does ooze out through their skin, and its molecules do evaporate as fast as ever. But other water molecules *come back just as often* from the wet air in the room; water returns to a damp brow as fast as it leaves. There is no cooling. People's temperatures go up, and they feel uncomfortable.

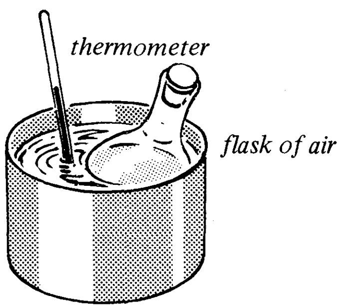
The stuffy feeling of a crowded room is *not* due to increased concentration of carbon dioxide. It is due to damp air preventing successful cooling by evaporation.

Progress Questions

COMPRESSING A GAS

15. Copy and complete:

When we make the volume of a gas smaller, the pressure gets [/*bigger*/*smaller*/]. When the volume is smaller, the molecules have [/*further*/*less far*/] to go between the walls, so they bump into the walls [/*more often*/*less often*/] and this makes the pressure [/*bigger*/*smaller*/].

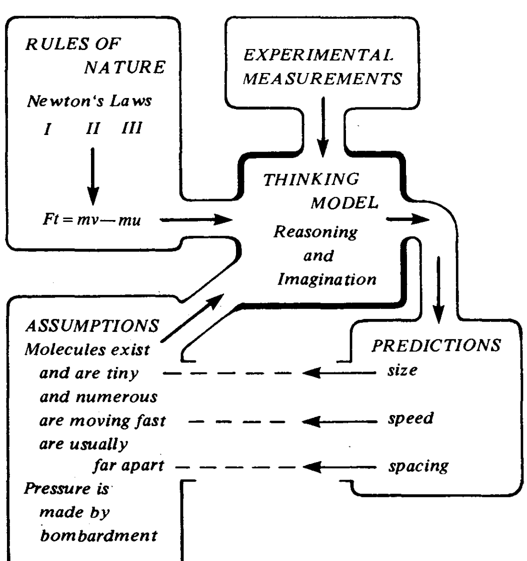


HEATING A GAS

16. Copy and complete:

When we heat the flask, the volume stays the same, but the temperature gets [/*higher*/*lower*/] and the pressure gets [/*bigger*/*smaller*/].

When the temperature is higher, the air molecules move [/*faster*/*slower*/]. They hit the walls [/*more often*/*less often*/] and [/*harder*/*less hard*/] and this makes the pressure [/*bigger*/*smaller*/].



Questions

GAS PRESSURE

17a. How does the molecular theory (thinking model) explain the fact that gases can exert pressure?

b. How does the theory explain the fact that a gas exerts a bigger pressure when you squeeze it to a smaller volume?

c. How does the theory explain the fact that a gas in a closed box exerts greater pressure if it is made hotter. (*Hint:* There are two 'causes' for the increase. Can you guess both of them?)

18a. You probably have a very good vacuum in your house—inside a television picture tube. Air has been removed from this tube until a *very* low pressure is reached. Is the average distance between the molecules in the tube less than the distance between the molecules in the air outside? Or greater? Or the same?

b. The TV picture is made by a stream of electrons which shoot along the tube and fall on the coated screen, thus making it luminous. What might happen if the pressure in the tube were *not very low*?

DIESEL ENGINE—FIRING THE CYLINDERS

19. There are no spark plugs, but after oil has been sprayed into the air in the cylinder the piston drives inward and compresses the air *violently*.

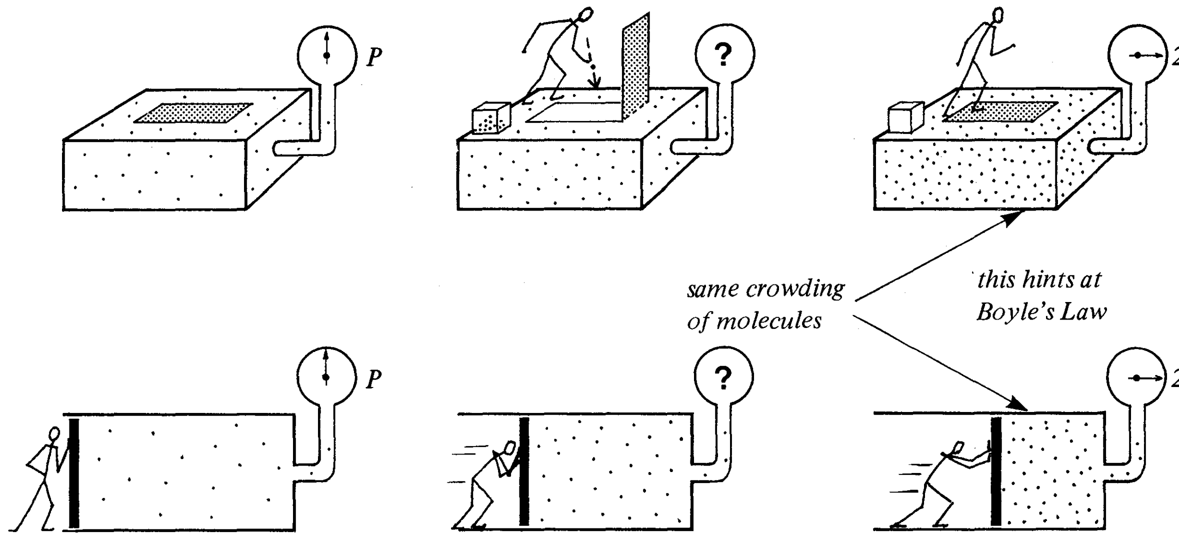
What happens then? Why is the piston driven outward again?

USEFUL THEORY?

It would not be good science to imagine gas molecules and tell stories about their moving to and fro very fast and colliding, and then make no use of our picture except to tell it to other people. That would just be inventing stories. But if we can put our picture to use in further thinking about gases and let it make predictions and help us to make new measurements, then it is useful.

Such a 'thinking' model, with the arguments that go with it, is a *theory* to sum up and develop our knowledge.

So we now do some thinking, and make a 'kinetic theory of gases'. ('Kinetic' means 'motion', as in 'cinema'.)



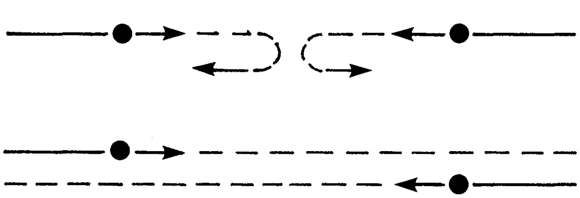
compress to HALF volume

SIMPLE THEORY: A QUICK PREDICTION

Suppose you have air (or any other gas) in a box. Imagine it is made up of molecules in rapid motion; and suppose that the pressure of the gas on the walls of the box is produced by the impact of bombarding molecules. Attach a pressure-gauge to the box of gas and read the pressure. Then suppose you put more and more molecules into the box until there are twice as many as before. (You might employ a microscopic demon to pop in additional molecules one by one, through a trap-door.)

When there are twice as many molecules as before, what pressure would you expect? With twice as many molecules to bombard the walls, you might expect double pressure.

Of course with more molecules, collisions will also happen more often in the middle of the box. But those internal collisions will not affect the bombardment on the walls, for the following reason. Suppose there are two molecules moving opposite ways, heading for opposite ends of the box where each will add its contribution to the pressure. If they *do not* collide but just pass by each other, each will arrive at its target end. If they *do* collide head-on, they will rebound, elastically. Then each of them takes on the other one's job and does what the other one would have done without a collision. (Remember the story of the two cars that meet on a very narrow mountain road. If the cars cannot pass, their drivers can still get to their destinations if each climbs into the other car and drives it backwards.)



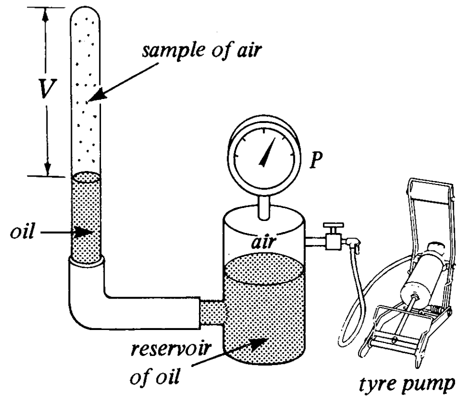
molecules collide and exchange motions or they may miss

Therefore we expect a double number of molecules to make double pressure. But all that the pressure-gauge can notice is a doubling of the local population of gas molecules, double *density*. And we can produce double density without putting in extra molecules if we push the end wall of the box in as a piston to make the volume half as big. Then the pressure-gauge would show double pressure in the same way.

Now we have got a prediction from our theory: *HALVING THE VOLUME WOULD DOUBLE THE PRESSURE.* Is that true?

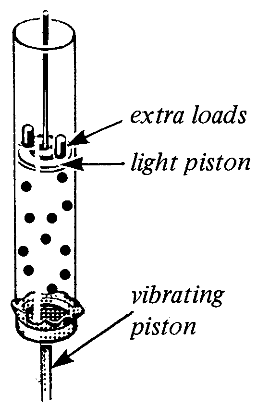
The experiment to find out was tried by Robert Boyle three centuries ago. He was not testing a theory as we are now, though he did make a theory about this experiment afterwards. He used a piston of mercury to compress some air to half the volume, then to smaller volumes still. He measured the pressures. He discovered a simple rule or law which we now name after him. And in 1661 he announced his law, which he said he discovered 'not without delight and satisfaction'.

Demonstration 70
Boyle's Law



See a test of the behaviour of air. A piston of oil compresses a sample of air. If experiment agrees with prediction we may think our argument has been a useful, clever, piece of science.

Demonstration 71a
Gas model to illustrate Boyle's Law



You may see the model used for this. Small loads are placed on a light movable piston above the tiny bouncing balls.

Experiment 71b
Crowding marbles in a tray: another illustration of Boyle's Law

a. First agitate the tray of marbles in the usual way. Then put a ruler across it to reduce the area occupied by the marbles. It is easy to hold the ruler still if you put a small book in the tray and hold the ruler firmly up against it.

What is the effect of reducing the area further still? Listen to the collisions with the walls.

b. Borrow some more marbles and add them to see how a 'compressed gas' behaves.

Questions

THEORY APPLIED TO BOYLE'S LAW

20. Answer questions (a) *i–v* and (b) *vi–x* by writing 'twice', 'half', 'three times', 'the same', etc., whichever you think to be the correct answer.

The sketch I shows air in a cylinder fitted with a very light air-tight piston. The air pressure is atmospheric inside and outside the cylinder. With no extra force applied, the piston stays where it is.

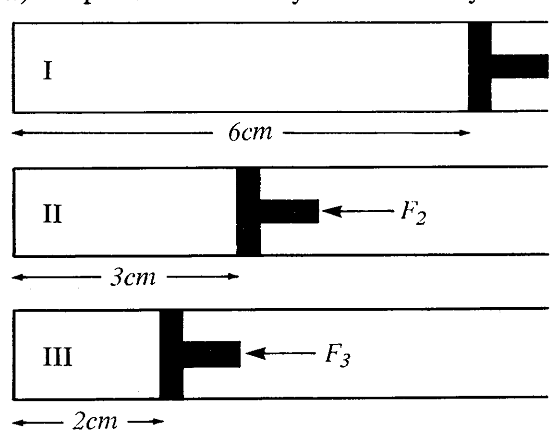
In sketch II the piston has been pushed in so that the enclosed air occupies half the length of the cylinder that it did before. Any heat produced has been allowed to leak away, and the temperature is the same as before. An extra force F_2 is now required to hold the piston in place. Similarly in sketch III the air occupies one-third of the length, the temperature is back at its original value and a larger force F_3 must be exerted.

a. Compare sketch II with sketch I. What can you say about:

(i) the total number of molecules enclosed? Is it 'the same' in II as in I, or 'twice', or 'one-third' or what?
(ii) the volume occupied by the air in the cylinder?
(iii) the number of molecules per cubic centimetre?
(iv) the average speed of a molecule?
(v) the pressure exerted by the air in the cylinder?

b. Now compare III with I. What can you say about:

(vi) the total number of molecules enclosed?
(vii) the volume of the air in the cylinder?
(viii) the number of molecules per cubic centimetre?
(ix) the average speed of a molecule?
(x) the pressure exerted by the air in the cylinder?



21. Robert Boyle tried to explain the behaviour he had discovered by making up a 'thinking' model. He imagined air to be made up of large particles that are close together but springy, like little balls of springy steel wool or sponge rubber.

a. How on his theory, would Boyle explain the pressure of a gas, and the fact that a gas resists being compressed?

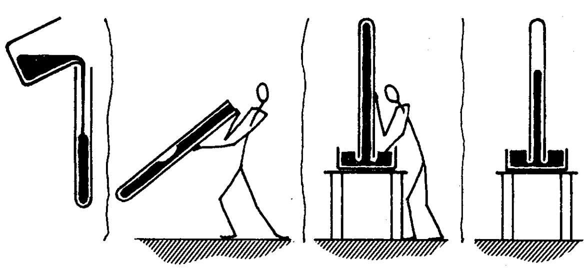
b. Boyle's observations and his law were based on good experiments; but his theory did not fit the facts well. Also it needed special assumptions that were no use elsewhere in science. We now have a different theory, which explains gas pressure by the idea of tiny particles far apart but in rapid motion.

How does our modern theory explain the fact that gases can exert pressure?

SPEED OF MOLECULES: NECESSARY EXPERIMENTS

Now we use our theory—our 'thinking' model of a gas to predict the speed of air molecules. Whichever way we do this, we shall need measurements from three experiments.

Experiment 72
Barometer



Watch a barometer being set up by your teacher. Measure the column of mercury that balances the atmosphere's pressure. Record this measurement. We call this the 'barometer height'.

Demonstration 73
Measurement of the density of air

How many kilograms of ordinary air fill one cubic metre?

Watch a demonstration of weighing a sample of air, and record it.

This may be done by weighing a glass flask before and after pumping the air out. The volume of air pumped out is found by letting water rush in to fill the flask.

(Or you may see it done by pumping a lot of air *into* a large rigid plastic container, which is weighed to find the mass of *extra air* pumped in. The extra air is let out and collected to measure its volume.)

From one of those experiments, calculate the *mass of air that occupies one cubic metre.* This is called the DENSITY OF AIR.

With air at room temperature, you will find a DENSITY about 1.2 kilograms per cubic metre.

Experiment 74
Quick comparison of the densities of water and mercury

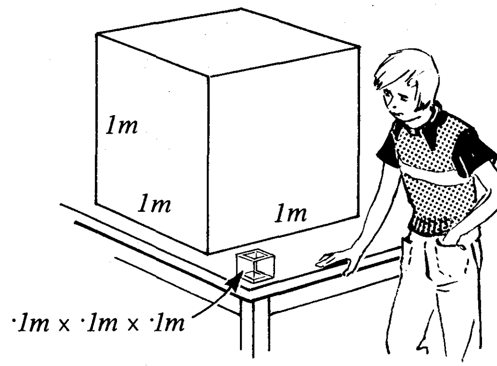
How many kilograms of *mercury* fill one cubic metre?

(i) You need to remember the density of *water*; then you can compare mercury with it. Here are details:
One cubic *centimetre* holds 1 *gram* of water. (That was the way the size of a gram was chosen, long ago. Nowadays you should either simply learn and remember this or see a demonstration of 1000 cubic cm of water being weighed.)
A box of inside dimensions 10 cm × 10 cm × 10 cm has volume 1000 cubic centimetres (1000 cm^3). That is 1 cubic decimetre or 1 litre. It holds 1 kilogram of water.
A metre cube is 100 cm × 100 cm × 100 cm; volume 1 000 000 cubic centimetres (1000 litres). Therefore a cubic metre holds 1 000 000 grams or 1000 kilograms of water.

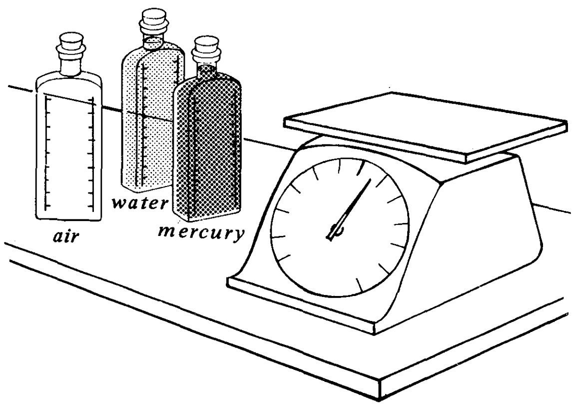
A value to remember: *density of water*, in modern units, is 1000 kg for each cubic metre.

(ii) Comparison of water and mercury.

Weigh three bottles of the same size, one full of



mercury, one full of water, one empty (air). Such weighings show that mercury is 13.6 times as dense as water.



(iii) From *(i)* and *(ii)* *density of mercury is 13 600 kilograms per cubic metre.*

SPEED

With our 'kinetic' theory we can predict the speed of air molecules. We offer two ways of making the prediction, one way here, the other in the next chapter.

SIMPLE METHOD OF PREDICTING AIR-MOLECULE SPEEDS

The usual method of making a theory of gas molecules and using it to find their speed does need some algebra. Here is a simple method, with some risky imagining to save doing the algebra. Try this method if you like.

The ocean of air above us Think of the atmosphere pressing on everything. The pressure is made by air molecules bouncing on every surface; but we can think of it in a different way. You would feel great pressure if you descended as a diver to the bottom of the sea. We experience atmospheric pressure because we are, so to speak, at the bottom of an ocean of air.

As you climb higher through that ocean, the pressure gets smaller as the air gets thinner. In imagination a man in a rising balloon experiences a Boyle's Law experiment.

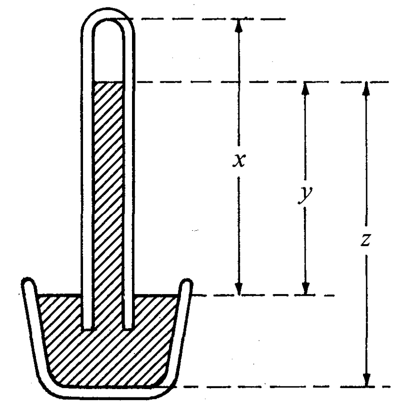
The demonstration model can show you this.

Demonstration 75
Model showing thinner atmosphere higher up

Look at the 'atmosphere' of 'molecules' carefully.

Look at a barometer and record the *height of mercury* that balances the pressure of the ocean of air above us.

Questions



22. The diagram shows a simple barometer.

a. What does it measure?

b. Which height does one measure x, y or z?

c. Why use mercury in it (not more than two reasons)?

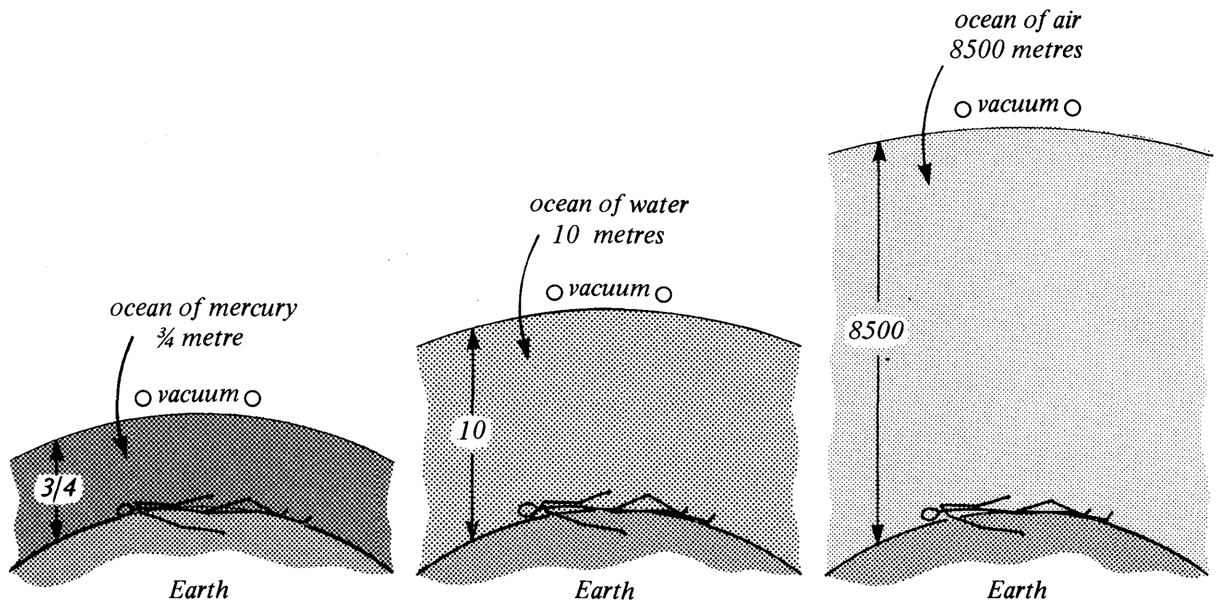
d. What is there in the tube above the mercury?

e. Does the temperature of the barometer make any difference to its reading? Explain briefly.

f. Suppose mercury were used which was still damp with water after a previous experiment. Would this make any difference?

23. After seeing the density of air measured, make a rough estimate of the mass of air in your lab or classroom. Is it nearest to 1 kilogram (2.2 lbs), 10 kg, 100 kg, 500 kg ($= \frac{1}{2}$ tonne), 1 tonne . . . ?

Which weighs more, you or that air?



The argument Now imagine, just for fun, that you are living at the bottom of an atmosphere of *mercury* instead of the real air. You lie on the floor and feel the mercury pressing on you. How high will that 'mercury atmosphere' have to be from the floor to the top of the mercury, if that is all there is to make the pressure on you? The pressure is to be the same as the real atmosphere's pressure.

When you have guessed the answer to this question, think about an ocean of *air* above you: *air which is as thick as the air in the room* all the way up to the 'top of the atmosphere', with nothing more above it.* Air is much less dense, so a much greater height of room air is needed to make the same pressure. To find the height of that atmosphere of 'room air' you need to compare the densities of mercury and air.

If a bottle of air weighed $\frac{1}{1000}$ as much as a bottle of mercury, the air atmosphere would have to be 1000 times as high—but the real proportion makes a still bigger difference.

The density of air is 1.2 kg per cubic metre, but the density of mercury is 13 600 kg per cubic metre. That is, mercury is $\frac{13\,600}{1\cdot 2}$ or about 11 300 times denser than air.

Then the imaginary ocean of 'room air' must be 11 300 times as high as the mercury atmosphere you guessed. *How much is that?*

Now think of the tiny molecules in that atmosphere. A molecule which happens to be at the very top must be at rest.** It is only at rest for the moment; it falls, faster and faster, accelerating like any other falling object. It does not flutter down like a sheet of paper, slowed by air resistance, because it *is* just an air molecule itself, falling freely through the empty space between other molecules.

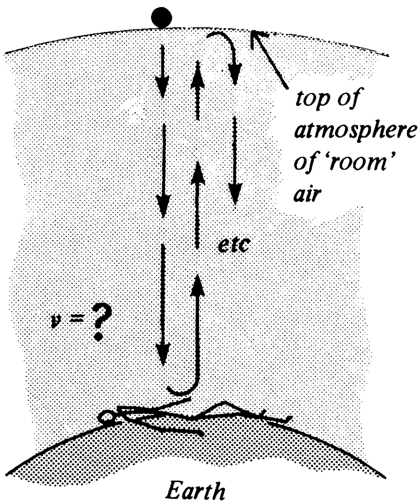
Then it will be moving very fast when it reaches you on the ground and bounces on you. No wonder air molecules can make a big pressure.

Many such molecules fall, arrive at you or the floor, and bounce back upward without losing energy. They go up and up, slower and slower, to the top of the atmosphere, stop there momentarily, then fall down again . . . and so on.

* This is not a realistic picture: the real atmosphere gets thinner and thinner as you go higher and higher, and it extends up a very long way. (Look at the demonstration model of a gas.) But this is an artificial short cut to help you to find out about molecule speeds.

This is a case of 'desperate measures for desperate needs'. We call this 'desperate physics'. Such a short-cut is neither an insult to your age nor a scientific lie. Scientists often attack a problem in this way in science, especially in the most modern science of all. They think of a much simpler problem than the real one and try to solve it to get at least a rough answer. The rough answer is like knowing which county some town is in, before one goes into more detail with a map. We call that an 'order of magnitude estimate'.

** It cannot be moving *upward* at the top, or the top would have to be higher still! And it cannot be moving *downward* at the top or it would have to have fallen from higher still! So at the top it must just be at rest.



(If a falling molecule happened to hit another molecule on the way down, they would simply exchange motions; so we forget about that possibility.)

Calculate the speed of an air molecule just before it hits you at ground level. Use the formula for an object falling from rest with gravity acceleration (from Chapter 1A):

$$s = \tfrac{1}{2}at^2$$
$$8500 \text{ metres} = \tfrac{1}{2}[9.8 \text{ metre/second}^2]\,t^2$$
$$\therefore t^2 = 2 \times 8500/9.8$$
$$\therefore t = 42 \text{ seconds}$$
$$\therefore v = at = 9.8 \times 42 = 410 \text{ metre/second}$$

Or if you know $v^2 = 2as$, use that:

$$v^2 = 2 \times [\text{ACCELERATION}] \times [\text{DISTANCE FALLEN FROM REST}]$$
$$= 2 \times [9.8 \text{ metre/second}^2] \times [11\,300 \times \text{BAROMETER HEIGHT}]$$

Put in your measurement of BAROMETER HEIGHT in metres. Take the square root to find v.

This is a *very* rough estimate of the speed of an air molecule when it reaches you. That is not the speed of all air molecules around you, but only an average of many different speeds. And in fact this story of imagining a special atmosphere leads to a fairly large error. Yet the result gives a fair idea of the air molecules' terrific speed.

A real speed Gas molecules do move with such great speeds, even at room temperature, and faster still when the gases are hotter.

It would be difficult to show you a direct demonstration of the speed of air molecules, because we cannot make them visible. But you can see the motion of the molecules of bromine vapour because it is brown. See the demonstration which is described at the beginning of the next chapter.

CHAPTER 7

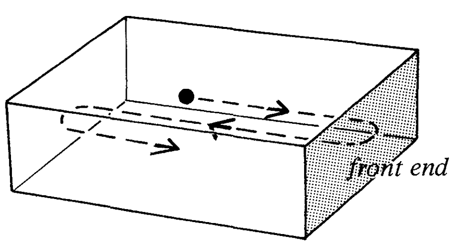
GASES II
RICHER PREDICTIONS

Molecular theory and its predictions: molecules' speeds; diffusion; a suggestion of Boyle's Law and support from speed of sound.

MORE ADVANCED METHODS

PREPARING THE THEORY

We shall take for granted the picture of gases made of tiny speedy molecules making perfectly elastic collisions. We imagine a box full of gas molecules flying about in all directions at random. At first we pretend to know the SPEED of the molecules, the mass of each molecule, the *number of molecules* in the box. We try to calculate how big the pressure would be on the wall of the box *ASSUMING* that the pressure is simply due to bombardment by molecules.



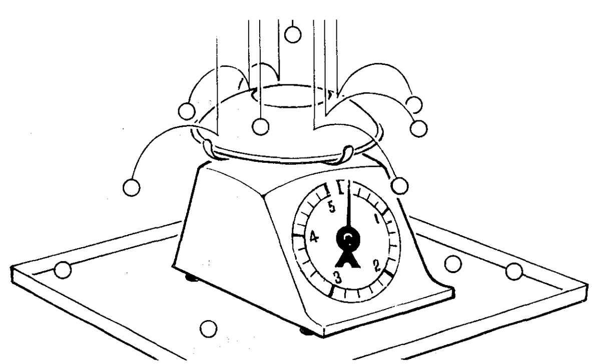
one molecule in a box

Think about one molecule which is moving along the *length* of the box. It hits the front end, *bang*; it bounces back and flies along towards the opposite end and hits that, *bing*; rebounds and flies back to the front end, *bang*; . . . *bing*; . . . *bang*; . . . *bing*; . . . *bang*; . . . and so on.

The front end of the box receives a small bang from a molecule every so often: *bang*. . . . . . *bang*. . . . . . *bang*. . . . . . and so on. Each bang is a tiny blow, but if there are millions of millions of millions of millions of molecules in the box, these blows coming one after another in rapid succession will make something that feels like a smooth, steady pressure. See the following experiment to illustrate that.

†Demonstration 67
Pressure made by collisions of a stream of balls

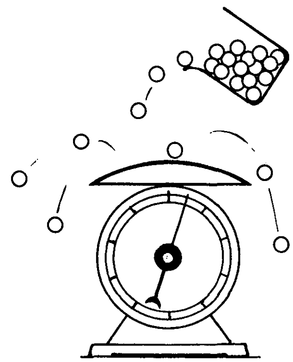
Pour a stream of marbles, or metal balls or dried peas onto a spring weighing-scale from above. There should be a curved pan upside down on top of the scale, so that the balls roll off and do not build up a stationary load on the scale.



Progress Question

A SERIES OF BUMPS

1. This balance has had its pan turned over. Marbles or steel balls are then poured onto the pan, but can't stay on it.



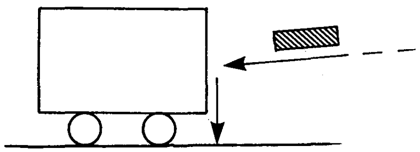
a. What do you see the pointer doing if the balls come slowly after one another, bump, bump, bump?

b. What do you see the pointer doing if balls come in a steady stream to hit the pan?

Questions

COLLISIONS

2. Some children are trying to move a small truck by throwing bricks at it. Each brick has mass 0.5 kg and is moving horizontally at about 10 metre per second when it hits the truck. After hitting the truck, each brick falls straight to the ground.

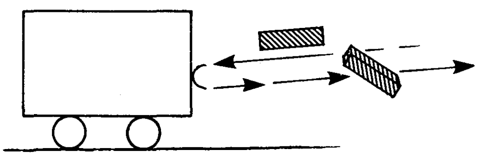


a. How much momentum does each brick have:
(i) just before hitting the truck?
(ii) just after hitting the truck?

b. How much momentum does each brick lose in a collision?

c. How much momentum does the truck gain in a collision?

Next, the children use very elastic rubber blocks, each of mass 0.5 kg. These hit the truck at 10 metre per second *but bounce straight back again* with the same speed.



d. How much momentum does each block have:
(i) before it hits the truck?
(ii) after it hits the truck?

e. So what is the *change* of momentum of a block because of its collision with the truck? *Hint:* the answer is *not* zero.

f. How much momentum does the truck gain at each collision?

g. If 20 blocks per second hit the truck, how much momentum does it gain in a second?

3. You can calculate the force, F, on the truck in Question 2 due to a stream of 20 blocks per second hitting it.

$$Ft = \text{change of MOMENTUM}$$

$$F \times 1 \text{ second} = \text{change of MOMENTUM of truck in 1 second}$$

Work out F from here.

In the predictions ahead, we can calculate:
how much one *bang* will do to the end wall;
how big a FORCE the steady series of bangs will make;
how big the FORCE will be for *ALL* the molecules in the box;
then THE PRESSURE, by dividing that FORCE by the AREA of the end walls.

That will be our prediction of the pressure.

This *is* theory: the thinking scientists do to tell them what to look for and to help them build more knowledge. As you read ahead, watch how we do it. You may find this difficult the first time but much easier later on: and it should be something that you will enjoy understanding.

You will *NOT* have to write all this out in an examination, but you should know what we did, and why we did it, and what we found.

Here are two methods of developing the theory, one that uses arithmetic, and another that goes quickly by using algebra. Try whichever you prefer as a series of learning-questions.

THE ARITHMETIC ATTACK

This long Question 4 is really a set of connected problems A to F. These lead you through stages of learning so that you understand what we can calculate for air molecules.

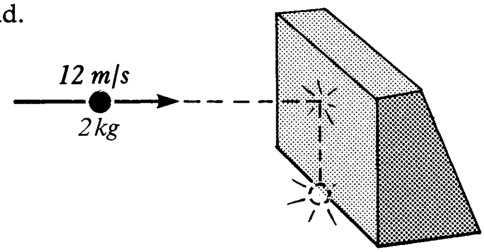
Then go on to Question 5 which is a set of connected algebra problems G. Work your way through them to understand the quick method that scientists use.

Question 4
(A series of problems to help learning)

COLLISIONS

Problem A Impact of a ball on a wall

A ball of mass 2 kilograms, moving 12 metre per second, hits a massive wall *head-on* and stops dead.



a. How much MOMENTUM did the ball have *before* impact. Answer . . ? . . kg·metre/second.

b. How much MOMENTUM does the ball have when it has stopped, *after* impact?

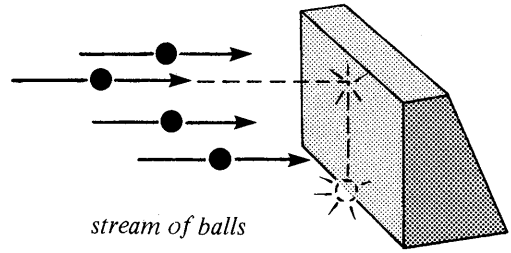
c. How much MOMENTUM did the ball *lose* during impact?

d. Assume that Newton's Third Law is correct and applies to this case. How much MOMENTUM did the *wall* gain?

Problem B Force due to a stream of balls hitting a wall

Now suppose the wall is hit by a *stream of balls*, each a 2-kilogram ball, moving 12 metre per second. The balls hit the wall *head on* and stop dead.

Suppose 1000 such balls hit the wall in the course of 10 seconds.



stream of balls

a. How much MOMENTUM do the 1000 balls lose?

b. How much MOMENTUM does the wall *gain* in that 10-second period?

c. Now calculate the FORCE on the wall. Remember that:

(FORCE) × (TIME) = (CHANGE OF MOMENTUM)

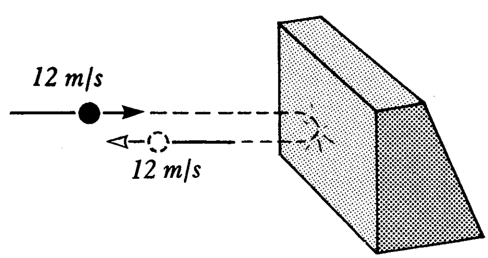
(*Hint:* all that momentum was given to the wall in a time of 10 seconds.)

What force is it that you have calculated there? The balls arrive one after another, each making a bump on the wall. Yet here you have calculated a force for the whole 10-second period, while 1000 balls bump the wall.

You have *not* calculated the very big force that a ball makes *for the very short time while it is bumping and coming to a stop*. You have calculated a 'smeared-out', average, force.

(Suppose, instead of the solid wall, the balls hit a light target of plywood, hung from a tree. The target would certainly show something like Brownian motion as the balls hit it and make it swing irregularly. But if a massive steel target were hung up instead, its Brownian motion would be too small to notice: and a device for measuring the force on that massive target would register the smoothed-out value.)

Problem C Force due to a stream of elastic balls



Suppose the wall is hit by a stream of 2-kilogram balls each moving 12 metre per second.

But in this case each ball arrives with speed 12 metre per second *and bounces straight back* with equal speed 12 metre per second in the opposite direction. As in Problem B, 1000 balls arrive at the wall in 10 seconds.

a. Calculate the CHANGE OF MOMENTUM when *one* ball arrives at the wall and bounces away.

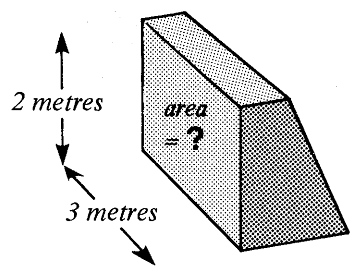
(*Hint :* the change of momentum is *not* zero. When something changes from $+5$ to -5, how much is the total change? For example: suppose a boy climbs from a cellar 5 metres *below* ground to an attic 5 metres *above*. How far does he climb, 0 metres or 10 metres?)

b. Calculate the CHANGE OF MOMENTUM for all the 1000 balls.

c. Calculate the AVERAGE FORCE on the wall during that 10-second period.

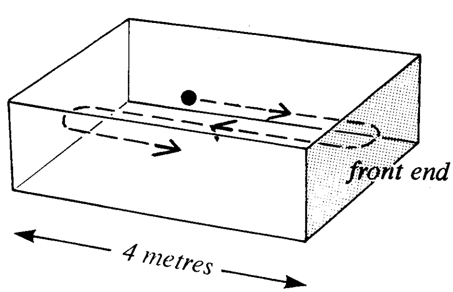
Problem D Pressure on a wall

In Problem C you calculated the FORCE on the wall. Now calculate the PRESSURE on the wall if the balls hit various places all over a wall which is 2 metres high by 3 metres wide. (Remember that pressure is FORCE/AREA.)



Problem E Pressure on wall of a box

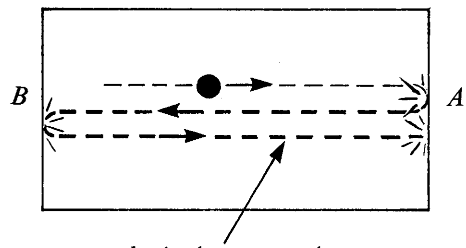
Now suppose that you have a *closed box* containing just *one* elastic ball moving to and fro between the ends. It is a 2-kilogram ball moving 12 metre per second parallel to the length of a box 4 metres long. Calculate the AVERAGE FORCE on one end.



In this case, instead of using the *number of balls* hitting a wall once you must use the *number of hits made by one ball* on its repeated returns to the front end. Calculate how many times the ball hits the front end in 10 seconds, by the stages (a) to (e) below:

a. How far does the ball travel *altogether* in 10 seconds with speed 12 metre/second?

b. How far does it travel between successive hits on the front end A? (It hits the front end A, travels all the way to the other end, B, and back to A.)

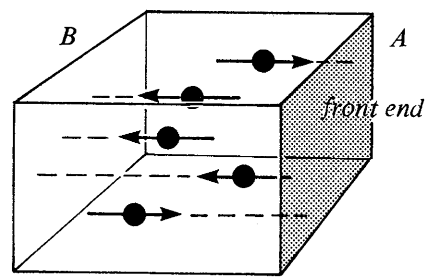


round trip 4 metres + 4 metres

c. Then, how many 'round trips' does it make (from A to B to A) in 10 seconds?

d. How many hits does it make on end A, in 10 seconds?

e. Using the same method as before, calculate the average force on end A, and then the pressure.

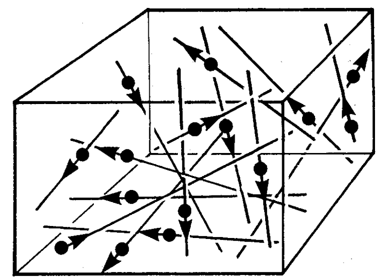


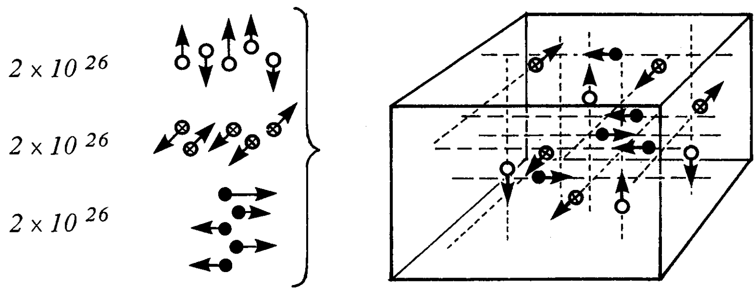
Problem F Molecules in a box *(arithmetic version of the Theory of Gases)*.

Now we are ready to calculate force due to bombardment by molecules and the pressure which that makes. Suppose we have a box 4 metres long by 3 metres by 2 metres, containing ordinary air at room temperature. Such a volume contains about 6×10^{26} molecules of air. At room temperature, air molecules move with average speed 500 metre per second. The average mass of an air molecule is 5×10^{-26} kilogram. Now, we have a very complicated picture: molecules flying about in all directions, like tiny birds in a large cage.

It is hard to calculate changes of momentum with molecules moving in slanting directions and rebounding from collisions in other directions. So we use a trick. We pretend that the molecules are arranged in three regiments, one moving to and fro between the ends, another moving forward and back between front and back faces of the box, another moving up and down between top and bottom. We pretend there are just $\frac{1}{3}$ of all the molecules in each of these 3 regiments. Therefore to calculate the pressure on end A of the box we take only 2×10^{26} molecules as moving to and fro between the ends A and B.

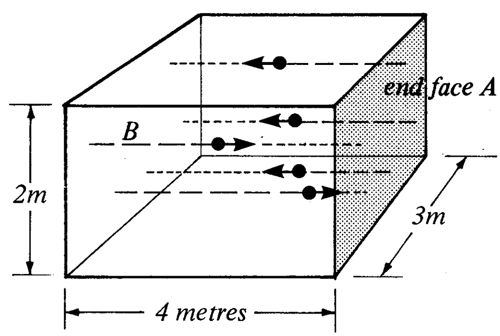
Box containing 6×10^{26} molecules in random motion





Instead of random directions of motion, pretend there are three regiments, each of 2×10^{26} molecules having full velocity and moving parallel to one edge of the box.

Assume that the pressure on end face is due to impacts by one regiment of 2×10^{26} molecules, moving to-and-fro parallel to the length of the box.



a. How much momentum has one molecule got, as it moves towards the end A? . . ? . . kg m/s.

b. How much momentum has it got after rebounding from end A? (Remember it is now moving in the *opposite direction*.)

c. What is the change of momentum when the molecule hits the end wall? (Calculate this from the two answers above.)

d. To find how many hits the molecule makes on end A in 10 seconds, calculate:
(i) The total distance the molecule travels in 10 seconds, with its speed 500 metre/second.
(ii) The length of one round trip from end A to end B and back to A.
(iii) The number of round trips in 10 seconds. . . .

e. Calculate the total change of momentum at end A that happens to this single molecule in 10 seconds.

f. Remember that according to our imaginary scheme of three regiments there are 2×10^{26} molecules moving to and fro between the ends A and B of the box. What is the total change of momentum at end A for all of them in 10 seconds?

g. What is the force on end A, due to those collisions?

h. What is the pressure on end A?

That is a long piece of arithmetic. If you have carried it through successfully you will find the force is just about 100 000 newton per square metre.

THE ALGEBRA METHOD

In that arithmetic we gave you all the data in numbers, including the speed of the molecules. That was just for practice. Now try using algebra in the same way and you will find that you can reverse the calculation and estimate that speed from some simple measurements.

Question 5
A series of steps to help learning
ALGEBRA VERSION

Problem G Molecules in a box

Suppose there are N molecules in a box. The box has length a and other sides b and c. Each molecule has mass m, and moves with average speed v.

a. What is the MOMENTUM of one molecule moving along the length of the box to hit the front end of the box, A? (See Problem E.)

b. What is the MOMENTUM of that molecule when it has just bounced back from end A? (We have to assume that the molecules are completely elastic, so we expect the same *speed* afterwards. But the molecule is moving in the *opposite direction*.)

c. What is the CHANGE OF MOMENTUM of the molecule when it hits end A and bounces back?

d. How far does the molecule travel altogether in time t with speed v?

e. How far does the molecule travel in one round trip along the length of the box, between one hit on end A and the next hit on end A?

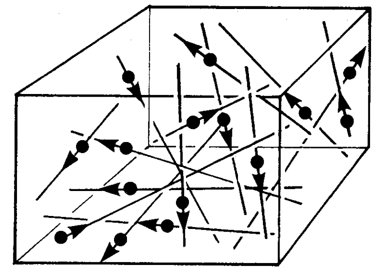
f. How many round trips does it make in time t? (Use the answers to d and e.)

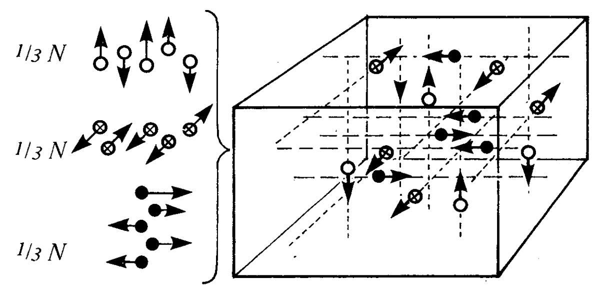
g. How many hits does it make on end A in time t?

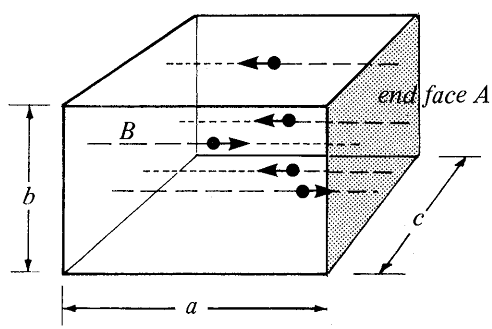
h. What is the *total* CHANGE OF MOMENTUM at end A in time t, for one molecule moving to and fro along the length?

i. Now use a simplifying trick. Instead of the molecules moving in many different directions, as they really do, pretend that there are only three armies of molecules, one army moving to and fro parallel to the length of the box, one moving to and fro across the width of the box, one moving up and down vertically. This is an artificial trick but it will lead to the same answer as full statistics of motions in all different directions. So if there are N molecules in a box, each of those three armies will have $\frac{1}{3}N$ molecules. Write down the number of molecules in the army moving to and fro between the ends A and B.

Box containing N molecules in random motion







j. Calculate the *total* CHANGE OF MOMENTUM at end A in t seconds.

k. Calculate the FORCE on end A.

l. Calculate the PRESSURE on end A, which has area $b \times c$. (Remember that PRESSURE = FORCE/AREA.)

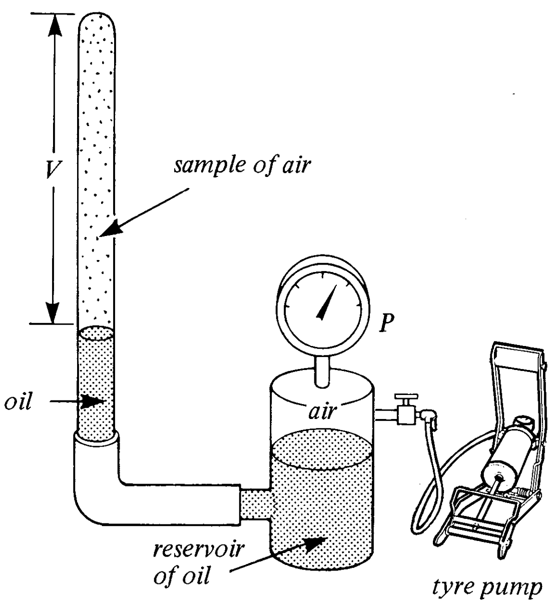
m. What is the volume of the box whose sides are a, b and c?

n. Then express in symbols the value of PRESSURE × VOLUME. $P \times V = \ldots ? \ldots$

That may seem a long, puzzling calculation the first time you try it, but you have carried out a great piece of theory in science. When you try it again it is likely to seem much easier. Now put it to use.

A PREDICTION: THE SPRINGINESS OF AIR: BOYLE'S LAW

What happens to the pressure of a sample of air if you compress it to half the volume? You can answer this question by an experiment. You should see that experiment if you have not seen it already and understood its message.



†Demonstration 70
Boyle's law

Compress a sample of air by a piston of oil, with the pressure measured on a gauge. If you wait at each stage until the air settles down to room temperature, you will see a simple rule of behaviour—though it is not the same rule as Hooke's Law for compressing a metal spring. This experiment was done by Robert Boyle three hundred years ago. He was pleased with his discovery concerning 'The Spring of the Air', and he said that he observed his successful test 'not without delight and satisfaction'.

You can predict Boyle's Law, by arguing from your new theory. If you could be sure that the molecules' average speed *stays the same when you compress the gas* (so that v^2 remains the same), then everything on the right-hand side of your result for $P \times V$ stays constant. In that case Pressure $\times$ Volume is constant. And that *is* Boyle's Law.

Doubts But *does* the average speed v stay the same? In fact it does, as long as you keep the sample of air or other gas *at the same temperature.* But you need some experimental assurance of this; and you will hear about that later. So, *if* you accept that v stays constant, you can say $P \times V$ is constant at constant temperature.

Magic? We seem to have got Boyle's Law out of the algebra like a conjuror getting a rabbit out of a hat. But, just as the conjuror really has to get the rabbit secretly *into* the hat first, we have to get many assumptions into our theory to build up that result $PV = \frac{1}{3}Nmv^2$. We assumed that molecules exist. What else did we assume concerning them? Think of as many assumptions as you can.

Question

BOYLE'S LAW

6. You saw an experiment using this apparatus to find out about changes in volume and pressure of a gas (air). Readings were taken of the pressure P and of the volume V of the air trapped in the tube.

a. Was the temperature of the trapped air changed during the experiment, or not?

b. Did you let any air in or out?

c. If the pressure was doubled, did you find that the volume was doubled, or stayed the same, or was halved?

d. Which of the following statements best fits the results obtained?
(i) $P \times V$ always came to about the same answer.
(ii) $P + V$ always came to about the same answer.
(iii) $P - V$ always came to about the same answer.
(iv) $P \div V$ always came to about the same answer.

If $PV = \frac{1}{3}Nmv^2$, then $v^2 = 3PV/Nm$
Nm = (NUMBER of molecules) × (MASS of one molecule) = the TOTAL MASS, M, of gas in the box.
∴ v^2 = 3(PRESSURE) × (VOLUME)/(MASS of gas in that sample)
∴ you can calculate the speed of air molecules from measurements of PRESSURE and the VOLUME and MASS of a sample.

PRESSURE of air in the atmosphere is measured with a mercury barometer. This is just a U-tube with mercury in it, with air pressure on one side (the large open pool) and vacuum on the other side. The atmosphere's pressure is balanced by the pressure of the 'barometer height' of mercury, h, which you should measure.

†Demonstration 72
Barometer to measure pressure of the air

If you did not see a mercury barometer being set up to measure the pressure of the air in the room, you should see that being done now. In any case, go to a barometer and measure the height of the pillar of mercury that balances atmospheric pressure.

PRESSURE is force on each unit area, or FORCE/AREA. You need to calculate the atmosphere's pressure, in *newton per square metre*, from the barometer height, h. Suppose the cross-section area of the inside of the barometer tube is A. (You do not know the actual value of A and you will not need it because it will cancel out.)

Pressure due to the barometer's column h is its WEIGHT (the pull of the Earth upon it) divided by its AREA A. To calculate this pressure, proceed as follows:

(i) Calculate the *volume* of mercury in the column h, whose pressure balances the atmosphere. It is (BAROMETER HEIGHT) × (AREA) $h \times A$.

(ii) Calculate the *mass* of mercury in this volume. (1 cubic metre of water has mass 1000 kilograms, and mercury is 13.6 times as dense as water. So one cubic metre of mercury has mass 13 600 kilograms.)
∴ The mass of mercury in the pillar is (BAROMETER HEIGHT) × (AREA) × (13 600) = $h \times A \times 13\,600$.

(iii) Calculate the weight of this pillar of mercury which sits on 1 square metre. The Earth pulls on each kilogram of matter near the Earth's surface with a force of 9.8 newtons.

Therefore the WEIGHT of that pillar of mercury is:
$h \times A \times (13\,600\ \text{kg/m}^3) \times (9.8\ \text{newton/kg})$.

Divide by area A to find the pressure.

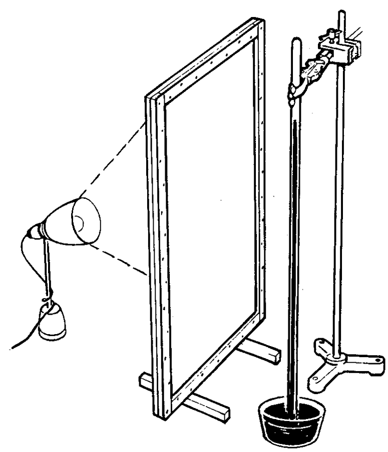
$$\text{PRESSURE} = \frac{h \cdot A \cdot (13\,600)(9.8)}{A}$$

And with h in metres, the units are:

$$\frac{\text{m} \times \text{m}^2 \times \dfrac{\text{kg}}{\text{m}^3} \times \dfrac{\text{N}}{\text{kg}}}{\text{m}^2}$$

which boils down to $\dfrac{\text{newtons}}{\text{square metre}}$

So PRESSURE = $h(13\,600)(9.8)\ \text{N/m}^2$



WEIGHING A SAMPLE OF AIR

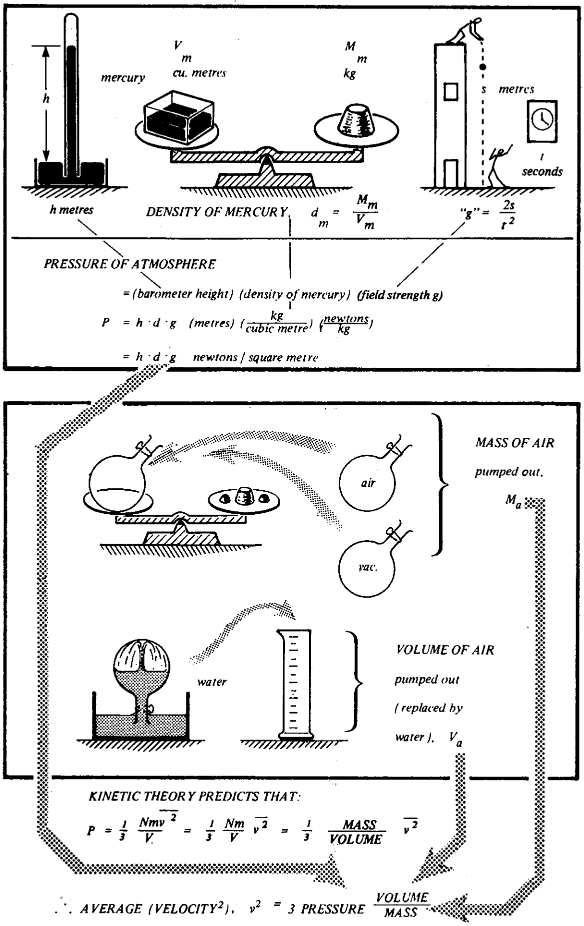
If you have not seen this done, see it now.

†Demonstration 73A

How many kilograms of air fill one cubic metre?* A large glass flask full of air is weighed, then weighed empty (vacuum). The difference tells you the mass of air pumped out. The volume of this air is measured by letting water rush in to fill

* You may see another method instead, †Demonstration 73B. A large plastic box full of air is weighed. Then some more air is pumped in and the box is weighed again. The *extra* air is let out and collected over water and measured. Then you know the MASS of *extra* air and its VOLUME and you use these in the calculation.

the vacuum. The volume of water is measured. Then use the MASS and VOLUME of that sample in your calculation of v^2.



Questions

WEIGHING AIR

7. You have a foot pump, an empty plastic cider flask, a balance, rubber tubing, a trough of water and a perspex box which holds 1000 cm^3. How would you use these to weigh air?

8. 1000 cm^3 of ordinary air weighs 1.2 grams.
1000 cm^3 of liquid air weighs 900 grams.

How many times more dense is liquid air than ordinary air? So how many times more molecules are there in 1000 cm^3 of liquid air compared with ordinary air?

If 1 cm^3 of liquid air turned suddenly into ordinary air, which you could catch, at room temperature, how much space would it take up?

Calculating the speed

Then $v^2 = 3$(PRESSURE) (VOLUME)/(MASS)

$\therefore v = . . ? . .$

This is an *average* speed.

An incredible speed! What has gone wrong? Can air molecules really be moving as fast as this? In fact, air molecules *are* travelling at this kind of speed and you will see a demonstration to support that surprising idea.

Of course, some molecules are travelling faster than this estimate, and others slower, just as in a large group of people some are richer than average and some are poorer than average; but—unlike rich and poor, who often stay like that—an air molecule that is moving slowly now may be moving much faster than average after the next collision; and a faster one may be slowed down. Air molecules collide with each other frequently and exchange kinetic energy in collisions, so their speeds change often and a lot. Yet the whole collection keeps the same total kinetic energy all the time. Therefore (dividing by the total number of molecules), the *average kinetic energy per molecule* stays the same all the time.

A tally of molecule speeds looks like the one sketched in Question 4 of Chapter 8.

Question

9. Some of the following statements are not true. Others are correct. Copy out the correct ones:

A. When gas molecules are on their own, they travel very fast.

B. Gas molecules always move at the same speed.

C. When gas molecules are packed together, they move quite slowly because they keep bumping into each other.

D. All the molecules in a gas have the same speed.

E. In a gas some molecules will be moving very fast and some very slowly, so we should talk about the *average* speed of the molecules.

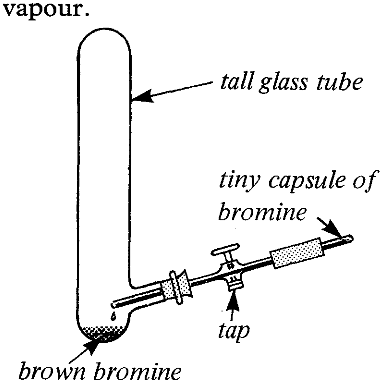
F. Each molecule keeps moving at the same speed.

G. Each molecule keeps changing its speed as it bumps into other molecules.

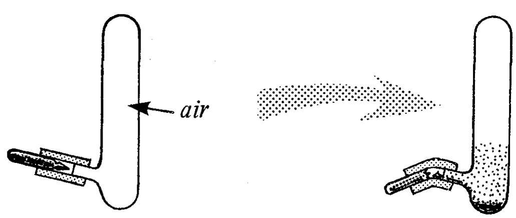
A direct illustration of molecule speed? It is possible to show, and even measure, the speed of gas molecules—just as you can time the motion of rifle bullets. It is difficult to do that with air molecules because they are invisible. But we can do that with the molecules of brown bromine vapour.

Demonstration 76
High speed molecules? Bromine 'gas' diffusing in air

Even if you have seen this before, watch it again now. A little bromine in liquid form is released and put in a tall tube of air. Watch the progress of the brown vapour.




bromine in glass capsule



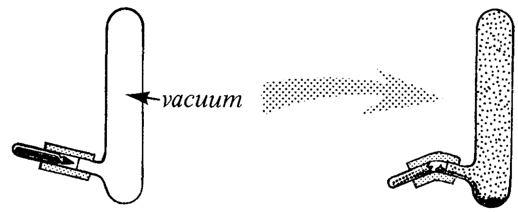
bromine released in air

When you have seen this, think about the motion. Was it as fast as you hoped? What experiment would you like to see next?

Now watch an experiment which might show you the great speed of bromine molecules.

Demonstration 77
High speed molecules! Bromine diffusing in vacuum

See the demonstration repeated with the air removed from the tall tube beforehand.



bromine released in vacuum

Progress Question

BROMINE EXPERIMENT

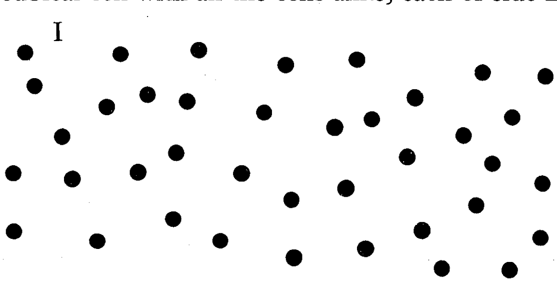
10a. You start with the large tube full of air. What do you see when you let the brown gas in?

b. You start again, and this time you pump the air out of the large tube first. What do you see when you let the brown gas into the empty tube?

c. What you see in **b** is different from **a**. Explain why.

MORE HELP FROM THEORY: HOW FAR APART ARE THE MOLECULES IN AIR?

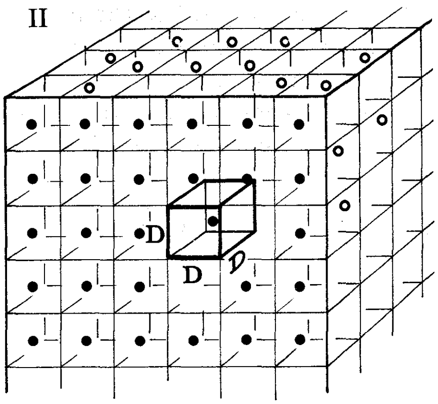
Sketch I shows a 'snapshot' of air molecules. They are in random disorder, and of course they are really moving fast. Pretend you can re-organise them into a regimented pattern, each molecule in a cubical cell with all the cells alike, each of side D,



Sketch II. Then the distance of one molecule from its nearest neighbour is also D. So D would tell you some kind of 'average spacing-apart' of molecules in common air. Then the volume of space in which there is one molecule is D^3, Sketch III.

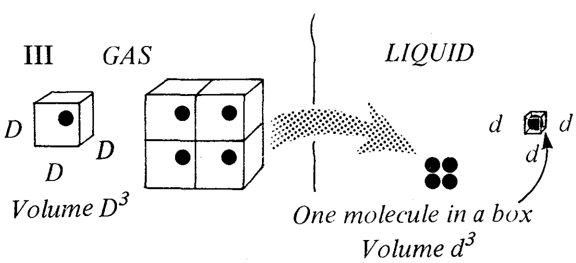
Now use your scientific imagination and think about molecules in liquid. They must be much closer together, though still mainly in random disorder and still moving quite fast between their very frequent collisions. For a rough idea, you may picture each molecule in a small box that just fits it, a cubical box of side d, where d is the 'diameter' of a molecule.

II



Picture these boxes stacked side by side in a cubical array. Then one molecule in liquid would occupy a space of volume d^3 and in gas form it would occupy a volume D^3. The proportion between D^3 and d^3 must be the same for every molecule. So it is the same for the whole lot, for all the molecules in a sample.

III



Volume change We need to measure that proportion of volume:

$$\frac{\text{(VOLUME OF SAMPLE IN GAS FORM)}}{\text{(VOLUME OF SAME SAMPLE IN LIQUID FORM)}}$$

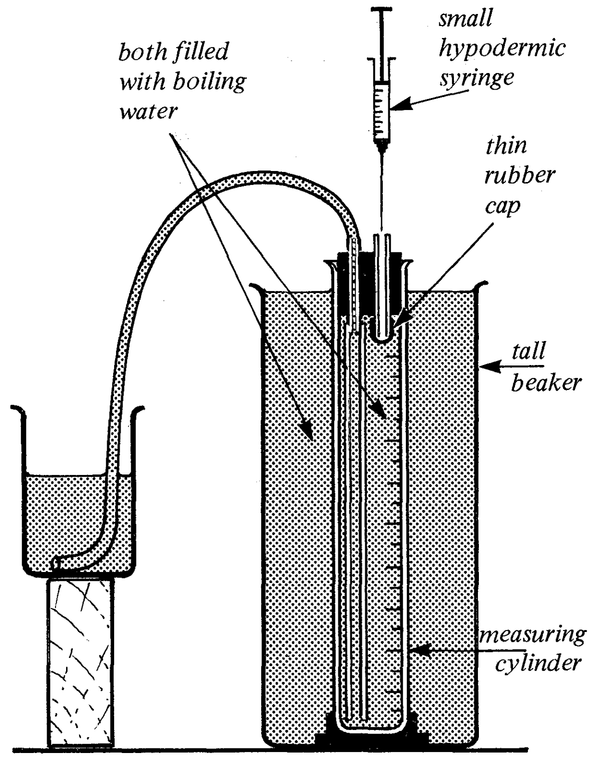
because this will tell us D^3/d^3, from which we can find D/d, which tells us how by many molecule diameters air molecules are spaced apart.

If your school is lucky enough to be able to get some liquid air, you may see that volume-change measured with air itself, Demonstration 78.

Otherwise, see the measurement made with petrol, which shows a similar expansion.* (You are now entering a region of 'desperate physics' where we resort to short cuts and rough estimates because we are so anxious to get *some* information about molecules and atoms.)

Demonstration 78
Change of volume, liquid to gas, using petrol

See this tried, with the apparatus sketched.



Then think about the case of air molecules. If you could see it done, the expansion from liquid air to air would be about 1 to 750. Then if D^3/d^3 is 750 what would D/d be? How far apart are air molecules spaced according to this, compared with their diameter?

ANOTHER LINE OF EVIDENCE: SPEED OF SOUND

Think about sound waves travelling through air. If the molecules are far apart and moving about independently, how can a sound wave travel from one person's mouth to another person's ear? The mouth must bunch some molecules closer together (and soon after that some spread farther apart); and then the close bunching must travel out through the molecules of the room. It cannot travel faster than the molecules themselves—how could the message of bunching do that? But since it is probably carried by the moving molecules, the bunching should travel with a speed something

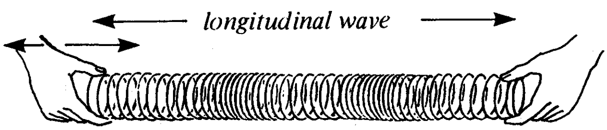
---

* Most materials show similar large changes of volume, between 1 to 500 and 1 to 1000. Water is exceptional. The change from water to steam is 1 to 1600.

like molecule speed, but a bit smaller. (In fact, both calculations with Newton's laws of motion, and experiments, show that the bunching, which *is* a sound wave, travels at about $\frac{2}{3}$ of molecule speed.)

You should see the speed of sound measured, but first watch some models to remind you of this kind of wave motion.

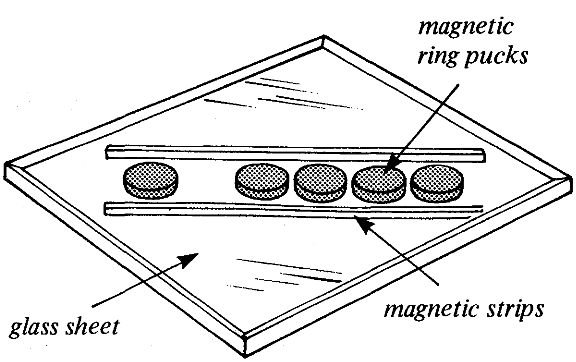
†Demonstration 79
Longitudinal wave along a slinky



Stretch a long slinky on the floor and send a longitudinal pulse along it by giving one end a tug. See how the pulse travels fast and is reflected at the far end.

Demonstration 80
Longitudinal wave along a line of pucks

You may see the demonstration sketched. The



pucks are a short distance apart, each riding on a cushion of carbon dioxide like a hovercraft. When they move closer they repel much more and these repulsions enable a wave to travel along the line. Perhaps the repulsion of air molecules, when they are very close in collisions, enables sound waves to travel in some such way.

Demonstration 81
Waves along a line of trolleys *(OPTIONAL)*

You may see a demonstration with a collection of trolleys, showing longitudinal waves—also, perhaps, transverse waves.

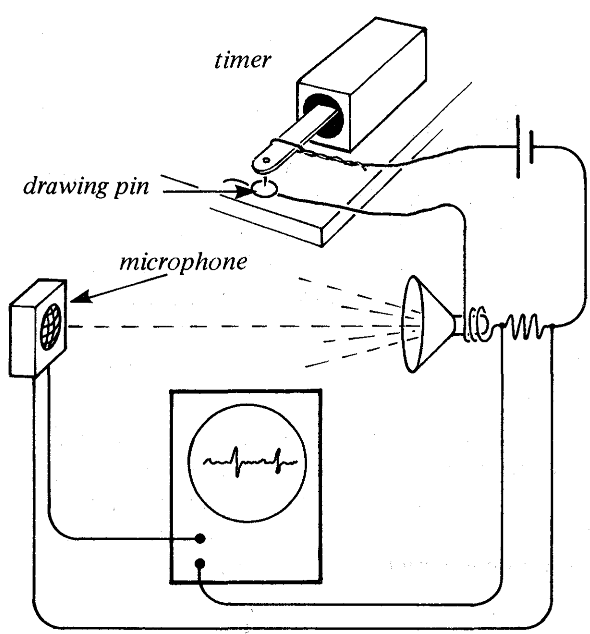
Now think about air molecules How could a longitudinal sound wave travel through a collection of air molecules, when there are no connecting springs between one molecule and its neighbours? (We know that there are no such 'springs' because, if there were long-range springy forces, we should not find Boyle's Law holding.)

When we start a sound wave we push some air molecules closer together (in addition to all their motions). The sound wave makes us pay for that a little later by stretching the next lot of molecules a little farther apart. And that pattern of compression and rarefaction travels out with about two-thirds of the speed of molecules. When you sing a musical note a whole chain of those changes travels out: compression . . . rarefaction . . . compression . . . rarefaction . . . and so on.

If you live near to a great hill which reflects an echo you might measure the speed of sound by giving a loud shout and estimating the time for the echo to get back; but an echo from a nearby wall takes too little time to measure easily. So, instead, you are likely to see a special measurement with an oscilloscope.

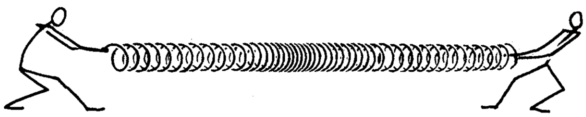
Demonstration 82
Speed of sound: direct method

The sketch shows the apparatus. The ticker-timer makes a regular series of clicks come from



Progress Questions

11. A pulse travels along a slinky spring held at both ends. How can you tell where the pulse was at the instant the picture was sketched?



12a. *SOUND WAVES*

Think about a relay race.

Each runner hands the baton to the next one.

Each runner takes about 20 s to reach the next person.

(i) About how long does it take the *baton* to reach the finish?

(ii) What is the speed of the runners?

(iii) What (roughly) is the speed of the baton?

(iv) What do you notice about these two speeds?

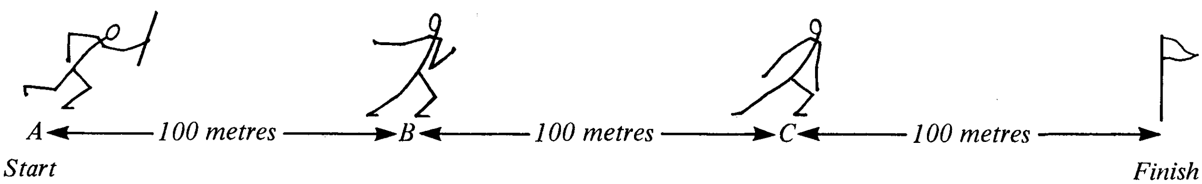
b. Think about sound travelling.

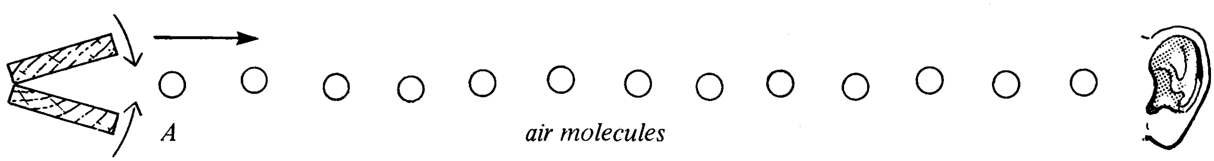
When you bang blocks together, you give the nearest air molecules some extra energy and they move forward.

(i) What happens when these molecules bump into the next ones?

(ii) This is a bit like the relay race—but what have we got instead of runners? And instead of the baton that the runner hands on?

(iii) Sound travels at about 350 m/s. What (roughly) do you think the speed of the air molecules must be?





the loud-speaker and the oscilloscope shows a peak on its trace for a click. The oscilloscope is arranged to repeat its pattern every click so that all these peaks fall on top of each other and you can see the combined peak clearly. The microphone picks up the sound of the click—when it has got there—and makes another peak on the oscilloscope trace. The distance between these two peaks shows how long the sound takes to travel from the loudspeaker to the receiving microphone.

You may see that experiment used to make a measurement of the speed of sound. Or it may just serve as an illustration of the way one might make a measurement; and that will be enough for the next experiment, which is very important.

Demonstration 83

Critical test: Speed of sound in air at different pressures *(OPTIONAL)*

See the previous experiment repeated in a glass pipe. Some of the air in the pipe can be pumped out to show what happens to the speed of sound at lower pressure.

This will give strong support for the attempt to predict Boyle's Law from our theory. Remember we could not do that honestly unless we were sure that the speed of air molecules does not change when the pressure changes (though it does change when the temperature changes). If you trust the speed of sound to give an indication of molecule speed, then this demonstration can provide the necessary support for an honest prediction of Boyle's Law.

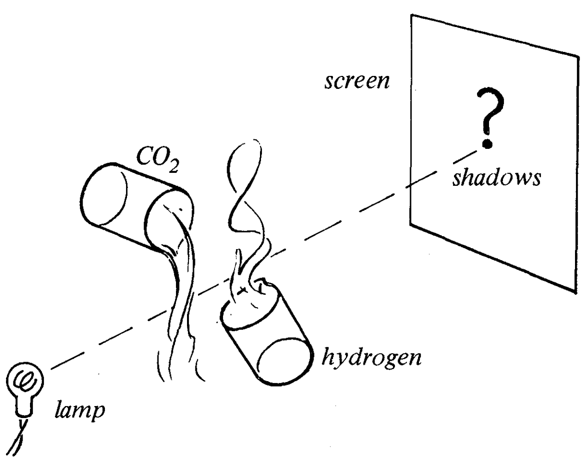
RELATIVE SPEEDS

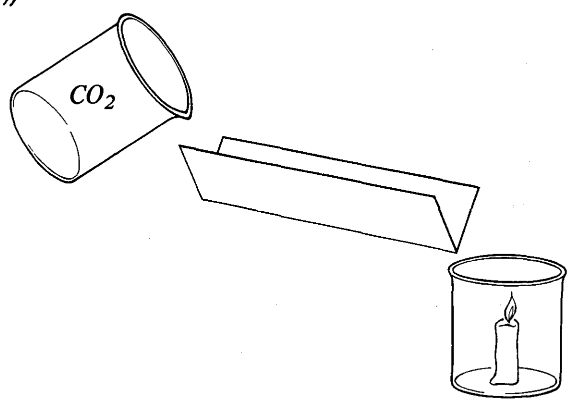
Return to the general prediction, $PV = \frac{1}{3}Nmv^2$. Suppose you have samples of several gases, each of them the same volume, each at atmospheric pressure and room temperature. Then P and V are the same for all the samples and the only things that can differ are v^2 and Nm ($=M$ the total mass). So to keep the predicted relationship true, v^2 will have to be smaller for a gas which has bigger M, that is, for a gas which is more dense.

Thus, if we change from air to a denser gas such as carbon dioxide we expect to find the molecules moving slower. If we change from air to hydrogen, which is much less dense, we expect to find molecules moving faster (about 2 kilometre per second). See the demonstration of different gas densities.

Demonstration 84
Floating and sinking gases: different densities

See shadows of carbon dioxide falling through air; and of hydrogen rising through air, even being poured *upwards* from one beaker to another.



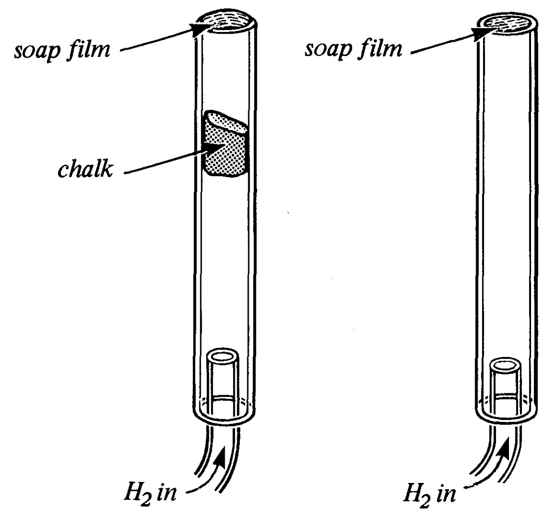


DIFFUSION

If you have two gases, one with faster molecules than those of the other, and let them meet so that their molecules can mingle, you may see a strange effect of the difference of speeds. See the demonstration sketched.

Demonstration 85
Diffusion of gases

Air and hydrogen are separated by a porous barrier which is a short stick of blackboard chalk. Air molecules travel through the chalk in a long series of staggers and collisions. Hydrogen molecules travel in a similar way but faster. Then more hydrogen arrives on the air side of the chalk than air arrives on the hydrogen side. This makes extra pressure on the air side, which is shown by blowing a soap bubble.



Can you be sure that the extra pressure is due to the difference of speed and not just 'hydrogen rising up because it is so light'? See a special test of that, without any chalk. This is called a *control experiment*.

Such control experiments are very important in all good science. You will meet them often in biology. And you should meet them often if you study psychology or economics or any scientific treatment of affairs.

Nuclear energy supplies Uranium can yield enormous energy, from nuclear form to heat, when its atoms undergo fission (splitting apart of the nucleus). But of the mixture of uranium atoms that we get from rocks only one kind, less than 1% of the total, undergoes fission easily. It is difficult to separate this very valuable brand of uranium atoms from the others, because all uranium atoms have the same chemistry. However, physics provides several methods of separation, and the chief method uses diffusion of molecules of uranium fluoride through a porous barrier. Diffusion has to be repeated through many stages to obtain the wanted uranium in sufficient purity but it does succeed; and then the product can be used for nuclear power stations.

Questions

DIFFUSION

13. *(If you have not seen these experiments, leave the questions unanswered.)*

a. Draw a sketch of one experiment you have seen which shows diffusion occurring in a liquid.

b. Explain briefly what happened in the experiment as diffusion occurred.

14a. Draw a sketch of one experiment which shows diffusion in gases. Explain briefly what happened.

b. Explain the difference between the following two processes:

(1) Air, which has been heated by hot water pipes or by an electric fire, travels by convection and warms a room.

(2) A layer of carbon dioxide gas resting below ordinary air diffuses slowly into the air.

General Questions

CONFIDENCE

15. A railway engineer tells you about the train he has designed which travels at 400 km/h. His ideas sound reasonable but you don't know whether to believe him. Ten years later, you watch such a train and measure its speed. Now you have to believe the engineer!

Reasonable ideas led us to $PV = \frac{1}{3}Nmv^2$.

From $PV = \frac{1}{3}Nmv^2$ we calculated a value for v, the average speed of an air molecule. You don't know whether to believe this.

a. If it were possible, what kind of experiment would you like to be able to carry out to see whether the speed of a molecule is really hundreds of metres per second?

b. If such an experiment showed that molecules really did have such speeds, would this make you believe less strongly or more strongly in $PV = \frac{1}{3}Nmv^2$?

PUZZLE

16. Remember the tray in which you had marbles moving about irregularly:

a. Was it usual for a marble to go straight from one side of the tray to the other side? If not, what was happening to it?

b. If an average marble has a speed of 50 cm per second, would it take 1 second to get across a tray 50 cm wide? or would it take longer? Why?

SPEED AND TEMPERATURE

17a. What happens to the average speed of the molecules when the gas is heated?

b. So what happens to the kinetic energy of the molecules when the gas is heated?

c. If we cool down a gas, what happens to the kinetic energy of the molecules?

d. If we could get a gas down to absolute zero, what would the molecules be doing?

e. Does it sound sensible to say that heat energy in a gas is the same thing as the kinetic energy of its molecules?

f. What could we say about heat energy in a liquid? or in a solid?

MOLECULES' K.E.

18. In talking about gases, we are always trying to see whether our *theory* of moving molecules fits our actual *measurements* of what gases do.

Our *measurements* showed that pressure goes up steadily as temperature rises. Now to raise the temperature we have to put heat into the gas, and we can make a guess that the gas molecules get extra *kinetic energy*—they are moving faster. The questions below are concerned with:

A: How kinetic energy increases when the speed of an average molecule increases.

B: How pressure rises when the speed of an average molecule increases.

A: Remembering that kinetic energy $= \frac{1}{2}mv^2$

(i) What is the kinetic energy, if
$m = 1$ unit of mass, $v = 1$ unit of velocity?

(ii) What is the kinetic energy, if m is still 1 unit of mass but v increases to 2 units of velocity?

(iii) How much bigger is your answer to *(ii)* than your answer to *(i)*—is it twice as big or four times as big?

B: If pressure is due to molecules bumping the sides,

(iv) How much more force is one molecule likely to give if its velocity is doubled? (Would it be the same force or double it?)

(v) If the velocity were doubled, would the same number of molecules arrive at one end each second, or would it be double the number?

(vi) If the factors of *(iv)* and *(v)* both affect pressure, would doubling the velocity make the pressure twice as large or four times as large?

C: Have you found that your answers to *(iii)* and to *(vi)* give the same factor for rise in pressure as for rise in kinetic energy?

What do you think would be the increase in (a) kinetic energy, (b) pressure, if the velocity changed to three times as big as before? Would they rise to three times as big? or nine times as big? or what?

CHAPTER 8

GASES III
A GREATER PREDICTION—AFTER A HARD CLIMB

Measuring mean free path and estimating size of molecules and Avogadro number

FURTHER KNOWLEDGE OF MOLECULES

Ordinary large-scale measurements have enabled you to find out something about the *motion* of molecules in the microscopic world. And by measuring the volume-change from liquid to gas you have found out something about the *spacing* of molecules in air. You could go farther and even find the size of a molecule or atom by ordinary large-scale measurements.

That can be done by making measurements in an experiment which you have already seen—bromine spreading through air. You can use the brown bromine molecules as scouts wandering through a forest of air molecules, to tell you something about the size of molecules themselves. But the line of argument which leads from the measurement to the size of a molecule is long and hard. To follow it will be like climbing a great mountain, with guides and ropes—and even extra oxygen. If you think it will be worth your while to follow the long story for the sake of reaching very important atomic knowledge, you should try this 'climb', and you will be rewarded by success in adding to your own atomic knowledge.*

THE FIRST STEP

You will find out how far an air molecule (or a brown bromine molecule acting as a stand-in for it) travels from one collision to the next. Then we shall lead you on from that to estimate the size of a single molecule.

First find the distance between collisions, by watching the wanderings of an army of bromine molecules and then making a calculation. Imagine you have 'super-microscope spectacles' and can see a bromine molecule wandering through air. It travels very fast for a short distance, collides with another molecule (usually an air molecule) and bounces away in a new direction. Then it makes another collision . . . and so on. How much progress can a molecule make with that sort of zig-zag path?

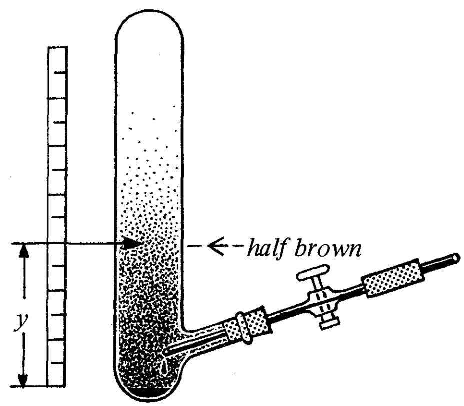
It would be good to be able to find the tiny size of a molecule (and then halve that for an atom) just by watching bromine in a tall tube, without using any microscope at all.

Watch real bromine You have seen bromine 'gas' (vapour) flying up through a vacuum in a glass tube. You also saw its slow progress through air, when the tube had not been pumped out. Now look at bromine spreading in air again; but now try to time its progress.

* You need not worry about examinations. There would be no question that asked you to repeat all the advanced argument—an exam would not ask you to make the difficult 'climb' in a hurry, all on your own. At most, a question might offer you an opportunity to show that you have read this chapter and enjoyed the 'climb' well enough to tell a younger brother or sister an interesting tale about it.

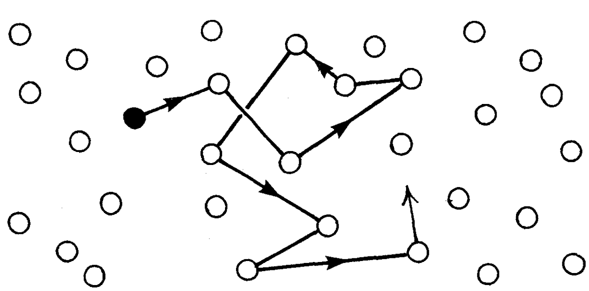
Demonstration 86
Measuring the diffusion of bromine in air

Release some liquid bromine at the bottom of the tube of air. Wait for a measured time, say 500 seconds. Then estimate the average progress of the brown bromine, in centimetres. It will be best if every member of the class makes his own guess and then your teacher pools the guesses.



At the bottom of the tube the saturated vapour is dark brown: we call that 'FULL BROWN'. At the top you hardly see any tinge of brown. We call that 'NO BROWN'. Just where would you say it is 'HALF BROWN'? Look carefully and make your own decision. That will be your estimate of the average progress of bromine molecules as they stagger through air, in 500 seconds. Call that distance y. You will make use of it soon.

Random walk A bromine molecule's path is rather like the path you would have if you tried to walk through a rush-hour crowd in a busy station, blindfolded so that you had no idea of direction after each collision. We call that a 'random walk'. Watch a model of that with a tray of marbles.



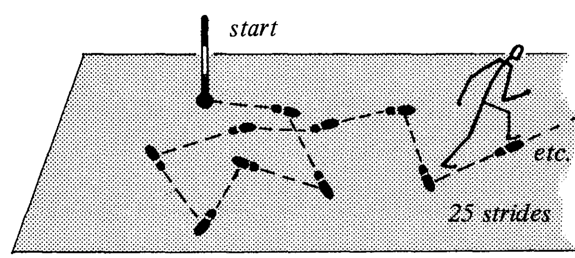
'random walk' of a marble

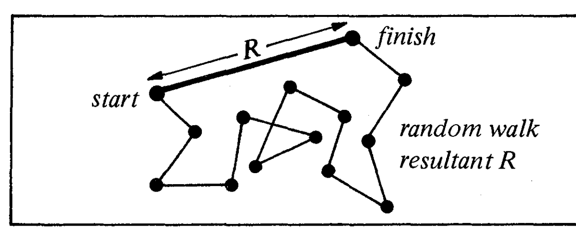
Experiment 87
Watching a random walk: mean free path

Put several dozen marbles in your tray, with one distinctively coloured marble which is different from all the others. Agitate the tray and watch the random walk of the marked marble from collision to collision.

Then, if you like, make a rough estimate of that marble's MEAN FREE PATH—more for the sake of understanding the idea than for a measurement. 'Mean' means 'average'; and the mean free path is the average distance of travel from one collision to the next.

Imagine you are taking a random walk yourself Take one stride from your starting point. Then choose a new direction—at random; you do not know or mind which direction—and take a stride in that new direction. Again choose a new direction at random and take one stride. Continue like that until you have taken 25 strides. How far will you then be from your starting point, *as the crow flies*?

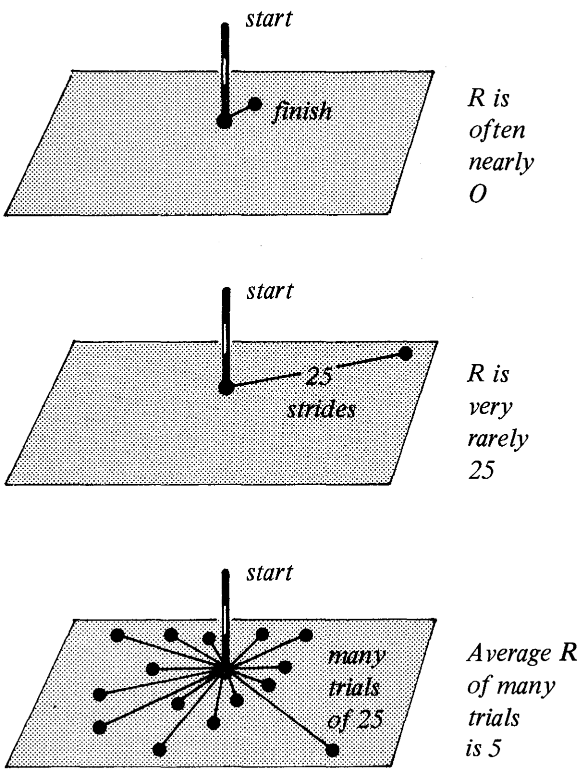




Quite often, your 25 strides will have brought you back near to your starting point: in such cases your resultant progress straight from start to finish, is almost 0. In a very rare case you might by chance take all the strides in one direction, and then your resultant progress would be 25 strides.

Imagine you repeat that game a very large number of times and take the average of all the results. What average would you expect?

There is a surprising rule for predicting that average distance. The average will not be 25 (a very



rare maximum) or zero (a frequent minimum) but about 5 strides. That is because 5 is the square root of 25; and the general rule says that for N strides the average progress is $\sqrt{N}$ strides.

You would need some algebra—the mathematics of statistics—to add and average those many wild wanderings and predict this strange rule with $\sqrt{N}$ in it. Instead of trying the algebra, you should play a game of random walks and see if you and the other members of the class can test the rule for yourselves.

Experiment 88
Test of a random walk

Each member of the class should plot a random walk on a piece of paper ruled in centimetre squares (or any convenient squares).

Starting in the middle of the sheet, plot a walk of 25 strides, each stride being one centimetre UP or DOWN or LEFT or RIGHT on the paper. Let the choice of direction for each stride be decided by pure chance as follows:

Throw an oblong block of wood with four sides marked UP, DOWN, LEFT, RIGHT and obey the instruction that falls uppermost—that is like casting dice.

Or you may be given a bag of beads in four colours. Select one bead, *without looking*, and obey its instruction: for example,

RED bead, UP 1 cm
BLUE bead, DOWN 1 cm
GREEN bead, LEFT 1 cm
YELLOW bead, RIGHT 1 cm

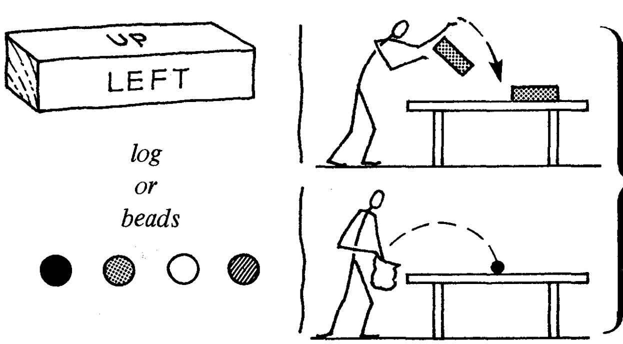
Then *put that bead back in the bag* and shake the bag to mix the beads before taking a bead out for the next move.

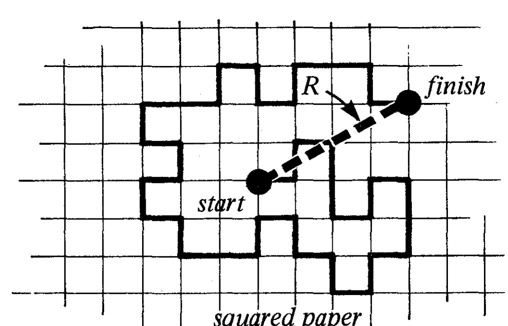
Take such a chance instruction 25 times altogether, making 25 moves on your squared paper. Draw a straight line from start to finish (a 'crow-flies' line) on your paper and measure it. Take your measurement to your teacher for the pool of random walks.

Then make two more random walks, each of 25 strides.

Your teacher's pool will have something like 100 walks. Everyone should then help to find the *average* length of walk. How does that compare with the square-root prediction of 4 or 5 strides?

(The square-root prediction assumes that you take a special kind of average, called the 'root-





Random Walk calculation with algebra *(OPTIONAL EXTRA)*

In this advanced discussion of molecules, you may take the random walk result for granted. But in case you wish to see how it is arrived at, here is an outline of the algebra. It is not a very good 'proof' from the point of view of professional statisticians but it shows you how the square root arises.

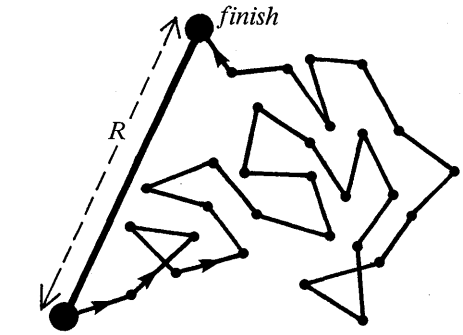
If a man takes a large number (N) of strides each of the same length (L) in succession, but in random directions, what is his resultant distance (R) of travel?

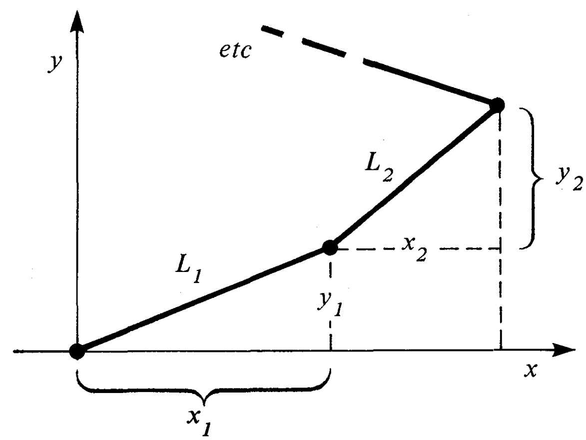
Obviously this will vary from one batch of N strides to another, and may often be zero (in the cases when he comes back to the starting point) and may be as large as NL (in the very rare cases when he happens to take all strides in the same direction). We want the *average* distance from start to finish, *averaged over many batches* of N strides.

We observe a walk of N strides and find the resultant travel-distance R from start to finish. We observe a large number of such walks starting afresh each time and find the average value of R for all those walks. Because it leads to the simple result, we find the average value of R^2 and take the square root, obtaining a root mean square (R.M.S.) average. We can show that this average should approach the value $\sqrt{NL}$. Here is a *two-dimensional* proof. The three-dimensional one is similar.

Sketch the first few strides of a random walk. Choose a set of perpendicular axes, x and y, arbitrarily. Using x- and y-co-ordinates, resolve stride no. 1 into components x_1 and y_1, stride no. 2 into x_2 and y_2 and so on. Then the resultant of that walk, R, has

x-component $(x_1+x_2+\ldots+x_N)$
and y-component $(y_1+y_2+\ldots+y_N)$





$$\begin{aligned}\text{and } R^2 &= (x_1+x_2+\ldots+x_N)^2+(y_1+y_2+\ldots y_N)^2\\ &= x_1{}^2+x_2{}^2+\text{etc.} \qquad +2x_1x_2+2x_1x_3,\text{ etc.}\\ &\quad+y_1{}^2+y_2{}^2+\text{etc.} \qquad +2y_1y_2+2y_1y_3,\text{ etc.}\\ &= L^2+L^2+\text{etc.} \qquad +ZERO\\ &= NL^2\end{aligned}$$

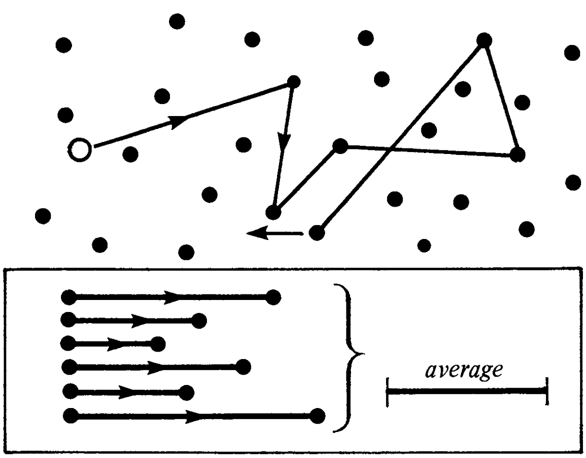
The 'cross terms', such as $2x_1x_2$, add up to zero in averaging over many walks, because those terms are as often negative as positive, and they range similarly from 0 to $2L$. Similarly for the y- 'cross terms'.

Then average value for $R = \sqrt{NL}$

mean-square' average—like the average taken by an ammeter that measures alternating currents. If you take an ordinary average, by adding up and dividing by the number of trials, you should not expect quite the square-root result, but about $\frac{8}{10}$ of that. So, instead of 5, you may expect 4. You will not get exactly 4 for your class group, perhaps not even an average close to 4, because you have averaged only a hundred trials. If you had made many thousands of trials, the class average would be much more likely to be close to 4.)

But now you are going to use real bromine molecules, millions of millions of millions of them, each making a random walk among air molecules, an enormous number of trials. So there you can trust the square-root prediction. If you let the bromine wander through air for quite a long time, say 500 seconds, each bromine molecule will make many millions of strides between collisions. So N, the number of strides in a walk, will also be very large. Then we can say confidently that the average progress of brown bromine molecules will be $\sqrt{N}$ strides.

The mean free path is the average distance that a molecule travels between one collision and the next. We shall call that one 'stride', of length L. The real free paths of a molecule are not all of equal length in a real gas; we take an average and call it L.



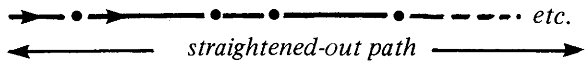
Then if bromine molecules make N collisions in the measured time their average progress, y, is $\sqrt{N}L$. So $y = \sqrt{N}L$.

Suppose, for example, 'half-brown' is 0.10 metre* (10 cm) above the 'full brown' at the bottom. Then:

$$0.10 \text{ metre} = \sqrt{N}L$$

Straightened-out-path Now get help from another line of attack. Calculate the total distance a bromine molecule travels in 500 seconds. That is its straightened-out path.

Bromine vapour is $5\frac{1}{2}$ times as dense as air at the same pressure. So, for the same volume of sample,



for bromine molecule,

100 000 metres in 500 seconds

M in $PV = \frac{1}{3}Mv^2$ is $5\frac{1}{2}$ times larger. That makes average v smaller, about 200 metre/second at room temperature, instead of the 500 metre/second for air molecules.

In 500 seconds a bromine molecule travels 200×500 (metre/second) $\times$ (seconds). That is 100 000 metres. An amazing distance. A hundred thousand metres, sixty miles, in eight minutes and twenty seconds. Yet those bromine molecules do not get very far—you can see that they don't: they end up only a dozen centimetres from their start *on the average*, because they make so many collisions with air molecules. Each molecule *must* make an enormous number of collisions if its *net* progress is so small.

You can calculate just how many collisions a bromine molecule makes (or, rather, just how many strides between collisions). That number will be 100 000 metres divided by the length of one stride, L. And that *is* the number which we have called N.

$$\therefore N = \frac{100\,000 \text{ metres}}{L} \quad \text{and} \quad L = \frac{100\,000 \text{ metres}}{N}$$

Now we can put that value for L in our earlier equation, $y = \sqrt{N}L$

$$\therefore y = \sqrt{N}\frac{100\,000 \text{ metres}}{N}$$

$$= \frac{100\,000 \text{ metres}}{\sqrt{N}}$$

Then calculate N. Use the value your class estimated for the 'half brown' distance, y.

A specimen calculation Here we pretend y is 0.10 metre.

If so, 0.10 metre = 100 000 metres/ $\sqrt{N}$

$$\therefore \sqrt{N} = \frac{100\,000}{0.10} = 1\,000\,000$$

$$\therefore \quad N = 1\,000\,000\,000\,000, \text{ as an estimate from } y = 0.10 \text{ metre}$$

Your own estimate for N will be enormous,

---

* In calculations with the real experiment, use *your* estimate, *not* this specimen 0.10 metre.

something like a million million collisions (or strides) in 500 seconds.

One stride, the mean free path Now you can find the length of one stride from collision to collision. Divide the total straightened-out path by the number of strides, N, which you have just calculated.

$$\therefore \text{ one stride, } L = \frac{100\,000 \text{ metres}}{N}$$

$$= \,.\,.\,?\,.\,.\, \text{ from collision to collision}$$

That is for a bromine molecule staggering through air. You may assume it is much the same for an air molecule staggering through air.

ESTIMATES FROM MEAN FREE PATH

How many collisions in air in one second? Remember that an air molecule travels about 500 metres straightened-out path in one second. Take your estimate of mean free path (assuming it is roughly the same for an air molecule in air as for a bromine one in air) and calculate how many collisions an air molecule makes with neighbours in one second.

[Using the example we gave, if $L = 0.000\,000\,1$ metres, number of collisions in 1 second is

$$\frac{500 \text{ metres}}{0.000\,000\,1 \text{ metre}} = 5\,000\,000\,000]$$

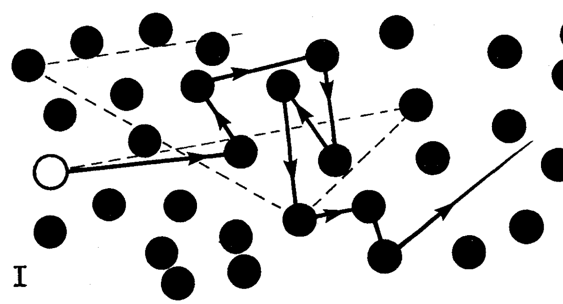
Time for a long journey How long would it take, on the average, for a molecule on one side of a room to wander across to the other side, if there were no draughts or convection currents to sweep it across among a crowd? (In a train a passenger diffuses slowly down a crowded corridor to the buffet even with the strong driving field provided by hunger, although the train carries the whole crowd of passengers along in a rapid 'convection current'.)

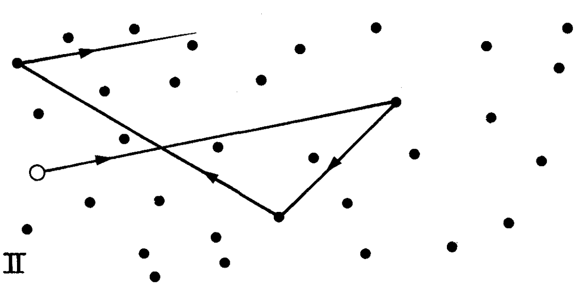
Suppose it takes t seconds for a molecule to travel across the room by diffusion (a random walk). Calculate the number of collisions it makes in that time. Use the random walk relation and your knowledge of mean free path to calculate the value of t for a room 6 metres wide. (It will come out as an enormous number of seconds. Is that result nearest to a minute, an hour, a week, a year, or what?)

The same kind of story applies to neutrons diffusing out from the inner regions of a nuclear reactor. And for the 'particles' of light (photons) cannoning their way out from the inner layers of the Sun.

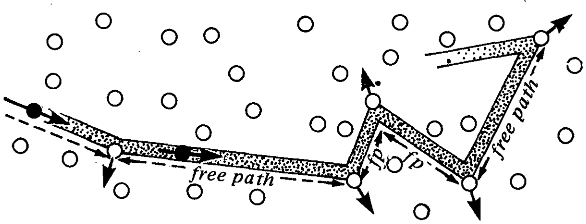
THE NEXT STEP: FROM MEAN FREE PATH TO SIZE OF A MOLECULE

Size of a Molecule? We still do not know the size of a molecule, or how many molecules there are in a room full of air. We can find out how big an air molecule must be (roughly) from the bromine measurement of mean free path. If molecules were great fat things, one molecule could not travel far without blundering into another—so the mean free path would be very small (sketch I), perhaps almost as small as the spacing between neighbouring molecules. On the other hand, if molecules had no size at all, were just points, one molecule could fly through a crowd of others without ever hitting another—the mean free path would be very great indeed (sketch II). Therefore, somehow in the size of mean free path there is information about the size of a molecule.


I


II

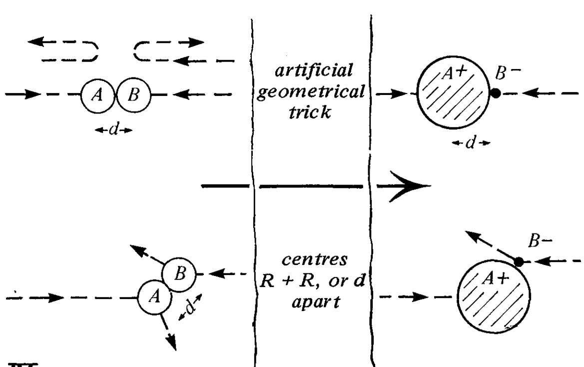
Picture one molecule whizzing through a crowd of others. That missile molecule traces out a long pipe, like a microscopic drinking straw. When the missile molecule hits another molecule (after travelling one free path) it bounces off in a new direction. The 'straw' must bend there. Look at sketch III, where the grey stripe shows the path of the black missile molecule.



III

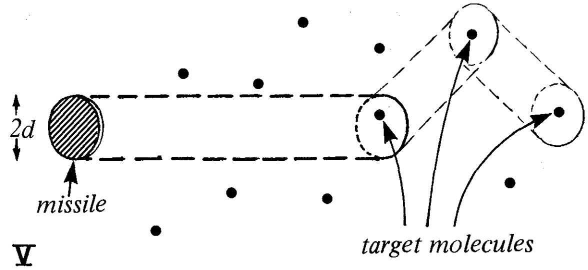
If you like, take a real straw and lay it on the grey stripe, bending it for each collision. Take your straw and cut it at each of the bends you have made; place the pieces side by side and make a rough guess (just by looking at them) at the average length of bits. That is the mean free path for the small sample in the picture. This will be a useful illustration of the way we are going to find the size of an air molecule.

Now use a trick for seeing how far a missile molecule goes before it hits another. We imagine a missile of double size. This trick has been invented by scientists and it is not what really happens; but you will see that it gives an interesting result; and you may be glad to use it. At any collision the centres of the two colliding molecules must be (1 radius + 1 radius) apart—that is (1 diameter) apart (sketch IV). Instead of sketching the collision like that, the trick is to pretend that the molecule flying along to make this collision is much bigger; and any other molecule that it hits is much smaller—we should get the same result as long as we have the centres of the two molecules just one molecule-diameter apart at the instant of collision.



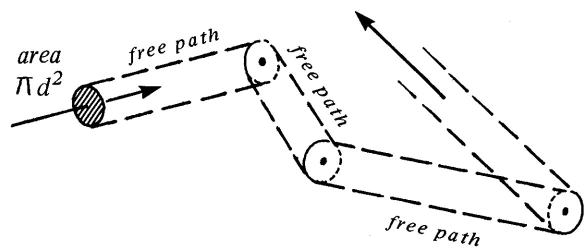
IV

We push that to the limit, and make the missile molecule have double size, so that its *radius* is just one molecule *diameter*. Then we must make all the other molecules (the targets) have no size at all: we draw each as a point.



V

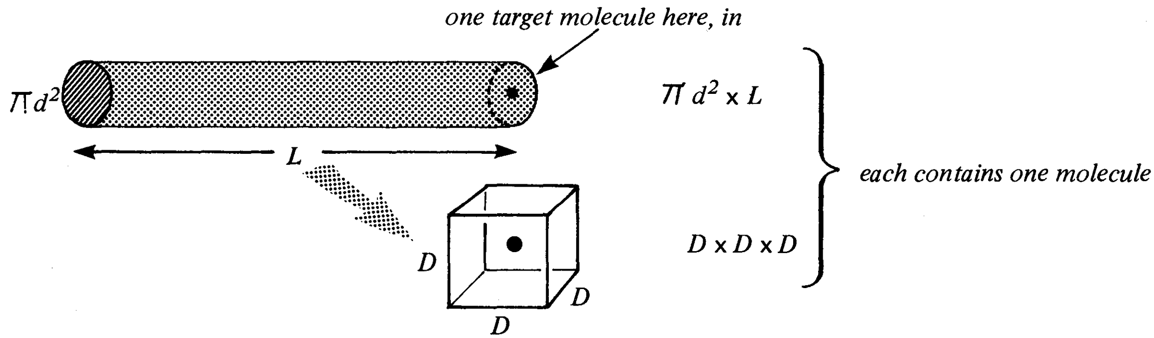
Now start the story all over again. The missile, an artifical molecule with *radius* one molecule *diameter*, flies along marking out a 'straw' pipe *two diameters wide* (sketch V). Where must one of the targets be if it is to be hit by the flying molecule? It must be *somewhere inside* the new wider 'straw'. Then there will be a collision. So this is the story: the flying molecule travels along until it meets a target molecule in its 'straw' pipe. There its path bends and it flies along in a new direction; then it hits another molecule; and so on.



Think about the path swept out by the flying molecule which is possessively patrolling its 'share' of the volume of the containing box. We pretend that this extra big molecule is a round ball, of RADIUS d. It sweeps out a straw pipe or sausage of cross-section area πd^2—where d is the *diameter* of a real molecule. What is the length of sausage between one collision and the next? You already know that: it is the distance from collision to collision, whose average we call the mean free path, L. You have measured that with the bromine experiment. In ordinary air it is somewhere between 60 and 120×10^{-9} metre.

[In our example with $y = 0.10$ metre, L is (100000)/(1000000000000) strides, or 100×10^{-9} metre]

Each straight piece of pipe starts from a collision and ends with the next collision. So the missile molecule starting along such a section makes no collision until the end and then hits one molecule. Therefore there are no other molecules with their centres inside the pipe. The whole space



of the straight piece of pipe contains just one molecule, at the far end. But, when we discussed in Chapter 7 the volume change from liquid air to air, 1 to 750, you saw a molecule boxed in d^3 in liquid and a molecule boxed in a 'prison cell' D^3 in air. Then $D^3/d^3 = 750/1$

The space containing one molecule in air, is the volume of one mean free path of pipe.

$$\therefore D^3 = \pi d^2 \times (\text{mean free path})$$
$$\therefore 750 d^3 = \pi d^2 \times (\text{mean free path}). \text{ Now cancel } d^2$$
$$\therefore d = \pi \times (\text{mean free path})/750$$

[In our example with $y = 0.10$ metre,
$d = \pi(100 \times 10^{-9} \text{ metre})/750$
$\approx 0.4 \times 10^{-9}$ metre]

Now at last you know the size of an air molecule. Calculate

$$\pi \times (\text{mean free path})/750$$

and you have your own estimate.

When you have tried that with *your class* estimate of y, you have found the diameter of a single molecule of air (N_2 or O_2 but CO_2 may be larger). An atom is probably about half that size.

This is not very accurate, because our measurements were difficult and we have made some risky moves in carrying through our calculations. Yet this is a good guess for general knowledge of atoms—it is in the right county: it is of the right 'order of magnitude'.

HOW MANY AIR MOLECULES IN YOUR CLASSROOM?

Calculate the volume of the room in cubic metres, from rough measurements with a metre ruler. You know that there is one molecule in a volume D^3, which is the same as $750\, d^3$. Therefore, you should divide the volume of the room by 750 d^3 to find the number of molecules there.

THE AVOGADRO CONSTANT A USEFUL NUMBER IN CHEMISTRY

If you meet the 'Avogadro constant' in Chemistry, you may wonder how it was measured. One method is to use just the experiments that have been done here: diffusion of bromine in air and change of volume from liquid to gas. The Avogadro constant is the number of molecules in one 'mole' (one 'gram-molecule').

At room temperature and normal atmospheric pressure, one 'mole' of any gas occupies about 24 000 cm^3, or 0.024 cubic metres. Divide that volume for one mole by D^3 for one molecule, and you will find your own rough estimate for the Avogadro constant. You should not despise it because it is rough: in the world of atoms we often make rough guesses, 'desperate measures for desperate cases'—some people even call this 'desperate Physics'.

Mass of a single molecule You could find the mass of a single molecule in a roundabout calculation from the Avogadro constant. More directly, you know by weighing a sample of ordinary air that one cubic metre has a mass of about 1.2 kg. The number of molecules in 1 cubic metre of air is (1 metre^3)/D^3. Then the mass of one molecule is (1.2 kg)/(1 metre$^3/D^3$) or 1.2 kg $\times D^3/1$.

Comparison with oil molecule measurement You probably did an experiment of taking a tiny drop of olive oil and letting it spread on clean water. That gave you an estimate of the length of an oil molecule. From chemistry, we know that an olive oil molecule is about a dozen atoms long, so if you divide the result of the oil film measurement by 12 you should have another estimate for the size of an atom, in this case probably a carbon atom in the long chain of the oil molecule. How does that agree with half the size of an air molecule?

CHART OF MOLECULAR DATA FOR AIR

DENSITY

at room temp. and standard atmospheric pressure $1.2\ kg/m^3$.

ONE MOLE (one gram-molecule)

has mass (if air)	28.8 grams
occupies	22.4 litres at 0°C
	23–24 litres at room temp. Say, 0.024 cubic metres

VOLUME-CHANGE, liquid air to air, about 1 to 750

MEASUREMENTS FOR MOLECULES, AT ROOM TEMPERATURE AND STANDARD ATMOSPHERIC PRESSURE

From pressure, density, and $PV = \frac{1}{3}Nmv^2$	*Average speed* of molecules	500 m/s
From change of volume (liquid to gas)	*Average spacing* (distance between neighbours: the side of a cube in space that would hold one molecule)	9 or 10 molecule diameters
From bromine diffusion, and random walk	*Average travel* between collisions ('Mean free path', mfp)	100×10^{-9} metre
From mfp and densities	*'Diameter' of a molecule*	0.3 or 0.4×10^{-9} metre
	∴ *Average spacing* (See above)	3 or 4×10^{-9} metre

Knowledge of molecules We have some knowledge, built on assumptions about molecules, but reinforced by some cross checks, that has now grown to a fairly definite picture. We think of air molecules as 0.3 or 0.4×10^{-9} metre in diameter: moving 500 metre/second on an average with an average spacing, in common air, of 3 or more $\times 10^{-9}$ metre: and travelling a distance about 100×10^{-9} metre between one collision and the next. We know how many there are in a large room. We know the mass of a single molecule. All this came from imagining a theoretical picture—guided by things we know about nature, such as Newton's Laws of Motion—and then making measurements.

Questions

1. The 'average distance' between the centres of two molecules in air at normal pressure is 9 or 10 times the diameter of a molecule.

Suppose you have a sample of such air in a Box A. Suppose you also have another Box B of the same size with a sample of a different gas also at atmospheric pressure and room temperature. There will be the same number of gas molecules in Box B as in Box A.

Suppose the gas in Box B has molecules of the same mass as air molecules but twice as fat, twice the diameter.

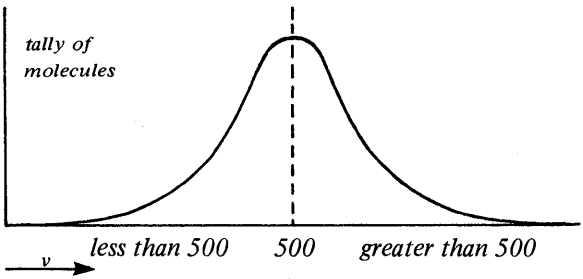
a. Does the different size of molecules in B make any great difference to the average spacings centre to centre? Give a brief reason for your answer.

b. Does the difference of size in B make any serious difference to the mean free path of the molecules? Give a brief reason for your answer. If you like, illustrate your answer with a sketch.

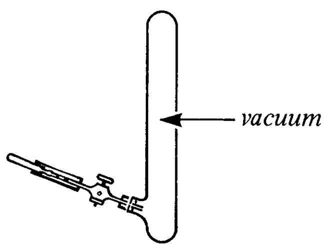
2. *(Advanced optional)* Suppose air molecules attract each other with a force which is greater the closer they are together. Suppose that, when two molecules are 10 molecular diameters apart (as they are, on average, in ordinary air) the force is negligibly small. But when they are 2 molecule diameters apart the force is large enough to matter.

A measured volume of air at atmospheric pressure is compressed so much that the molecules are less than 2 diameters apart, and the new volume is measured. We now calculate, from that new volume, what the new pressure would be if Boyle's Law still held. Then we measure the actual pressure. Would you expect the actual pressure to be more, or less than, or the same as, the calculated pressure? Give a reason for your answer. Just consider the effect of attractions between molecules, and do not worry about any effect due to the *size* of the molecules.)

3. *(Advanced)* If a real gas, such as air or hydrogen, is cooled to a low enough temperature it becomes a liquid. How could you 'explain' this by your molecular picture?



4. Use the graph above to explain something important about the speeds of molecules in a cubic metre of atmospheric air. (500 metre/sec is the result of calculating v from measurements of pressure, volume and mass of a sample of air.)



5a. The sketch shows apparatus you have seen used. When air has been pumped out of the large tube, the nozzle of the ampoule containing liquid bromine is broken off inside the rubber connection. The liquid bromine is set free into the vacuum by opening the stopcock.

Draw the large tube and show by shading what it looks like 1 second after the stopcock has been opened.

b. Suppose, in part (a), we had said '$\frac{1}{100}$ second' instead of 1 second, this would make no difference to your sketch. Why? (Bromine vapour molecules have a speed of about 200 metre per second.)

c. But suppose we said draw a 'snapshot' picture after only $\frac{1}{1000}$ second—would the picture be different? Explain. (The large tube is about 40 cm high.)

6a. Draw another large tube, as in the question just above, but this time, instead of a vacuum inside, let it contain air. Show by shading, what the large tube looks like 10 minutes after the stopcock has been turned on.

b. Explain why the bromine seems to have moved so slowly now, though it moved so rapidly throughout the tube in the question before.

7. *(Advanced, optional)* Bromine vapour is liberated in a tube containing air. After 500 seconds the top of the large tube still looks practically colourless, while the bottom, near the side tube, looks 'full brown'. The 'half brown' point seems to be about 10 cm (0.1 metre) up.

a. In a vacuum, bromine molecules could travel 100 000 metres in 500 sec. How is this figure obtained? (Speed of bromine molecules = 200 metre/sec.)

b. But in fact the bromine molecules seem to have progressed, not 100 000 metres but, on average, only 0.1 metre. This is because they keep hitting air molecules, and bouncing off in all directions.

If L = the length of the average travel between collisions, how many collisions does a bromine molecule make in 500 seconds? (Call this number N.)

c. You have a formula which tells you that in N steps, each of length L between collisions, a molecule travels on average $\sqrt{N}L$ from its starting-point. This average distance, the 'half-brown' distance mentioned above, is 10 cm, which is 0.1 metre.

Then $\sqrt{N}L = 0.1$ metre:
and part (b), $N = 100\,000/L$
Calculate L

This is the distance a bromine molecule moves, *on the average* between collisions.

8. *(Advanced. Read the whole question first)* What do you think is meant by the size, or diameter, of a molecule? Do not just say 'the distance measured across it'—the distance measured where? across what? and most important, measured how?

Illustrate the difficulty of answering this question by considering what is meant by the 'size' of a rather limp sausage-shaped balloon, whose 'size' is measured by some method involving collisions with the balloon. Or, if you like, consider the difficulty of saying what is meant by the 'size' of a jelly fish which is constantly moving beneath the surface of the sea. Then go on to consider the molecule by writing a paragraph beginning 'In the same way . . .'

9a. Suppose you have guessed that the diameter of an air molecule is 0.4×10^{-9} metre, what is the volume (in cubic metres) of the smallest cubical box that holds 1 molecule of liquid air?

b. One cubic metre of liquid air has mass 900 kilograms. One cubic metre of 'room' air has mass 1.2 kilograms. What is the volume of space, in the room you are in, that has one molecule of air in it?

c. Estimate in metres the length, breadth and width of the room you are in. Calculate the number of air molecules it contains.

10a. In answering the question just above you should have found that the volume which contains one molecule of ordinary air is $750 \times (0.4 \times 10^{-9})^3$ cubic metres. How many air molecules are there in a room 4 metres $\times$ 3 metres $\times$ 2 metres, that is, 24 cubic metres?

b. An important quantity for the chemist is the Avogadro constant, that is, the number of molecules in 22.4 litres of a gas, at 0°C and a standard atmospheric pressure. (The number of molecules in a given *volume* of a gas is the same for all gases, including air.) 22.4 litres at 0°C expands to about 24 litres at room temperature—all at one atmosphere. 1 cubic metre = 1000 litres. You have found in (a) the number of molecules in 24 cubic metres. How many in 24 litres?

That is the Avogadro constant or number.

CHAPTER 9

ENERGY AND ITS GRAND TOTAL: CONSERVATION

This is a chapter about one of the most important pieces of knowledge in all science: our belief concerning 'total energy'. It is a chapter to read for yourself and remember when you are paying your electricity bill or buying some machine or arguing with friends about the future of the world's fuel.

Reminders In this chapter we take it for granted you know about the forms of mechanical energy and how we measure them. Unless you are sure you understand how useful jobs need fuel and know the different forms of energy you should go back to Chapter 5 and read the 'Discussion for catching up'. And re-read the explanation of WORK, so that you know that it measures the energy-transfer *FROM* one form *TO* another. Work is calculated by multiplying FORCE by DISTANCE and its units are newton·metres, which we call *joules* for short. Since *changes* of energy are measured in *newton·metres* these units also serve for any stock of energy.

Two forms have been treated rather vaguely before this year, kinetic energy and heat.

Kinetic energy was called 'motion energy' then; and you knew that fuel is needed to get a car or a train or a man, moving; and you could see exchanges between 'motion energy' and other mechanical forms of energy. Now you know, from Chapter 5, how to calculate the amount of motion energy. It is $\frac{1}{2}mv^2$ in newton·metres.

Heat is also something you get from fuel. But you cannot measure heat directly by FORCE × DISTANCE: you have to weigh some material such as water and use a thermometer. Is heat really like mechanical energy, a different form of the same thing? Read this chapter for the answer to that question.

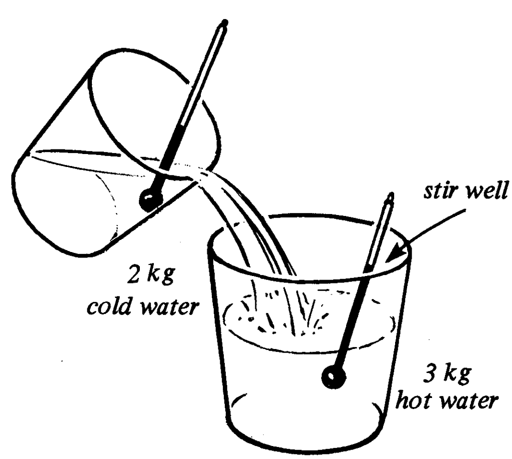
EXPERIMENTS FOR CATCHING-UP: MEASUREMENTS OF HEAT

In discussing Conservation of Energy you will need to know about heat as something measured. If you did not make such measurements before, see and do the following experiments† for catching up.

†Demonstration 89a Exchanging heat between hot and cold water

Watch while a 2-kg mass of cold water is poured into 3 kg of hot water in a light container. The temperature of each lot of water is read carefully as is the temperature of the mixture after stirring.

What can you see that stays almost the same when the mixing is done? Is the *gain of temperature* equal to the *loss of temperature*? Or do you get almost the same numbers if you multiply amount of water by change of temperature?



†Experiment 89b
Measuring heat

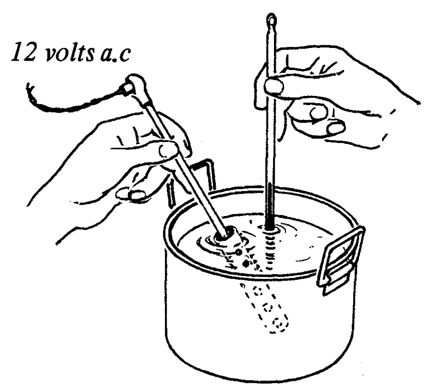
Use an immersion heater to give heat to water in a metal saucepan. The heater has a coil of fine wire made of high-resistance alloy. As long as the heater is water-cooled it will work well. But if you run it when it is dry, its coil may overheat and break.

Put 1 kilogram of water in the saucepan. Immerse your heater in the water. Connect it to the 12-volt output of a transformer.

Stir the cold water and take its temperature.

Run the heater for five minutes, stirring the water all the time, using the heater itself to stir.

At the end of five minutes switch the heater off; continue stirring and take the highest temperature.



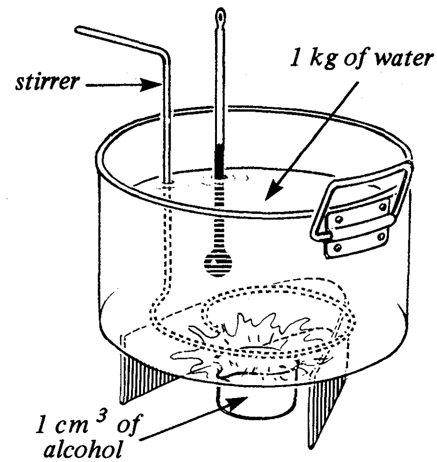
If you like, repeat the experiment with $\frac{1}{2}$ kilogram of water in the saucepan. You would have to cool the saucepan under the tap first so that you did not start with warm apparatus that would lose heat unnecessarily quickly.

Calculate how much heat your electric heater gives the water in five minutes. Your answer will be measured in kilograms-of-water × °C. You may call these 'thermal units' if you like. For our discussion of heat and energy we shall presently use a special temporary name, 'caloric units'.

†Experiment 89c
Measuring heat delivered by burning alcohol

Weigh 1 kilogram of water into the saucepan. Place the saucepan on the metal stand.

Ask your teacher for 1 cm^3 of methylated spirit in a small beaker.



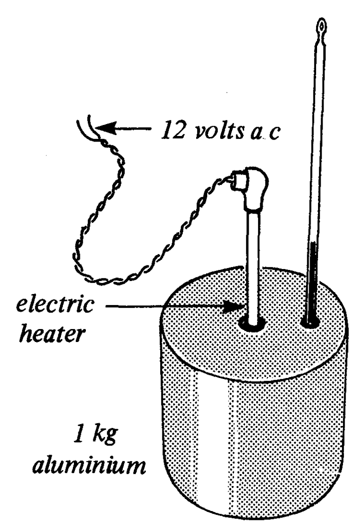
Stir the cold water and take its temperature. Light the methylated spirit. Let it all burn. Stir the water and take the temperature.

How much heat, measured in thermal units, does the burning of that dose of alcohol give to the water?

†Experiment 89d
Estimate the heat given to aluminium

Compare the warming-up behaviour of aluminium with the warming-up behaviour of water which you tried just before.

Weigh an aluminium block. Insert the electric heater in the central hole and the thermometer in the other hole. (Put a little oil in with the thermometer, to help it to make better contact in measuring the aluminium's temperature. Do not put oil on the heater: that might lead to damage



later on when the heater is out of the block and the oil has dried.)

Take the temperature of the aluminium and record it.

As before, switch the heater on for five minutes. Then switch it off and take the highest temperature that the aluminium reaches.

In your earlier experiment you stirred the water carefully. Otherwise your temperature-measurement would be unreliable, with some of the water hotter and some of the water cooler. You cannot stir the solid aluminium. *Why is this experiment not hopeless?*

Now look at your measurements. You may trust your electric heater to give the same amount of heat to a metal block as to a pan of water. (You pay the same amount of money for the electric supply, whatever the heater is heating.) Try multiplying MASS OF ALUMINIUM by TEMPERATURE-RISE. Is your answer the same as for MASS OF WATER multiplied by TEMPERATURE-RISE in your earlier experiment with the same heater? If so, you have found something interesting, the same for aluminium and water, therefore perhaps worth naming.

If not, you may still want to get the same number from both experiments, because you do know that the heater delivered the same amount of something you pay for in both experiments. You can force your answer for aluminium to agree with water if you multiply by one extra number, a special comparison-number (c-n) for aluminium. Find out what the number is by arithmetic.

Very careful experiments (with allowances for heat that escapes) give a c-n for aluminium about 0.22.

What value do you find?

Questions

MEASURED HEAT

1. How much heat is needed for a large hot bath? Suppose the bath is rectangular (uncomfortable to lie in but comfortable for calculations), 2 metres long by 0.6 metre wide. It is to be filled with water 0.2 metre deep. The water comes from the water main at 12°C. It is to be heated to 42°C for the bath.

a. How many kilograms of water go into the bath? (There are 1000 kg in one cubic metre of water.)

b. How many thermal units of heat are needed?

c. The water is heated by an electric immersion heater in a storage tank. The 1-kilowatt heater delivers about $\frac{1}{4}$ thermal unit per second.

How long will the heater take to provide one hot bath?

d. The heater costs about £0.06 to run on the electric mains for an hour. How much does the heat for a bath cost?

2. A heavy saucepan in a hotel kitchen is made of 5 kg of aluminium. It is filled with 10 kg of water. The saucepan of water is stirred whilst it is heated over a flame.

a. How does the heat taken by the aluminium compare with the heat taken by the water? (Assume the temperature-rise is the same for both.)

b. Therefore, the heat taken for heating-up the saucepan is equivalent to heating up . . ? . . kg of water.

Is it true that energy is never created or lost? We believe this is true, and we give our belief a special name, the 'Principle of Conservation of Energy'.

Conservation 'Conservation' is a very important word in modern science; it means 'keeping the same total, whatever happens'.

Conservation of *MOMENTUM* means that the total momentum of any collection of things is the same after an event as before. And we are sure this is true, however violent the event, elastic or inelastic. Trusting this to be true, we can predict the result of any collision; and we interpret measurements of collisions, even nuclear ones, with complete confidence.

The Conservation of *ENERGY* expresses a similar, extremely important, view about energy: that, whatever happens in a group of things, the total energy remains the same—energy only shifts from one form to another or from one place to another in the group. That guiding rule is very powerful: it enables us to predict what can happen and what cannot happen; and to work out how much will happen, in the world of machinery, atoms, stars . . . everything.

But is it true? You would be a weak scientist if you just let people announce this and didn't ask where the idea came from and why we believe in it. There is so much to learn in science that you need not ask for the whole story, but you should ask for some illustrations or evidence that Conservation of Energy is a true account of nature, of the Universe.

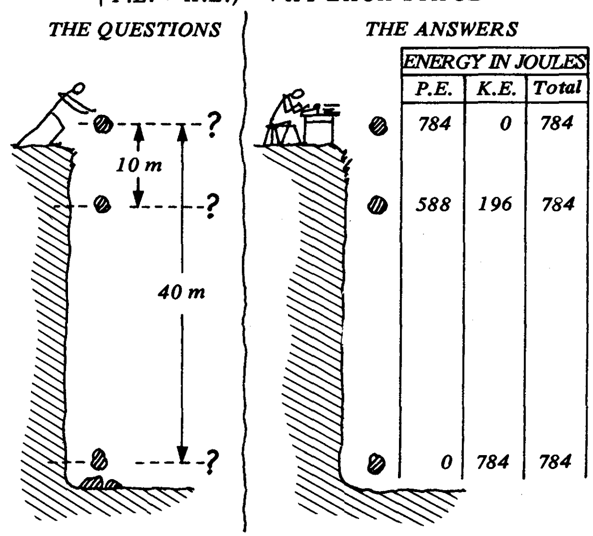
Two hundred years ago, a lot of physics was known: the mechanics of motion (Newton's Laws); the behaviour of lenses and mirrors and the working of optical instruments; a bit about magnets and a little bit about electric charges. . . . But the Conservation of Energy had not been discovered.

Some scientists had ideas of potential energy and kinetic energy then, though not with those clear names. Since the formula for kinetic energy, $\frac{1}{2}mv^2$, is produced by multiplying FORCE × DISTANCE while gain of potential energy is also calculated by FORCE × DISTANCE (IN THE OPPOSITE DIRECTION), it is not surprising that kinetic energy and potential energy add up to a constant total throughout many changes, for example, when a pendulum swings or when a stone falls. (See the sketch of a falling rock with its changes between potential energy and kinetic energy.)

We manufactured our ways of calculating those two forms of energy to *make* them show conservation—which they do when there are no irreversible forces such as friction.

ROCK (2 kg) IN FREE FALL

(P.E. + K.E.) = ? AT EACH STAGE



ENERGY IN JOULES		
P.E.	K.E.	Total
784	0	784
588	196	784
0	784	784

The growth of the Grand Principle The idea of Conservation of Energy on a grand scale—all its many forms always adding up to a constant total—took a long time to grow. It grew from vague beginnings as a wild suggestion through a long line of experiments that made it seem more and more probable, more and more 'true'. The most important evidence came from a series of difficult experiments that you are unlikely to repeat yourself or see repeated successfully. Each was a great battle against experimental errors, and only when done with special care did they build up convincing support. So we shall describe the experimental evidence as a chapter of history.

Your choice At this point, you have a choice, (A) or (B):

(A) You may 'swallow the Conservation of Energy whole' just accepting it as a very important rule, without asking why we believe it to be completely reliable as an account of nature. Then, taking it for granted, you can do calculations about energy, with every kind of energy measured in the same units, *joules*, since you feel sure this is right.

Or (B) if you wish to be an enquiring scientist you can read this chapter of history to learn why we believe in Conservation of Energy; so that you can decide whether you too think it a convincing story.

If you choose (B), you will hear about many experiments, like witnesses in a court to try the case for Conservation of Energy. It is good science to feel some doubts; so we welcome you to sit as jury in the court. You will need to read and criticise and think and decide; and you will learn a lot about energy.

(B) THE COURT TRIAL

Witness Suppose in a real court, trying a serious crime, all seven witnesses have red hair and crooked fingers, and all give evidence in much the same words, would you, on the jury, feel safely convinced? For a safe verdict you need to hear a number of different witnesses give overlapping parts of the story. If some disagree a little with others, it is still on the general agreement of many *different* witnesses that a good jury is likely to decide.

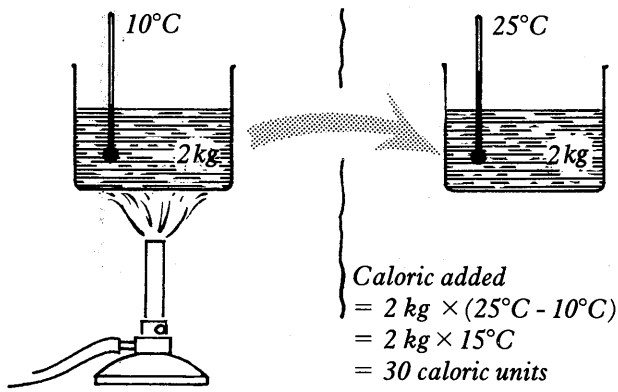
So, if you look at the experiments on energy-changes, you should look for variety of methods and watch for a general tendency towards agreement—you certainly should not be convinced by just one precise measurement of a single change of energy.

Preliminaries As in most studies of history we need to set the stage before the court can meet. It was clear long ago that in some experiments the two forms of MECHANICAL ENERGY, K.E. and P.E., add up to a constant value. You may have seen some experimental tests of this in trolley experiments. The difficult questions arose when some mechanical energy disappeared! You are sure, with your knowledge of modern science, that when that happens (say with friction stopping a moving object) heat appears instead. And you have been told quite often that heat is a form of energy. But 200 years ago this was very difficult to believe; in fact it was hardly suggested.

In those days, scientists believed that heat itself was never created or lost; it was conserved. Heat was called by a different name, 'caloric'. We shall call it just for now by that ancient name to remind you that we are going back two centuries, forgetting our modern knowledge until the court has met to try the case against caloric, and has listened to the witnesses and reached a decision.

Caloric Caloric was something invisible that made things hotter. Hot water had more caloric in it than cold water. When hot water and cold water were mixed, the hot water lost some caloric and the cold gained an equal amount; and the total caloric remained the same.

Measuring caloric When people wanted to *measure* caloric, they gave it to water.* MASS OF WATER × RISE OF TEMPERATURE told them how much caloric had been gained by the water. Using modern units for mass and temperature, you could measure caloric in (kilograms of water) multiplied by (degrees of temperature-rise). The unit quantity of CALORIC would be one-kilogram-of-water heated one Celsius degree.



Caloric added
= 2 kg × (25°C - 10°C)
= 2 kg × 15°C
= 30 caloric units

You, in some of your science (and some older people in dealing with their diet), might use a shorter name for that unit, a 'kilocalorie', or even a Calorie. That name is now considered out of date and unfashionable. So you may have to call the unit of caloric by a harmless long name: kilogram-of-water-warmed-up-one-degree or kilogram-of-water × 1°C.

In your earlier experiments we have given that unit a temporary nickname, *thermal unit*. And now, in the court trial of caloric, we shall use the temporary nickname *caloric unit*—but of course only during the trial.

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*To avoid uncertainties about the thermometer one wise experimenter gave the caloric to ice and measured the mass of ice that melted.

Caloric given to other substances Scientists tried experiments in which hot water and cold water were mixed and the exchanges of caloric were calculated. These experiments showed that caloric was conserved. Experiments with other materials showed again that caloric was conserved, but for each material a special factor had to be used in calculating the change of caloric. We shall call that factor the 'comparison-number' which compares the ease of heating up of any sample of the substance with the ease of heating up of the same mass of water.

Different substances have different comparison numbers: but the comparison-number for any chosen substance is more or less constant over a wide range of temperature. For example, aluminium needs only 0.22 times as much caloric as the same mass of water for the same temperature-rise. The c-n for aluminium is 0.22.

You will do an experiment with lead. The c-n for lead is extra small: measurements show it is only 0.03. Then, in any experiments with caloric given to lead the amount of caloric is calculated thus:

$$\begin{bmatrix}\text{mass} \\ \text{of lead}\end{bmatrix} \times \begin{bmatrix}\text{rise of temperature}\end{bmatrix} \times \begin{bmatrix}\text{c-n for} \\ \text{lead, 0.03}\end{bmatrix}$$

Things caloric could do When caloric was given to ice, the ice melted without getting warmer: some caloric seemed to disappear. Yet people were sure it just remained hidden somewhere among the molecules. And it would reappear on freezing.

When a sailor came sliding down a rope and burned his fingers, he was said to be squeezing caloric out of the rope.

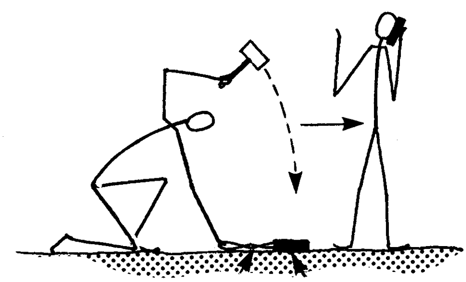
It all fitted together very well: caloric was never created, never lost.

Doubts and experiments Then an unexpected doubt was voiced by Count Rumford. When he was in charge of the cannon factory in Bavaria, he tried using a very blunt drill to bore out a cannon from solid bronze and he noticed it was producing an almost unlimited stream of caloric. He could not believe he was squeezing more and more caloric out of the bronze metal, particularly since the chips of bronze had the same 'appetite for caloric' as the rest. He suggested that caloric might be a form of energy. He thought it was manufactured in this case from the energy supplied by the horse who was driving the boring drill. This was a very strange idea, unpopular with other scientists. So, for a time, indestructible caloric still reigned supreme.

Then a Manchester brewer, James Prescott Joule, caught up the idea that perhaps caloric is created at the expense of mechanical energy. With its modern name 'heat', caloric presently came to be regarded as just another form of energy—thanks largely to the work of Joule.

Experiment 90a
Converting mechanical energy into caloric

a. Wrap a thin piece of lead round a stout wire handle. Place it on the floor or another suitable anvil, and hammer it violently.



Hold the lead against your cheek before and after to feel its temperature.

b. *(Optional)* See a piece of metal bored with a blunt drill, then feel it—this is Rumford's experiment.

c. Try an experiment with a bicycle pump. Push the piston in quickly while you hold your thumb on the outlet. Can you feel any heating?

Think, once again, what really happens to the air molecules in the pump in this case. What is the difference, to a ball, between blocking it with a stationary bat and giving it a big swipe?

When he was quite a young man, Joule started a long series of experiments. He arranged to let mechanical energy disappear in many different ways and he measured how much caloric appeared instead. Soon other scientists tried different experiments with the same aim. Every experiment looked for an answer to this question: *'DOES THE SAME AMOUNT OF MECHANICAL*

OR OTHER ENERGY ALWAYS DISAPPEAR FOR EACH KILOGRAM-OF-WATER-HEATED-ONE-DEGREE (A UNIT OF CALORIC) THAT APPEARS?'

If many different experiments point to the same answer to that question the jury might feel safe in drawing a clear conclusion.

The court's witnesses Such experiments in which caloric is measured are difficult to do accurately. Caloric leaks away very easily—as you would say nowadays, heat is carried away by conduction, convection currents and radiation waves. So, in looking at early experiments, you must not expect great accuracy. Instead, you should look for the results getting closer and closer to some central bull's-eye as time went on. Now hear some witnesses.

THE COURT WILL SIT

First witness: Water friction One of Joule's early experiments was simple: he had a piston in a cylinder of water. He drilled tiny holes through the piston so that when he pushed it down water could flow up through the holes. The holes were very fine, and the water suffered much friction in passing through them. So it came out a little warmer above the piston than below.

Joule found the mechanical energy lost in pushing the piston down, by measuring and calculating:

$$\begin{bmatrix}\text{FORCE ON}\\ \text{PISTON}\end{bmatrix} \times \begin{bmatrix}\text{DISTANCE MOVED DOWN}\\ \text{THROUGH CYLINDER}\end{bmatrix}$$

And he found the caloric* that appeared in the water by measuring and calculating:

MASS OF WATER ×
TINY TEMPERATURE-RISE.

Those two things were measured in different units, so he could not expect to find them equal. What he wanted to know was whether the proportion between them would come out the same in many different experiments.

In telling you his results, we shall use modern units, newton·metres, for the mechanical energy lost, and one-kilogram-of-water-heated-one-degree as the unit for caloric gained.

In that experiment with water-friction Joule obtained one unit of caloric from 4200 newton·metres of mechanical energy.

Second witness: Churning water in a large beaker Joule made a paddle wheel rotate and churn water like an egg-beater. He drove the wheel by two falling weights. He calculated the potential energy lost thus:

$$\begin{bmatrix}\text{MASS OF}\\ \text{LOAD}\end{bmatrix} \times \begin{bmatrix}\text{FIELD}\\ \text{STRENGTH, } g\end{bmatrix} \times \begin{bmatrix}\text{HEIGHT}\\ \text{FALLEN}\end{bmatrix}$$

and he measured caloric gained, as usual, by:

MASS OF WATER × TEMPERATURE-RISE

He obtained one caloric unit from 4800 newton·metres of potential energy lost. Two years later he improved his apparatus, ran twenty experiments, and obtained 4210.

The waterfall Joule also tried a giant continuous water-churning experiment. On his honeymoon in Switzerland he carried a large sensitive thermometer to the top of a waterfall and

Joule on his honeymoon

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* In most of the court testimony the heat appears in water, and, until the case is proved, we have to measure it in units such as kilogram-of-water °C, which we call, for now, 'caloric units'.

It would be stupidly illogical to measure that heat in joules, *which are energy units,* when we are trying to decide whether heat *is* energy. We should seem to be assuming what we want to prove if we asked after each experiment: 'Is a joule of heat equal to a joule of mechanical energy?' So, to emphasise the uncertain status of 'heat' during the trial, we shall call it by its ancient name, 'caloric', until the trial is over, and measure it in 'caloric units'.

took the temperature of the water. Then he went to the bottom of the waterfall and took the temperature of the water that was flowing away smoothly after falling and churning. He found a small temperature difference that agreed with his other experiments.

Third, a trio of witnesses: churning other materials In case critics complained that it was always *water* that was churned—so that the whole effect might be due to some special behaviour of water—Joule tried churning whale oil, and then mercury, instead of water. Using measured values of the comparison-number, c-n, of each material, he obtained 4220 and 4240. Some years later, he churned mercury again: result 4160.

In case critics complained that it was always a *liquid* that was churned, he rubbed rough plates of iron together (surrounded by mercury which collected the caloric). The result of that noisy* experiment: 4210.

Fourth witness: More careful churning of water Three years after his first paddle-wheel experiment, Joule carried out forty more experiments with greater care. He allowed for caloric lost to surrounding air and for the remaining kinetic energy of the falling weights when they reached the floor. In these experiments, he used a specially sensitive thermometer which could be read to $\frac{1}{200}$ degree. Result of forty experiments: 4150.

Fifth witness: Electric dynamo (This was one of the earliest witnesses, but we have not brought him into court until now because his testimony is more indirect. And yet since his testimony includes electrical effects, he is a powerful witness.) Joule built a large primitive dynamo, not long after electric motors and dynamos were invented. He drove it by means of falling weights and calculated the mechanical energy they delivered by:

WEIGHT × DISTANCE FALLEN

The spinning coil of the dynamo was housed in a box of water. He short-circuited the coil and measured the caloric given to the water by the short-circuit current.

To allow for the unmeasured energy that was wasted by pulleys etc. he repeated the experiment without the short-circuit. Then the dynamo ran at the same speed with smaller driving weights. He calculated the mechanical energy supplied by those loads falling and subtracted that from the mechanical energy spent in his main experiment. Results: 4760, 5380, 5600, 4900.

Sixth witness: Electric motor Joule used the same electromagnetic machine as a motor instead of a dynamo. He let a battery drive the motor, which hauled up some weights. Then he let the same battery send the same current through a wire in water and measured the caloric gained by the water. Results: 5510, 3150. He improved his apparatus and the results were then: 4620, 4620, 3950.

While Joule was trying still more methods, other experimenters joined in the business, all obtaining results much like Joule's.

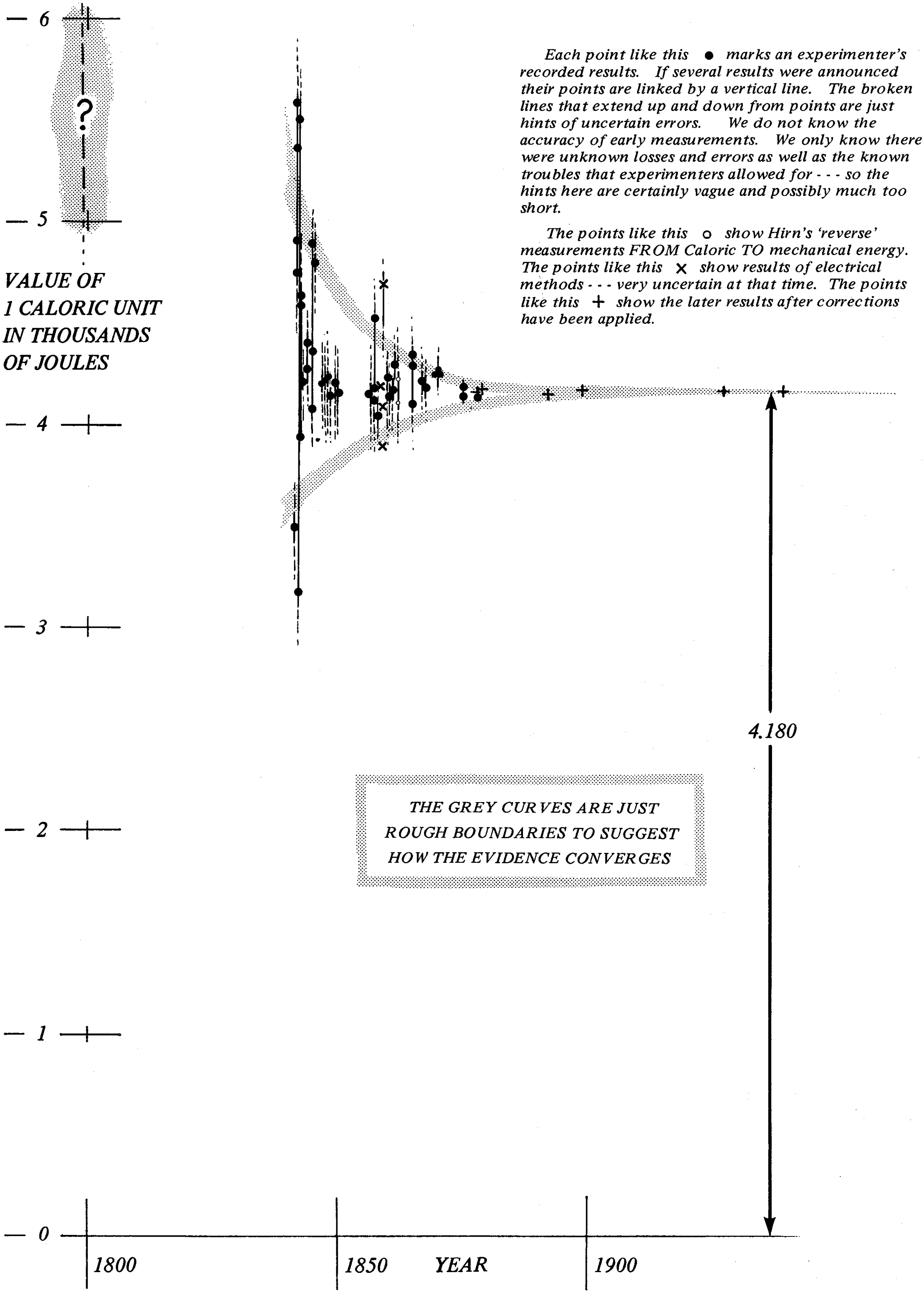
Seventh witness: Reverse experiment, FROM caloric TO mechanical energy A French engineer, Hirn, borrowed the use of a steam engine in a commercial mill. He estimated the total caloric given to steam by the furnace and allowed for caloric given away to the condenser and for the caloric wasted by radiation etc. He estimated the mechanical energy delivered by letting the engine haul up a load. Results ranged from 4120 to 4230.

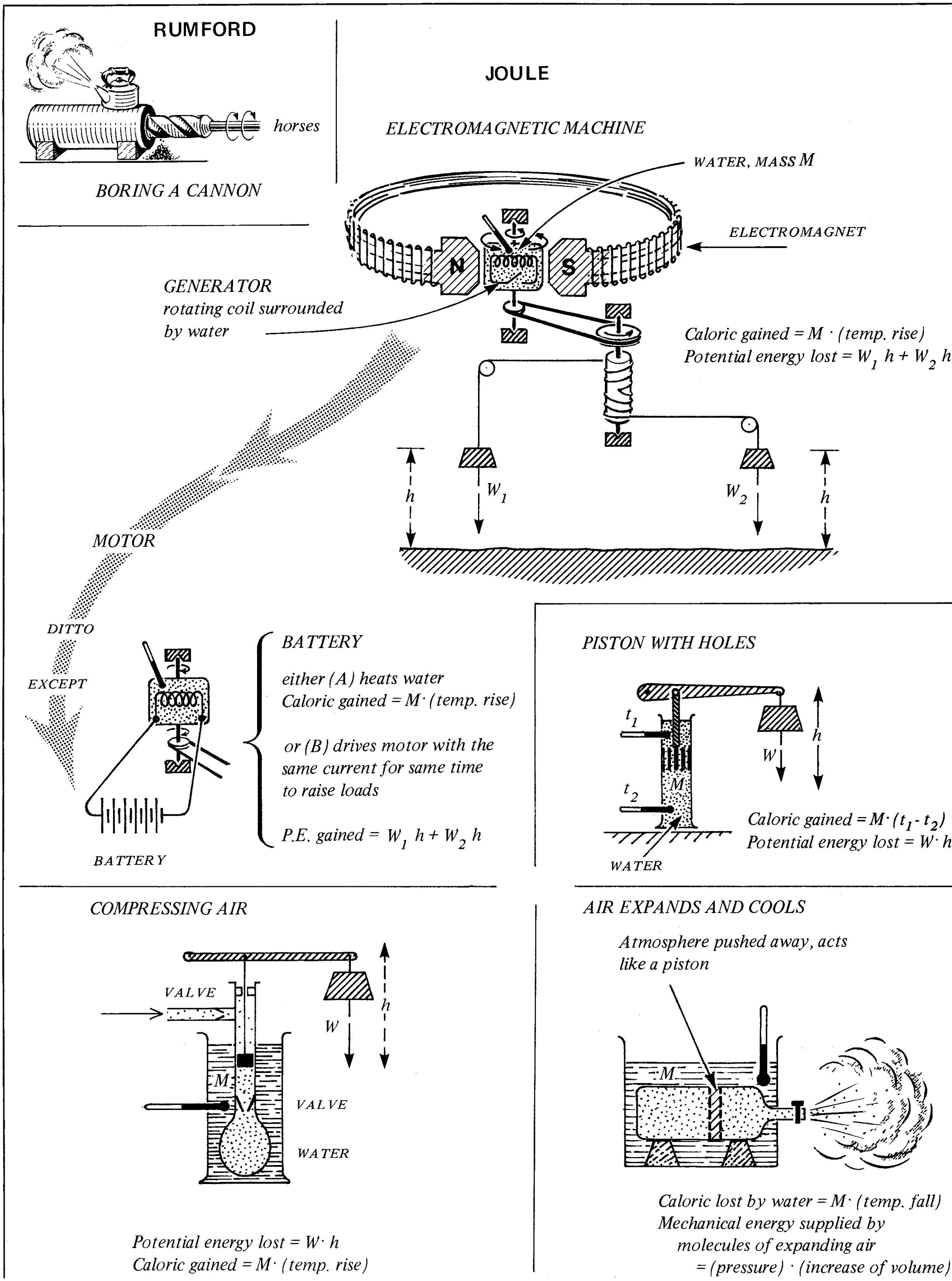
The rest of the trial Our 'trial', which started about 1840, continued with more methods and with increasing skill in accurate measurements until 1940. If you are interested in following the developments, you might consult your teacher about further reading. If you want to get on to other parts of physics and feel you have heard enough witnesses, you should now survey the results critically. First an informal graphical presentation—which you might regard as the prosecuting counsel's final presentation.

Then see the illustrated list of results, which is rather like the summing up by the Judge.

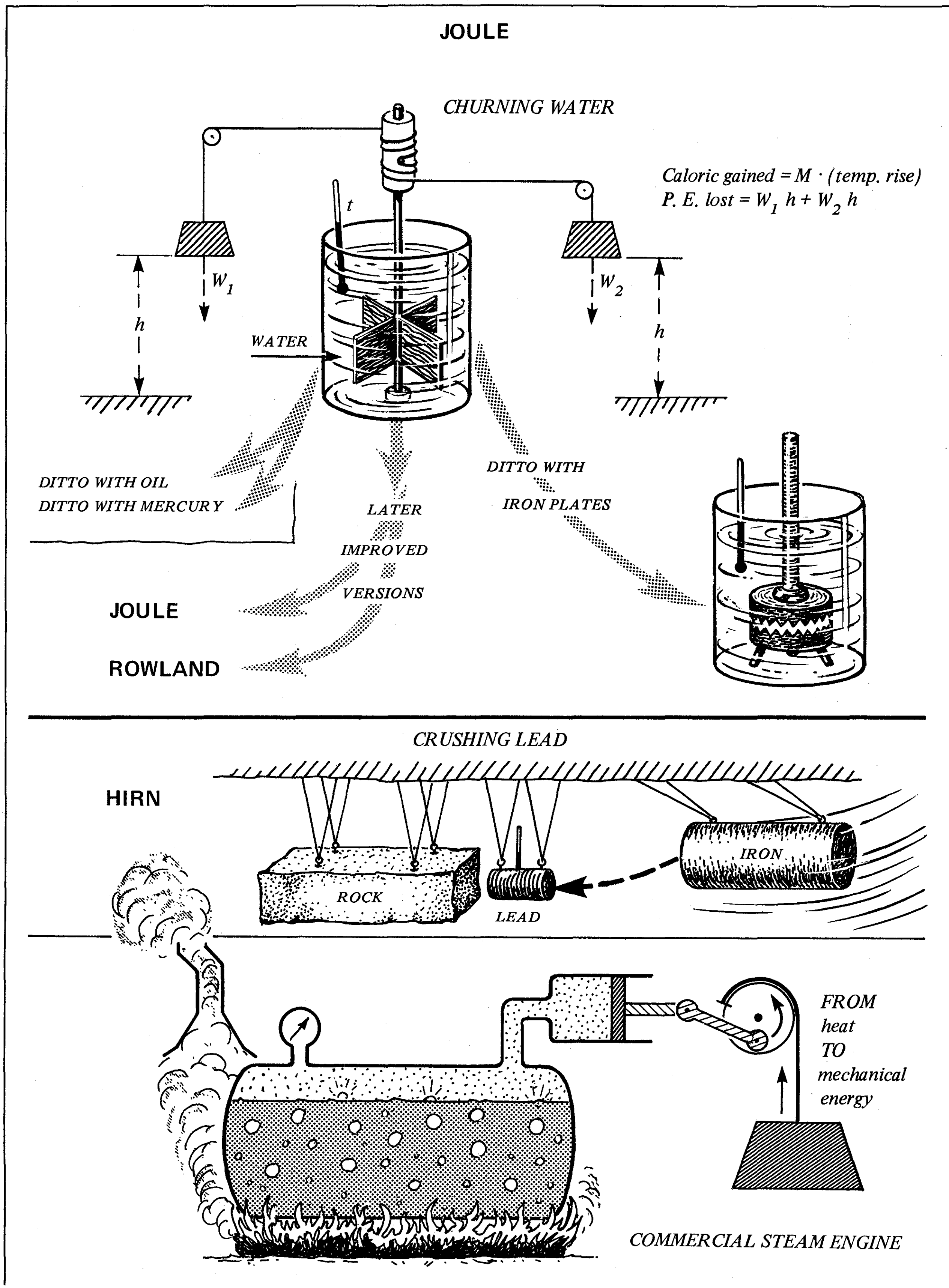
* Joule even tried to make an allowance for the energy carried away by sound waves. He asked a cello player to play loud enough to match the grinding noise. Then he multiplied FORCE and DISTANCE for the cello bow. But his estimate of that wasted energy was far from accurate.

A CHART OF THE COURT TESTIMONY




RUMFORD
horses
BORING A CANNON
JOULE
ELECTROMAGNETIC MACHINE
WATER, MASS M
ELECTROMAGNET
N
S
GENERATOR
rotating coil surrounded
by water
Caloric gained = M · (temp. rise)
Potential energy lost = W_1 h + W_2 h
h
W_1
W_2
h
MOTOR
DITTO
EXCEPT
BATTERY
BATTERY
either (A) heats water
Caloric gained = M· (temp. rise)
or (B) drives motor with the
same current for same time
to raise loads
P.E. gained = W_1 h + W_2 h
PISTON WITH HOLES
t_1
t_2
M
W
h
WATER
Caloric gained = M· (t_1 - t_2)
Potential energy lost = W· h
COMPRESSING AIR
VALVE
W
h
M
VALVE
WATER
Potential energy lost = W· h
Caloric gained = M· (temp. rise)
AIR EXPANDS AND COOLS
Atmosphere pushed away, acts
like a piston
M
Caloric lost by water = M· (temp. fall)
Mechanical energy supplied by
molecules of expanding air
= (pressure) · (increase of volume)

DATE	EXPERIMENTER	METHOD	RESULT *Value of 1 Caloric Unit in thousands of joules*
1798	RUMFORD	Cannon boring with blunt tool. Horse driving boring machine produced "endless supply" of heat. [Rumford made no estimate of mechanical equivalent, but guesses based on his record of horse's work and water heating led, according to Joule, later, to a rough value.]	5 or 6
1842	MAYER	Suggested the name, 'MECHANICAL EQUIVALENT OF HEAT'. Made an estimate from specific heat capacities of gases, using rough data, making serious assumptions.	3.5
1839–1843	JOULE	Experimented with electric currents, and wrote reports that showed he was interpreting heating effects and chemical effects in terms of his growing belief in something like energy-conservation, with heat a form of motion.	
1843	JOULE	Built simple electric machine which could be used as a generator or as a motor. Drove it as dynamo by falling weights; measured caloric produced when dynamo drove a current through coil immersed in water. (Coil was actually the rotating armature-coil of the machine.) Subtracted results of experiments with magnet turned off ("light run") from those with magnet on ("heavy"), to get rid of friction of bearings, etc.	4.76 5.38 5.60 4.90
1843	JOULE	Same electric machine used as a motor: (A) Battery drove motor, which raised weights: *or* (B) The same battery sent same current for the same time through a wire and heated it. [Actual arrangement was more indirect, but essentially like this.]	5.51 3.15
		ditto, improved apparatus.	4.62, 4.62, 3.95
1843	JOULE	Water, driven through fine tubes, was warmed up by fluid friction. (Piston with very fine holes drilled through it was pushed by measured force through water in a cylinder.)	4.22
1844	JOULE	Air, compressed by many successive strokes of piston-pump, warmed up. The compressed-air bottle was surrounded by large mass of water to remove and measure the caloric developed. In calculating mechanical energy used, Joule used Boyle's Law to allow for changes of compressing force.	4.42
1845	JOULE	ditto, greater compression.	4.27
1845	JOULE	Compressed air, from bottle in a water bath, expanded, pushing away the atmosphere (as a piston) and thus cooled.	4.08, 4.37, 4.91
1845	JOULE	Paddle-wheel, driven by falling weights, churned water and heated it by fluid friction. [The first form of Joule's great experiment.]	4.80
1847	JOULE	Improved paddle-wheel churned water. [Joule wound up the weights and let them fall again 20 times, to obtain enough temperature rise. He allowed for the caloric lost meanwhile to the air, etc. He allowed for K.E. which the weights had when they hit the floor.]	4.21
		ditto, churning *whale oil* instead of water [used known specific heat capacity of oil].	4.22
		ditto, churning *mercury*.	4.24


JOULE
CHURNING WATER
Caloric gained = M · (temp. rise)
P. E. lost = W_1 h + W_2 h
t
W_1
W_2
h
h
WATER
DITTO WITH OIL
DITTO WITH MERCURY
LATER
IMPROVED
VERSIONS
DITTO WITH
IRON PLATES
JOULE
ROWLAND
CRUSHING LEAD
HIRN
IRON
ROCK
LEAD
FROM
heat
TO
mechanical
energy
COMMERCIAL STEAM ENGINE

DATE	EXPERIMENTER	METHOD	RESULT *Value of 1 Caloric Unit in thousands of joules*
1848	JOULE	ditto, churning *water*. Forty more experiments with greater care. [Joule believed this result reliable to 0.5%.]	4.15
1850	JOULE	ditto, churning *mercury*.	4.16
1850	JOULE	Friction of *iron plates* rubbed together.	4.21
1857	FAVRE	Battery produced: (A) mechanical energy; *or* (B) caloric, for same current and time.	4.17 to 4.54
1857	HIRN	Bored metal with blunt borer.	4.16
1861	HIRN	Drove a water-cooled metal brake.	4.23
	HIRN	Liquid warmed up when driven through hole by high pressure.	4.16
	HIRN	Crushed a lead block. A 320-kilogram hammer moving 4.5 metre/second smashed a 3-kilogram block of lead against a 1000-kilogram anvil of stone. The lead warmed up about 5°C.	4.17
	HIRN	Compressed air expanded and cooled as it pushed against the atmosphere.	4.31
	HIRN	Steam engine (FROM caloric TO MECHANICAL ENERGY). Borrowed the use of a steam engine in a commercial mill; estimated total caloric given to steam by furnace; allowed for unmeasured caloric wasted by radiation, given to condenser, etc.; estimated mechanical energy delivered in hauling up a load.	4.12 to 4.23
1858	FAVRE	Friction of metals in mercury.	4.05
1857	QUINTUS ICILIUS	Indirect electrical methods. Measured: (A) caloric produced by current in a wire; (B) caloric produced in beaker of same battery-chemicals. Estimated mechanical energy indirectly by electrical instruments: absolute ammeter, voltmeter, and/or ohm. (The electrical units were still uncertain, so the results were not reliable.)	3.9
	WEBER		4.2
	FAVRE		4.2
to	SILBERMAN		4.2
	JOULE		4.1
	BOSCHA		4.1
1859	LENZ & WEBER		3.9 to 4.7
1865	EDLUND	Expansion and contraction of metals.	4.35, 4.21, 4.30
1867	JOULE	Caloric produced by known electric current through known resistance.	4.22
	WEBER	ditto	4.21
1870	VIOLLE	Disc rotated in magnetic field was heated by electrical 'eddy currents'. Measured mechanical drag and caloric output—no electrical measurements.	4.26 4.26 4.27
1875	PULUJ	Friction of metals.	4.167 to 4.180
1878	JOULE	Water churned by paddle: improved apparatus [weighted average of 34 experiments].	4.158(5)

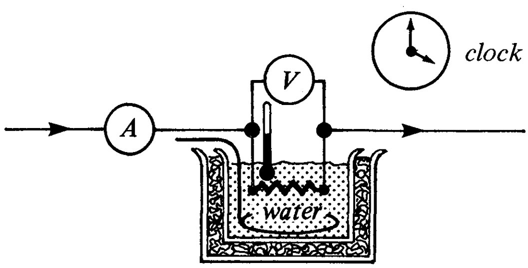
DATE	EXPERIMENTER	METHOD	RESULT *Value of 1 Caloric Unit in thousands of joules*

By then, the case was proved, and the remaining question was the exact length of sentence. The value of the mechanical equivalent, J was being measured so accurately that a careful measurement of g had to be used; and the value of 1 caloric unit (1 kg of water heated up 1°C) depended on whether the water was weighed against a brass kilogram in air or in vacuum without the buoyancy of air!

And it had become clear that water does not take quite the same energy to heat it up from 10° to 11° as from 17° to 18°. The specific heat capacity of water around 20°C (a comfortable room temperature) is slightly smaller than at lower temperatures. So, for statements accurate to 0.1% or better, we must state the temperature-region used for the thermal unit.

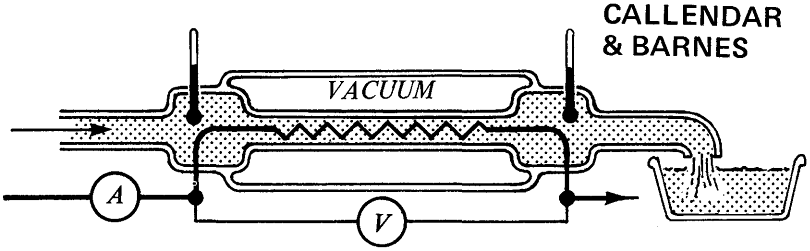
There have been several careful determinations of J in the last hundred years. A few are given below, with vacuum weighing, for a 20°C thermal unit (1 kg of water warmed up from 19.5° to 20.5°C).

DATE	EXPERIMENTER	METHOD	RESULT
1878	JOULE (England)	Water churned. Result of experiment above reduced to weighings in vacuum and corrected to gas-thermometer.	4.172
1879	ROWLAND (Johns Hopkins, U.S.A.)	Water churned by paddle wheel driven by steam engine. Tremendous care over apparatus design and thermometer corrections.	4.179
1892	MICELESCU (France)	Water churning.	4.166
1899	CALLENDAR & BARNES (England)	Continuous flow of water heated electrically. Temperature rise measured electrically.	4.183
1927	LABY & HERCUS (Australia)	Water churned by paddle.	4.1802 ± .0001
1939	OSBORNE et al. (National Bureau of Standards, U.S.A.)	Electrical heating of water.	4.1819



(MANY EXPERIMENTERS)

CALLENDAR & BARNES



continuous flow of water heated by electric current

As jury in the court, do you see the testimony growing closer and closer to a clear story—almost certainly the same whatever the method and materials—that one unit of caloric appears when about 4180 joules of mechanical energy disappear? (And the testimony from Hirn's experiment and one of Joule's suggest that the story is also true in reverse.)

In receiving the many witnesses (by reading the many methods and results), can you see that if there IS one fixed result to which they all point, it must hold for many forms of energy, not just mechanical P.E. yielding caloric? Springs, solid friction, expansion of metals, behaviour of gases, chemical changes, and—indirectly—electrical and magnetic effects, all came into the story. When Joule began his experiments most scientists thought he was a crank, suggesting a wrong view of nature; but by the time of his last experiments it was clear that exchanges between all the many other forms of energy and caloric always happen at a standard rate of exchange.

Heat a form of energy If you now agree with Joule and the other witnesses, you may adopt heat as a form of energy from now on. And therefore you may measure heat in standard energy units, newton·metres.

Since a newton·metre is a long name for something as important as the unit for energy in all its forms, we now give a newton·metre a short name, a joule. (Now you know why that name was chosen for the energy unit, to honour the great experimenter J. P. Joule.*)

THE END OF THE 'COURT TRIAL'

Measuring heat in joules We welcome heat as a member of the family of different forms of energy. And we shall measure heat, as well as other forms, in joules. When we write those units, we simply use the letter J for a joule or joules.

The modern universal unit Henceforward, a caloric unit is to be 4200 *joules*.

From now on, you need not use caloric units or thermal units any more: you can measure every form of energy in *joules*.

Whenever heat is given to water you should now calculate its value in *joules* as follows:

MASS OF WATER IN KG × TEMPERATURE-RISE IN °C × 4180

That last factor is the best, averaged, result of all the later 'Joule' experiments, expressed in (joules)/(kilogram-of-water × °C).

For most purposes, you should take the factor to be 4200.

Specific heat capacity For any substance, we say:

$$\text{heat supplied} = \begin{bmatrix}\text{mass}\\ \text{(in kg)}\end{bmatrix} \times \begin{bmatrix}\text{temperature-rise}\\ \text{(in °C)}\end{bmatrix} \times s$$

where s is the 'specific heat capacity' of the substance—roughly constant for that substance. Thus s is the heat that goes into 1 kg (or out of 1 kg) to change the temperature 1 °C.

The value of s for water is 4200 joules/kg·°C. For aluminium it is about 920 and for lead about 130 joule/kg·°C.

The usual fate of energy In most chains of energy-changes, the form at the end is heat. When you run upstairs to a higher floor, your muscles draw on chemical energy from your food as you gain gravitational potential energy. (You also convert some chemical energy to waste heat.) As you come downstairs again the potential energy is changed to heat, through your scuffing shoes and muscles. So, in the end, *all* the chemical energy you took has turned to heat—you have just warmed the house a tiny bit.

UNIVERSAL CONSERVATION OF ENERGY

The complete balance-sheet Expressing heat measurements with the factor 4200, we find complete Conservation of Energy in every kind of event. Whatever happens, the total energy (if we measure all the different kinds in newton·metres and add up the values) remains the same. If the total seems smaller after some event, such as an explosion, we think that is because we have forgotten to allow for some energy that escaped, perhaps in the form of radiation from the explosion.

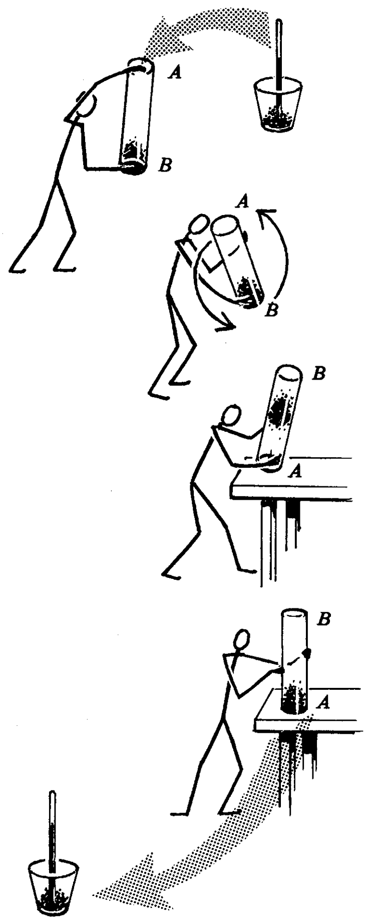
Scientists find this general rule of Conservation of Energy so useful that if they ever discovered an exception, they might be tempted to invent a special, extra type of energy to keep the balance entirely true!

* His friends pronounced his name 'jool'; and we pronounce the name of the unit like that.

TRY A JOULE EXPERIMENT

Experiment 91
The 'waterfall' of lead

Try an experiment like one of Joule's early ones. Instead of Joule's waterfall of water, try a 'waterfall' of lead shot. Let a handful of shot fall from top to bottom of a cardboard tube. Take the temperature of the shot before and after, by pouring it into a light cup and plunging a thermometer gently in among the shot.



What improvements can you make?

When you have found a measurable effect, consult your teacher about measurements and treatment of results.

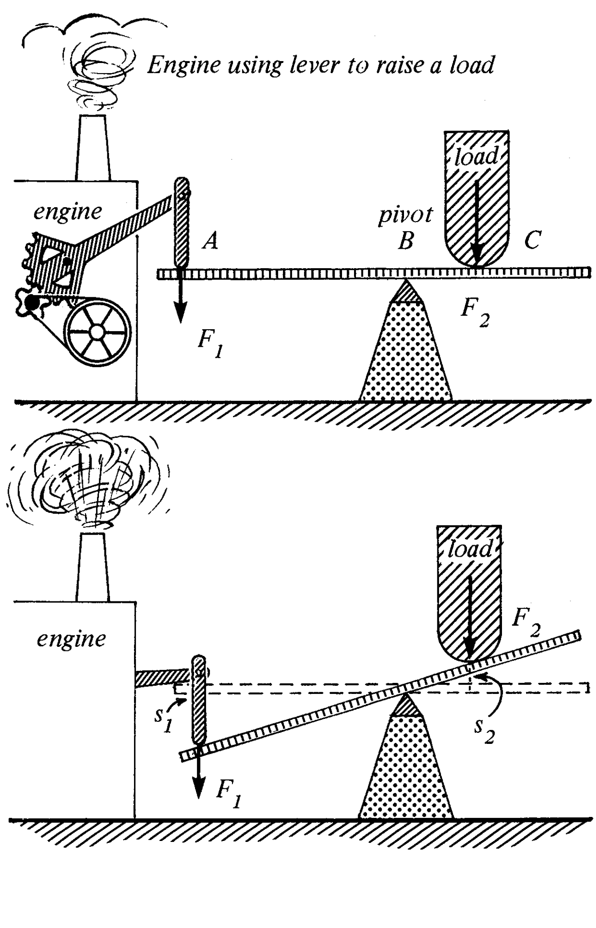
Note : The comparison-number (c-n) for lead is about 0.03. (That means that lead needs only 0.03 times as much heat as the same mass of water for the same temperature-rise.)

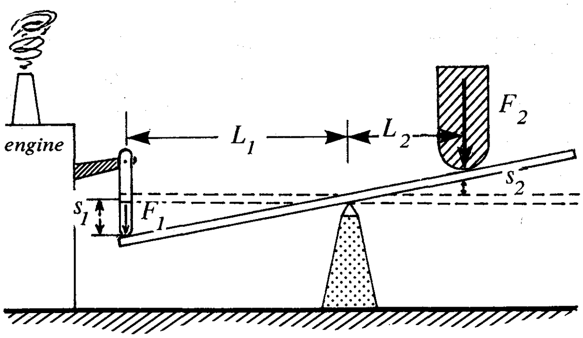
AN ACCURATE MEASUREMENT?

Experiments to measure 4180 Several apparatuses have been designed for doing a 'Joule experiment', measuring the important factor 4180 in school or university labs. If you had a great deal of time to spend on making precise measurements and allowing carefully for heat losses, you could add your own testimony to that of the other court witnesses. Or it might be good to try such an experiment quickly and roughly, just to see for yourself how difficult Joule's work must have been.

But if you just aimed at 'getting the right answer' quickly, that would be poor science; because no apparatus can yield 4180 honestly without tremendous precautions and allowances for losses. Apparatus that seems to give the right answer easily must do so with the help of unseen errors that cancel out.

Machines can multiply forces: Can they multiply energy? In science and engineering we meet many machines, such as a lever or a set of





The shaded triangles are similar. *So* $L_1/L_2 = s_1/s_2$

$$\therefore \frac{L_1}{L_2} = \frac{s_1}{s_2}; \qquad \therefore \frac{F_2}{F_1} = \frac{L_1}{L_2} = \frac{s_1}{s_2};$$

$$\therefore F_1 \cdot s_1 = F_2 \cdot S_2.$$

Input work = Output work

pulleys, which make it easy to handle things with suitable forces. *If you use a set of pulleys to raise a heavy load, how does the potential energy gained by the load compare with the energy you supply in pulling on the rope? Is the 'output' energy equal to the 'input' energy, or is it greater or smaller?* Calculate input and output each as a quantity of WORK,

FORCE × DISTANCE MOVED.

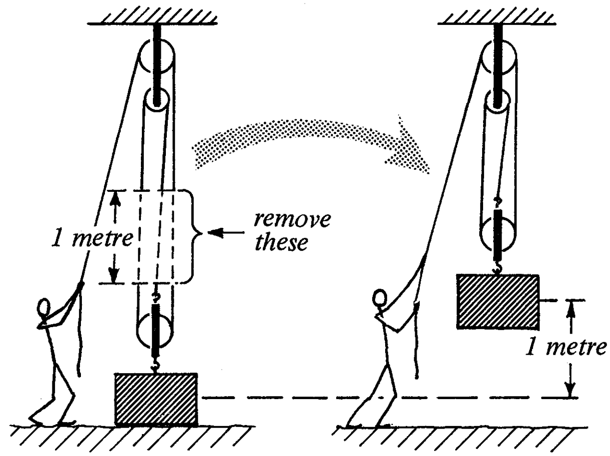
In theory—when you think about ideal pulleys or any other frictionless machine—you will find the output is exactly equal to the input: not perpetual motion, no gain of energy from anywhere, nor any mysterious loss.

In practice, the output is a little less than the input because friction takes a tax. However, energy has not disappeared but part of the input energy has gone to heat through the agency of friction, and the rest appears as output.

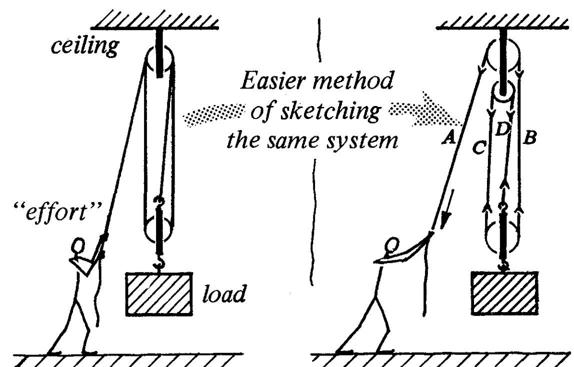
Here again we have examples of Conservation of Energy:

INPUT ENERGY = OUTPUT ENERGY + WASTE HEAT ENERGY

And our belief in that universal principle tells us never to expect more. A *machine* cannot multiply energy. Nor can an *engine*, which uses fuel, manufacture energy: it only transfers energy from the fuel to other forms.



Pulley system: Distance ratio



Pulley system: Force ratio

'PERPETUAL MOTION' AND 'PERPETUAL MOVEMENT': TWO QUITE DIFFERENT IDEAS

Perpetual motion machines For many centuries inventors have tried to produce a machine that would defy Conservation and *manufacture* energy. Such a machine would give out more energy than it takes in for its own running.

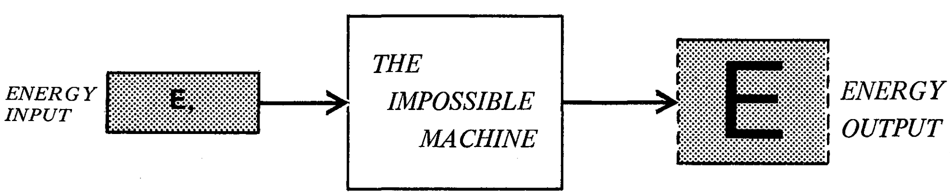
Think of the wonderful power station one could have with such a machine: some of the machine's output would be piped back to the input to keep the machine itself going, but the rest of the output could drive a dynamo to light a whole city. It would need no fuel—since it would provide its own 'fuel' from its output. That would be the richest invention in the world.

No wonder inventors tried to produce such machines. We call them 'perpetual motion machines'*. If you are interested you will find books that describe attempts at making a perpetual motion machine. All such attempts have failed. Sometimes the actual machine has been constructed and either failed at once or soon ground to a stop. Sometimes the invention never got beyond a sketch, because engineers and scientists could point to a defect that would prevent its success. We still hear of a hopeful inventor from time to time; but scientists' confidence in Conservation of Energy is so great that they feel sure that no machine will ever be made which puts out more energy than it takes in.

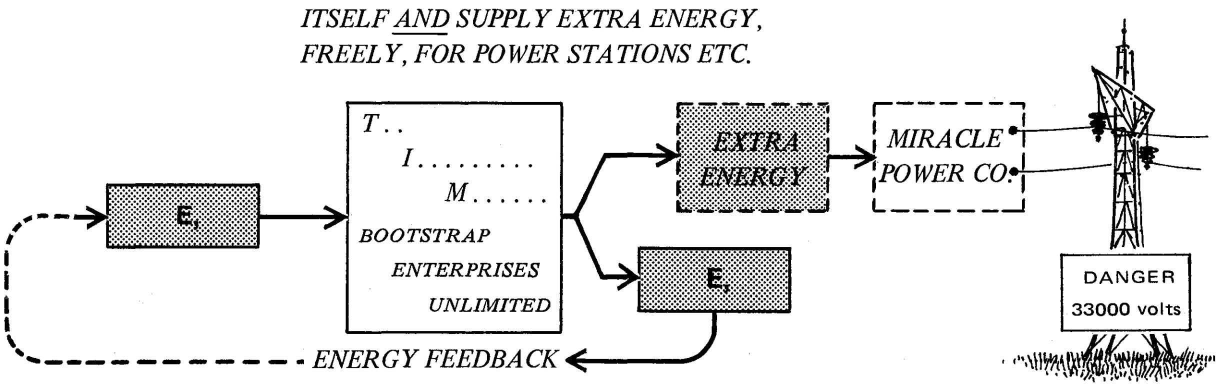
Perpetual movement However there is quite a different behaviour which is practically possible. This is what we should call 'perpetual *movement*': a machine running at *constant speed* without any continuing supply of energy. A spinning bicycle wheel on a well-oiled axle almost does this; the Moon orbiting round the Earth is still closer to perpetual movement; and air molecules are completely successful at this. It is good to have a different name such as 'perpetual *movement*' because a machine at constant speed would soon come to a stop if we took energy from it for other uses.

In practice, friction takes a tax, and practical machines do come to a stop unless supplied with energy to make up for friction losses. But that practical difficulty about maintaining *PERPETUAL MOVEMENT* is quite different from the absolute impossibility, as we now believe, of *PERPETUAL MOTION*.

* We use the name 'perpetual motion' because, if there were such a machine, it would run for ever without fuel. If we left it to run without using its extra output, it would run faster and faster, continually accelerating. A better name for that would be 'perpetually increasing motion'.



SUCH A MACHINE COULD FEED ITSELF AND SUPPLY EXTRA ENERGY, FREELY, FOR POWER STATIONS ETC.



Progress Questions

JOULE EXPERIMENTS

2A. Some lead shot falls from the bench to the ground. Copy and complete:

When the lead is falling energy changes from . . ? . . energy to . . ? . . energy, and when the lead hits the ground, the . . ? . . energy changes to . . ? . . energy.

3. A boy had $\frac{1}{2}$ kg of lead shot. He put it in an upright cardboard tube that was $\frac{1}{2}$ metre long. He turned the tube over quickly, so the lead was lifted up $\frac{1}{2}$ metre, and then fell. He did this 50 times. Then he tipped the lead into a beaker and he found its temperature had gone from 20°C to 22°C.

a. First work out how much uphill energy the lead was given.

(i) How high altogether was the lead lifted up?

(ii) What was the force on the lead? (The Earth's field strength is 10 newtons/kg.)

(iii) Use

ENERGY-TRANSFER = FORCE × DISTANCE

to find how many joules of uphill energy was given to the lead.

b. Now work out how much heat the lead got.

(i) What was the lead's rise in temperature?

(ii) 1 kg of lead, heated through 1°C needs $\frac{1}{30}$ thermal unit.

How many thermal units did the lead in this experiment need? (The answer will be a *fraction* of a thermal unit.)

c. Now put these two parts together.

(i) Copy and complete:

The experiment shows . . ? . . joules of gravity energy are transferred to . . ? . . thermal units of heat. So . . ? . . joules would give one whole thermal unit of heat, from this experiment.

4. The experiment in Question 3 is only rough.

a. It is important to let the lead fall freely, and not roll down the sides of the tube. Why?

b. It is important to measure the rise in temperature of the lead quickly afterwards. Why?

c. It is better to put the lead into a plastic cup, not a tin, while you measure the temperature-rise. Why?

d. Mention some ways in which you think this experiment could be made more reliable.

5. A girl did the *same* experiment as the boy did in Question 3. She had $\frac{1}{2}$ kg of lead shot in a tube $\frac{1}{2}$ metre long, and turned it 50 times. When she tipped her lead into a beaker, she found the temperature had gone from 20°C to 21.5°C.

a. What was the rise in temperature?

b. The girl and the boy in Question 3 did the *same* experiment. Why did they find different rises in temperature?

c. It would not be true to say one was right and one was wrong. Why not?

d. Copy and complete:

The boy worked out that 1 thermal unit comes from . . ? . . joules, and the girl worked out that 1 thermal unit comes from . . ? . . joules. I think (/the boy/the girl/neither/) was really right, because . ? . .

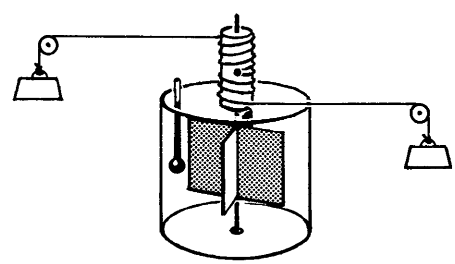
e. How many 'caloric units' did the lead gain in this experiment?

f. How many joules of uphill energy were given to the lead?

g. Copy and complete:

In this experiment . . ? . . joules of uphill energy disappeared and . . ? . . caloric units appeared. So . . ? . . joules would give one whole caloric unit.

JOULE'S OWN EXPERIMENT



6. Here is a rough sketch of apparatus used by Joule to find a value for J by converting the P.E. of the falling weights to heat in the water.

a. Copy the sketch and label the important parts. Describe how the apparatus worked.

b. Most of the P.E. of the weights goes to heating the water, but some goes to other places. List the other places where heat is produced.

c. Joule tried to make his experiment as accurate as possible by cutting down these heat losses. Explain what he did.

d. Why is it a good idea to have the apparatus as large as possible? (Assume you have a thermometer sensitive enough to measure the small temperature rise produced in a large amount of water.)

e. When Joule first reported to the British Association on 21 August 1843, his results were (in our units of joules/thermal unit): 4800, 5450, 5500, 4950, 5470, 3200, 4040, 4650. Why did he get a set of *different* results like this?

(It was only after many years of experimenting that he got sets of results which were close enough together to convince other scientists that there *was* a definite figure and that the same number of joules of mechanical energy always results in the same quantity of heat.)

ENERGY UNITS FOR HEAT

Now we use 4200 joules = 1 caloric unit (or 1 thermal unit). Copy and complete:

. . ? . . joules = 1 caloric unit
. . ? . . joules = 2 caloric units
12 600 joules = . . ? . . caloric units
. . ? . . joules = $\frac{1}{2}$ caloric unit

K.E. TRANSFERS TO HEAT

7. A car of mass 1500 kg is travelling at a speed of 30 metre per second (about 100 km/h or 60 miles per hour).

a. What is its kinetic energy?

b. The brakes are applied and the car is brought to a stop. How much energy is transferred to heat?

c. How many caloric units of heat are produced (roughly)?

8. As in Question 7, a 1500-kg car travelling at 15 metres per second is brought to a stop.

a. How many caloric units of heat are produced?

b. This car's speed is only half that of the car in Question 7. The heat produced by the brakes is only . . ? . . as great.

Questions

MECHANICAL ENERGY AND HEAT

9. You attempt to drill a hole through a small steel plate, using a drill and a blunt bit. Results: a squealing noise, a rise in temperature and a few chips of metal. The mass of the plate plus chips is the same as the mass of the plate before the hole was made.

a. What energy changes have taken place?

b. Your partner says that the energy has finally ended up as kinetic energy. Is he right? What do you think?

10. A bullet is fired from a rifle and hits a wall. After it hits, it gets so hot that it nearly reaches melting point. This means that each of its atoms has more kinetic energy. But before it hits the wall the bullet had a great deal of kinetic energy. Each of its atoms had a lot of kinetic energy. 'So', says your partner, 'there is no change; kinetic energy is still kinetic energy.'

You agree with this; but you point out there is a difference you would like to make. What difference?

11a. Describe two examples (different from those of Questions 9 and 10) of mechanical energy disappearing and heat appearing.

b. Mention also (no description of mechanism required) one means whereby some heat disappears and some mechanical energy appears in its place.

12. *(Advanced question: think and guess)* In Question 10 we carefully said 'nearly reaches melting point'. Suppose the bullet has so much energy that it melts when it is stopped. Is it now true that its energy is entirely in the form of molecular kinetic energy of molecules or atoms? Or is some of it now potential energy? What do you think? Give your reason.

CONSERVATION?

13. Sometimes some mechanical energy disappears and heat appears. Also, in special cases—a motor cycle engine for example—some heat disappears and mechanical energy appears. However, we cannot assume without experiments that for every kilogram-of-water-heated-or-cooled-1°C the same number of joules disappear or appear, though we may well think that this idea is likely to be true. Calling it 'Conservation of

Energy' does not prove it! Saying 'you can't get something for nothing' is no support because it just assumes (and states) what you want to prove!

What sort of experiment would convince you that 'Conservation of Energy' is true for heat and mechanical energy? (You need not describe the actual apparatus.)

A 'JOULE' EXPERIMENT

14. In an experiment performed by the French scientist, Hirn, a hammer weighing 400 kg moving at 5 metres per second crashed into a 3-kg block of lead held against a heavy anvil. The lead was crushed and its temperature rose by 7°C. (To raise the temperature of 1 kg of lead by 1°C requires 0.03 thermal unit.)

a. What was the kinetic energy of the hammer (measured in joules)?

b. How much heat in thermal units was produced in the lead?

c. Assuming that all the K.E. was converted into heat in the lead, calculate how many joules are equivalent to 1 thermal unit.

d. Give two reasons why the assumption in (c) is not fully justified. Will these errors tend to make the results too large or too small?

CALCULATIONS

15. A meteorite of mass 10 kilograms enters the Earth's atmosphere. Because of air resistance its speed is rapidly reduced from 4000 metre per second to 1000 metre per second.

a. How much heat energy (in joules) is generated as a result of this change of speed? (Use K.E. = $\frac{1}{2}mv^2$.)

b. Water takes 4200 joules to warm up 1 kg·1°C. Rock only needs about one-third as much, say 1400 joules, for 1 kg·1°C. Estimate the temperature-rise of the meteorite.

c. Rock is a poor conductor of heat: also, the meteorite takes only a short time to travel through the atmosphere—less than one minute. How do those two bits of information affect your answer to (b)?

d. What do you think is likely to happen to this meteorite?

e. Why is the hazard from meteorites much greater for a space traveller than for people on the Earth's surface?

16. If you trust the general principle of Conservation of Energy, you can calculate a pendulum's maximum speed from the height at which it started. The bob of a 50 cm pendulum is pulled aside a horizontal distance 40 cm. How high is the bob above its rest position (remember the shape of a 3-4-5 triangle)? As it swings back to its central position, the bob loses gravitational P.E. How much?

At its central position, it is moving with kinetic energy $\frac{1}{2}mv^2$. Calculate v.

In that calculation, if you wanted to know the mass of the bob you might take it to be $\frac{1}{2}$ kg. If you waited for that before calculating the speed, now work it out.

However, you did not actually need to know the mass. Suggest two reasons for not needing to know the mass:

(i) a reason connected with the actual calculation.

(ii) a reason from a different piece of experimental knowledge.

17. A 1500-kg car is travelling at 30 metre per second (about 100 km/h or 60 mph).

When the car stops, the brakes transfer energy from kinetic energy to heat energy.

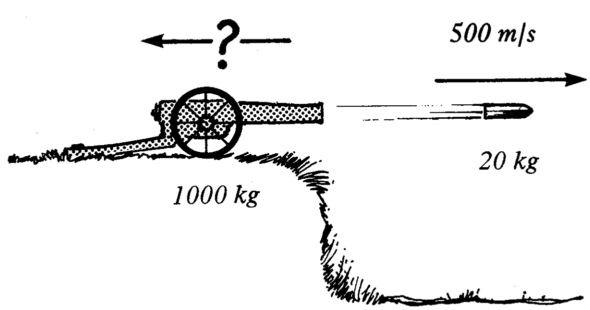
(i) How much kinetic energy must they transfer?

(ii) So how much is the work?

(iii) Suppose the braking force is 7500 newtons. Calculate the braking distance (use WORK = FORCE × DISTANCE).

USING MOMENTUM AND K.E.

18. A 1000-kilogram gun fires a 20-kilogram shell horizontally with a velocity 500 metre per second.



a. Calculate the velocity of recoil of the gun. (*Hint:* Assume that MOMENTUM is conserved, *as it always is.*)

b. Calculate the kinetic energies of the gun and of the shell just after firing.

c. What fraction of the total kinetic energy does the shell carry? This means, calculate the fraction

$$\frac{\text{K.E. of shell}}{\text{K.E. of shell} + \text{K.E. of gun}}.$$

d. Suppose the recoiling gun is brought to a stop in a distance of 40 cm (0.40 metre) by some machinery which exerts a constant force on the gun, opposing its motion. Calculate the size of that force.

PERPETUAL MOVEMENT AND PERPETUAL MOTION

19. Perpetual Movement means something going on moving for ever without any supply of energy. Perpetual Motion means something—a machine of some sort—providing a continuous output of more energy than is put into it.

a. Give an example of 'almost perpetual *movement*' that you might see in a laboratory, or in everyday life outside the laboratory.

b. Why only 'almost'?

c. *(Advanced)* You told your neighbour (who knows no physics) that two good examples of perpetual *movement* are: the movement of the Earth around the Sun, and the movement of air molecules.

Now he asks:

a. Why the Earth does not slow down and stop?

b. Why the molecules do not slow down and stop?

Do your best to explain (a) and (b) to him in two or three sentences for each.

20. After your chat with your neighbour about perpetual *movement*, you and he talk about perpetual *motion*, and you tell him, with one or two examples, that perpetual-motion machines are impossible. He says, 'I remember reading about a perpetual-motion machine some time ago. As far as I remember, it was an electric generator (dynamo) joined by wires to an electric motor, which is coupled by a pulley and belt to the generator. The generator provides current which runs the motor; the motor drives the generator which gives current for the motor; and so on.' He asks why that wasn't a perpetual motion machine.

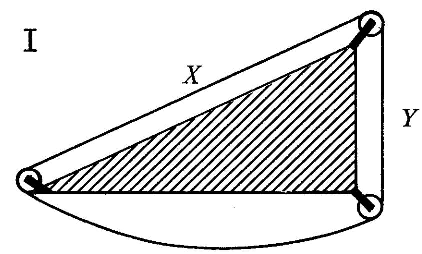
a. Write a few sentences of your conversation with your neighbour after that.

b. He then says, 'All right, I agree that the generator and motor machine would not provide a continuous supply of extra energy. But my great grandfather—he was clever—had a perpetual-motion machine. It was a windmill; it ground wheat. If you had seen the large wheels and shafts turning and the rotating grindstone, you would have had no doubt that it had plenty of energy. Yet he paid nothing for coal, gas, electricity or any thing of the sort.'

What do you reply to this?

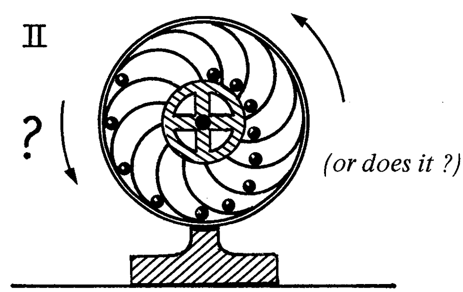
21. *(Advanced)* Here are two 'perpetual-motion machines'. Try to explain why they do not work.

I



In (I) a loop of flexible rope hangs over pulleys on an inclined plane as shown. The length at X is greater than the length at Y, therefore it is heavier. Therefore X goes down and Y goes up, continuously. What do you say?

II



In (II) as the wheel rotates, the balls on the left run out farther from the centre, so that they exert an anti-clockwise turning effect which is greater than the clockwise turning effect of the balls on the right. Therefore the wheel continuously accelerates in an anti-clockwise direction. What do you say?

Note: The machines in this question have friction which would oppose motion. But this is not the main reason why they do not work. Anyhow, you can suppose the friction is very small.

FUEL FOR A WATER PUMP

††**22.** An engine pumps water from a lake to a high reservoir. To raise 10 cubic metres of water 100 metres above the lake the engine burns 12 litres of diesel oil.

a. How many litres of oil would be required to pump 20 cubic metres to a height of 100 metres?

b. How many litres to pump 10 cubic metres to 200 metres?

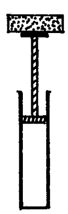
c. One cubic metre of water has a weight of 10 000 newtons. How many joules of energy does the engine provide when it uses one litre of fuel?

d. Not *all* the energy of the fuel goes into raising water. Suggest two or three ways in which energy is 'wasted'.

e. In what form does wasted energy finally appear?

ENERGY CHANGES IN A GAS

23. A piston P encloses air in a cylinder 50 cm high (like a bicycle pump with the end closed). When a brick is dropped on top of the piston it descends, bounces up and down a few times, and finally comes to rest 10 cm lower down than it was before. The gas is compressed when the piston moves down. The brick and piston together total 3 kilograms.



P

a. How much potential energy was lost as the piston fell 10 cm?

b. Why did the piston fall more than 10 cm just at first?

c. Why did it bounce up again?

d. Why did it finally come to rest? (That is partly due to piston friction but what else happens to slow it?)

e. What could have happened if there had been a very small hole in the top of the piston?

††**24.** Remember that we 'explain' gas pressure by saying that it is the effect of bombardment by moving gas molecules. A bicycle pump is held with the handle at the top, and *the lower end is open*. The handle (with the piston) is pushed down.

a. What change in the motion of the air molecules in the pump occurs as the piston moves down?

b. How does this change take place? That is, how does it happen?

c. What happens to the air?

Now think of the pump with the *lower end tightly closed*. Again the piston is pushed down, let us say, half-way along the pump barrel.

d. Does the change you mentioned in (a) still take place? If you say *it does not*, give the reason for your answer. If you say it *does*, then answer (e) below.

e. The air cannot now get out of the pump. Yet the piston pushed the molecules downwards (you have agreed). What has happened to this downward motion of the molecules? And what can you say about the temperature of the air in the pump?

WORLD USES OF ENERGY

Now you should view energy as having many interchangeable forms. And now you know that it is *interchanges* between forms that are useful to mankind—and not some impossible manufacture of energy from nothing.

See the chart of energy sources and uses. There is no need to copy it: just look at it from time to time. (Page 196.)

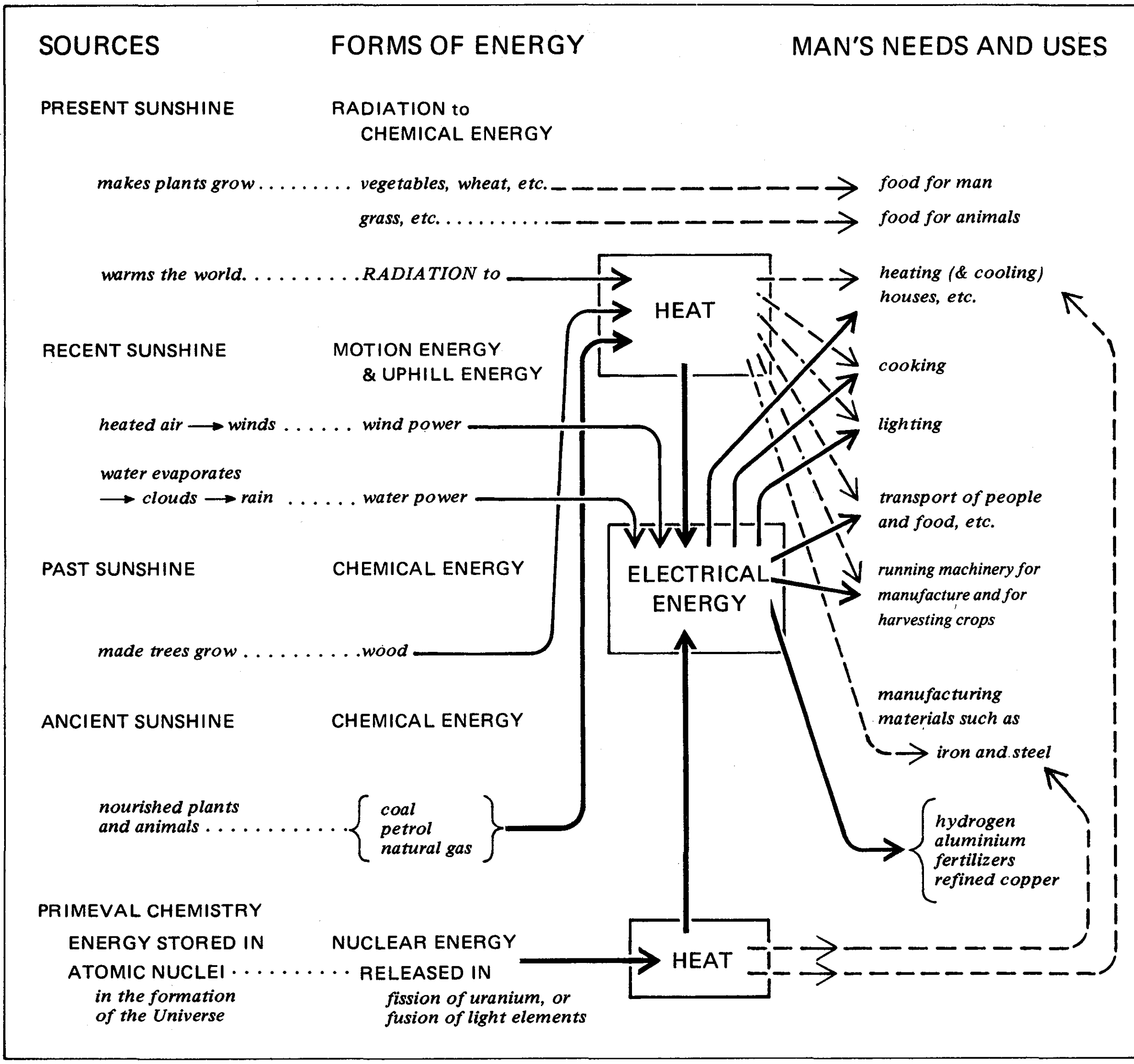
A SPECIMEN CHAIN OF ENERGY-CHANGES

Describing energy-changes The transfers of energy, from one form to another (or from one place to another) are so important to mankind that in learning science you should trace out many examples—such as the chain of changes from coal to an electric lamp bulb in your house.

If a question in a test or examination asks you to describe the changes in such a chain you should label the energy-forms with their proper names and say clearly where or how the transfers take place.

A vague answer to a question about throwing a ball such as 'FROM muscle energy TO mechanical energy' would not do. 'Mechanical' is unnecessarily vague here. K.E. of the moving ball would be better.

'Muscle' is not a proper name for a form of energy. Muscle energy is a definite name, but it is



better to use the formal name 'chemical energy'. (You may have met a slang name for this, 'breakfast energy', but this was only an amusing description for beginners.) Here is an example to help you answer questions about a chain of transfers.

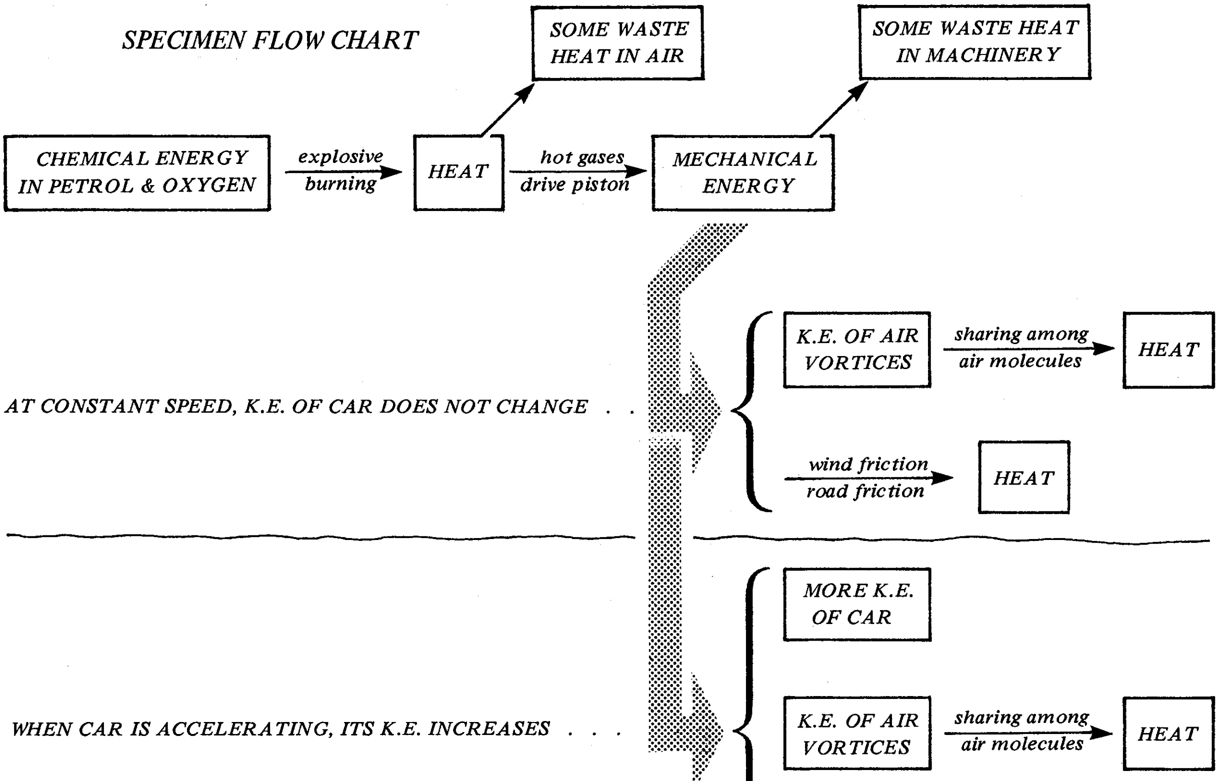
Specimen question Describe the energy changes in each of the following:
(i) A car starts from rest and speeds up to 50 km per hour.
(ii) The car then runs at *constant speed*, 50 km per hour, against a head wind and some road friction.
(iii) The driver puts on the brakes. The car slows to a stop.
(iv) As an alternative to *(iii)*, suppose the car meets a steep hill when it is running at 50 km per hour and runs up the hill, losing speed, so that at the top it runs along the level at 30 km per hour.

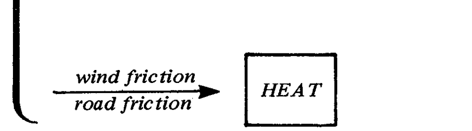
Specimen answers (These are longer than the answers you would be expected to give, but they show the kind of labels and explanations that are needed.)

(i) When the car is at rest, it has a store of chemical energy in its petrol. (Strictly speaking it is chemical energy which can be released by the petrol and oxygen from the air together.)

As the car accelerates, chemical energy in the fuel changes to heat in the engine, some of which is

SPECIMEN FLOW CHART





wasted to the surrounding air. The rest of the heat changes, as the hot gases drive the pistons, to the moving car's increasing store of kinetic energy. And the pistons and other machinery also waste some of the energy they receive in the form of heat, through friction.

(ii) When the car runs at constant speed its kinetic energy is not changing. Whatever friction or other opposition it encounters, no more energy is going from the fuel into the K.E. of the car's motion. The engine is still burning fuel and the heat from that goes into mechanical energy* which keeps the car moving steadily against wind resistance and road friction, etc.

Some of that mechanical energy goes via friction into heat in the road and car bearings, etc. Some goes into K.E. of air currents left behind the car in swirling vortex motion. Those air currents are soon brought to rest by fluid friction, and their kinetic energy turns into heat. Thus the air behind the car is left a little warmer than before.

All told, as the car proceeds at constant speed, the car continues to warm the road and air, so that heat is the final form to which the chemical energy of the fuel is converted.

(iii) As the car slows to a stop, it may still be burning fuel whose chemical energy will transfer to heat as before. But the car is also losing kinetic energy. The brakes which decelerate the car produce heat at the expense of that kinetic energy, so the brake drums get warmer. In the end, the air, road and car are all warmed a little.

Thus at the end of the journey, *all* the chemical energy of fuel that has been used has changed to heat, mostly in the air.

Specimen answers in flow-chart form This form is shorter and quicker to put on paper; but if you use it you need to think carefully about using the right labels. (See the specimen above.)

* It is difficult to describe the transition from heat in hot gases to kinetic energy etc. The energy must go through a stage of strain energy (P.E.) in the crankshafts etc, and temporary K.E. in piston and wheels etc.

We avoid trouble by lumping these possible forms together under the name 'mechanical energy'. That is a suitable name here, but you should not use it carelessly to save clear thinking.

Questions

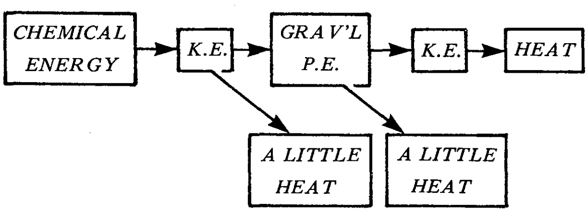
CHAINS OF ENERGY CHANGES

25a. Look at the long, wordy *specimen answer* to the *specimen question* on energy-changes. Rewrite that answer *MUCH MORE BRIEFLY*. (This does not ask you to think out the physics of the changes—the specimen question has already done that for you. This is a problem in précis-writing! See if you can get the correct names into a shorter account.)

b. A large diesel engine, burning oil fuel, drives a dynamo in a power station. Describe the energy-changes (or transfers) from the fuel oil to an electric lamp in your house. (Look at the *specimen question* and *answer* above, but use the skill you put into answering part (a).)

c. Sketch a flow-chart type of answer for (b). (Look at the *specimen flow-chart* on page 197 and note the comment on it.)

26. *(A question for guessing)* Here is a flow-chart that is insufficiently labelled.



a. Guess what it may describe. (Just tell a story about what you think may have happened.)

b. Say what is happening in each of the places where there is just an arrow now.

27. Copy out (a) to (g) below, completing (b) etc. in the same way as (a).

Note: Energy that men or animals derive from food is chemical energy.

a. A child spins a top, the top spins and hums and finally comes to rest. Energy changes are:

chemical E→kinetic E→heat (in floor and air).
↘ ↗
sound E

b. Car generator charges accumulator, which later on lights headlamps. Energy changes are: . . ? . .   . . ? . .   etc.

c. Wind turns the sails of a windpump which raises water out of a ditch into a canal at a higher level. Energy changes are: . . ? . . . . ? . . etc.

d. Water in high reservoir runs down large pipes and turns the blades of turbine wheel at the bottom, turbine drives dynamo, dynamo supplies current to electric fire which warms your room. Energy changes are: . . ? . . etc.

e. Bullet and explosive placed in rifle, trigger pulled, hot gases formed in gun-barrel; bullet shot out, bullet hits wall and stops dead. Energy changes are: . . ? . . .

f. Nuclear reactor makes high pressure steam which turns a steam turbine which drives a dynamo which drives electric current. Energy changes are: . . ? . . .

g. Radium atom emits fast alpha-particle which hits a fluorescent screen and makes a faint 'splash' of light. Energy changes are: . . ? . . .

28. Example: 'Some power stations turn the dynamo's coils with steam engines that run on coal. So *chemical* energy from COAL turns into electrical energy.'

There are lots of different ways of turning the coils. Think about the following. Then copy each one and complete the gaps. (See the list in Ch. 5 for names of forms of energy.)

a. I turn a bicycle dynamo when I pedal along. So . . ? . . energy from . . ? . . turns into . . ? . . energy.

b. A car dynamo works all the time the car is moving. So . . ? . . energy from . . ? . . turns into . . ? . . energy.

c. In Scotland, Canada, Norway, where there are big waterfalls, water is used to turn the coils. So . . ? . . energy from . . ? . . turns into . . ? . . energy.

d. Remote farms sometimes use small windmills to turn their own dynamos. So . . ? . . energy from . . ? . . turns into . . ? . . energy.

e. Some power stations drive their dynamos with steam engines that run on coal. So . . ? . . energy from . . ? . . turns into . . ? . . energy.

f. Some power stations run on oil, not coal. The oil is used to work . . ? . . engines that turn the dynamo's . . ? . . energy from . . ? . . into . . ? . . energy.

CHAPTER 10

HUMAN ENERGY AND POWER

POWER

Power is something very important in science and engineering. It is not ENERGY but the RATE* AT WHICH ENERGY IS CHANGED from one form to another.

Suppose you pull a cart with force 10 newtons along a distance of 3 metres. The energy-transfer, *FROM* your chemical energy *TO* some form at the cart, is 30 newton·metres or 30 joules. Suppose it takes you 5 seconds to do that. Then your *power*, or *rate-of-transferring-energy* (while you are doing that), is 30 joules in 5 seconds, or (30 joules)/(5 seconds) or 6 *joules per second*, or 6 *watts*.

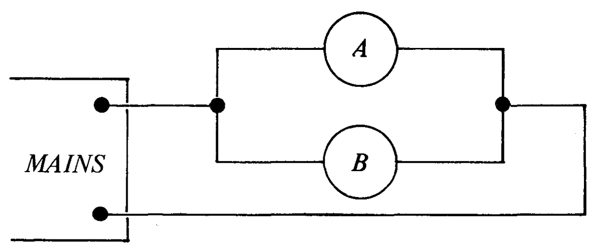
What is a watt? We give the unit *a joule per second* **a shorthand name: a watt (W). That is named after** James Watt, one of the early makers of steam engines. Until his time, railways and mining machinery etc., were run by horses. When the early steam engines were offered to mines the owners asked the inventors 'if I buy your engine, how many horses will it replace?' So Watt made experiments with a large cart horse hauling a load up—probably from a well—and the custom grew of rating an engine in 'horse-power'.

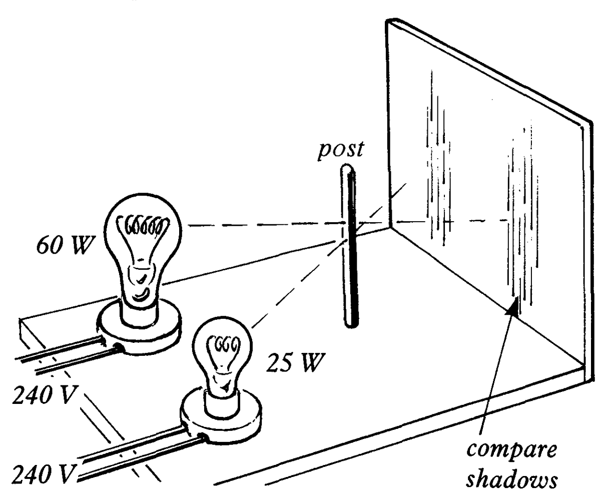
One *horse-power* (1 H.P.) is an old-fashioned unit now. It is the same as 746 *watts*, almost $\frac{3}{4}$ *kilowatt* (kW).

Demonstration 92
Lamps and watts: Comparison of powers of electric lamps

See two electric lamps, each lit from the mains, one labelled 60 watts, the other 25 watts.

How do they compare in *light-giving*? Do they both take the same *current*? (Each runs on the same mains voltage.)





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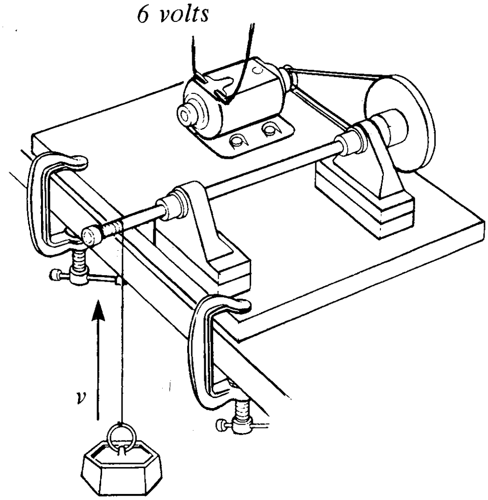
* A *rate* is often very important. The total amount of blood in your body is important—and that may be measured in *cubic centimetres*. The *rate* of blood-flow through one of your large arteries is very important and that may be measured in *cubic centimetres per second*.

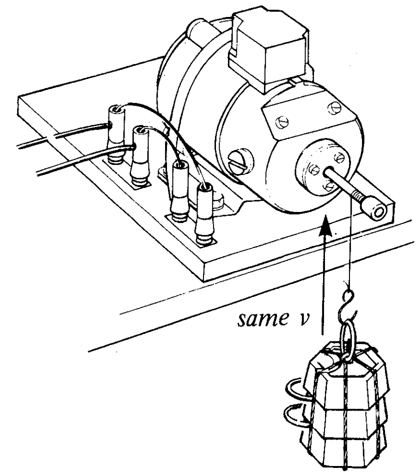
The length of a car drive, measured in *kilometres*, may be important; and the *rate* of covering that distance, measured in *kilometres per hour*, may be very important.

Your total money in a savings bank, *measured in £*, is important; but your rate of taking money out and spending it, measured in £ per week, may be more important still. A total of £10 of savings in the bank may feel good, but suppose you pay no more money *in*, but only take money *out*. With a *rate* of taking out 5p per week, the £10 will last for months. With a *rate* of taking out £5 per week you face disaster in a fortnight.

When an athlete climbs a rope, his total gain of potential energy, measured in *joules*, may be important; but his rate of gaining P.E. is likely to be very important—and that is *power*, measured in *joules per second*, or *watts*.

Demonstration 93 Motors and watts: Comparison of electric motors





See two electric motors, large and small, each running on 6 volts, each raising a load.

The loads and the gearing of pulleys can be chosen so that the two motors raise their loads at about the same speed.

The output *power* for a motor is:

$$\frac{\text{energy-transfer}}{\text{time}}$$

$$= \frac{\text{force (pulling up the load)} \times \text{distance raised}}{\text{time}}$$

$$= \text{force} \times \text{speed of raising load}$$

since (distance raised)/(time) is the speed of the rising load.

If the speeds are the same for the small motor's load and the big motor's load, and the applied voltage is the same, what things *are* different? Is the output *force* the same for both? Is the electric *current* the same for both?

As with the comparison of electric lamps, you need to compare the *current* as well as *voltage* at input; and here, the *force* as well as *speed* at output.

Examples of power: electric power; human power A 40-watt lamp transfers 40 joules every second *FROM* electric energy (from the power station) *TO* heat and radiation energy.

A large electric motor hauling up a lift full of people may be transferring energy *FROM* electric form *TO* gravitational potential energy at a rate of, say, 30 000 watts. Instead of calling that *power* 30 000 watts, we can call it 30 kilowatts. That is *useful* power. And the motor will take some more power from the electric supply and waste it as heat.

A small electric room heater transfers energy *FROM* electric form *TO* heat and radiation at a rate of 1 kilowatt; a large heater at 3 kilowatts; an electric iron at 1000 watts.

A human being doing manual labour all day can transfer energy *FROM* chemical energy *TO* useful mechanical energy at 90 watts. But he is at best 25% efficient when working fast, so he also transfers chemical energy to waste heat at 3×90 watts. His total rate is 360 watts. All that is supplied by his food.

A picture of a watt One watt is a name for 1 *joule per second*. And 1 joule is the name for 1 newton·metre. And 1 newton is, roughly, the pull of the Earth on 0.1 kilogram. So 1 watt is the useful power at which a small animal of mass 0.1 kilogram can transfer chemical energy to gravitational potential energy, climbing a tree at a rate of 1 metre/second. (Or a 0.2-kilogram animal climbing $\frac{1}{2}$ metre/second). Think about any small animals you know, monkey, rabbit, squirrel, mouse, mosquito. . . . As a rough guess, just for fun, decide which you would choose to illustrate a power of 1 watt: 1 monkey-power, 1 mosquito-power, or which of the others.

Kilowatt One kilowatt (kW) means 1000 watts, or 1000 joules/second—the rate of energy-transfer in a small electric heater.

Kilowatt·Hour One *kilowatt* is a *power*, a rate of energy-transfer, of 1000 joules per second. Suppose you let that rate continue for one hour. Then how much *energy* is transferred?

1000 joules/second continuing for one hour gives:

$$(1000\ \frac{\text{joules}}{\text{second}}) \times (60 \times 60 \text{ seconds})$$

$$= 1000 \times 60 \times 60\ \frac{\text{joules}}{\text{second}} \times \text{seconds}$$

$$= 3\,600\,000 \text{ joules}$$

We call that large chunk of ENERGY a ***kilowatt·hour*** (kWh).

If you buy energy from the electric supply, the electric meter—and your bill—will state what you have taken in *kilowatt·hours*. One kilowatt·hour costs about 3p.

Question

1A. How much would 1 kilowatt·hour of *energy* do for you if it is all used to haul you up vertically? Calculate by answering these questions:

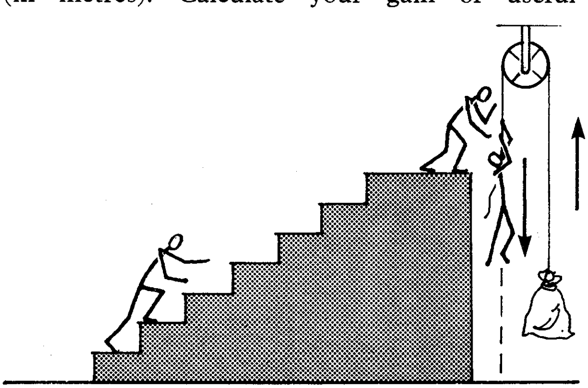
(i) What is your *mass* (measured in kilograms)?
(ii) What is your *weight* (in newtons)?
(iii) How much gravitational P.E. do you gain if you are hauled up *one metre* higher?
(iv) How high could 1 kilowatt·hour raise you?

Experiment 94
Measure your own useful power

Run upstairs as fast as you can, if possible up many flights of stairs in succession. Ask a partner to measure the time you take.

(If you have a weak heart, you should not run upstairs as fast as you can, but you may still do the next experiment, which all should try).

Measure the vertical height you have climbed (in metres). Calculate your gain of useful



gravitational potential energy. For that you need to know the HEIGHT you climbed and your WEIGHT (the pull of the Earth on you). Your weight is:

$$\begin{bmatrix}\text{your mass measured} \\ \text{in kilograms} \\ \ \end{bmatrix} \times \begin{bmatrix}\text{the Earth's field strength} \\ \text{9.8 newtons per} \\ \text{kilogram}\end{bmatrix}$$

If you are not sure of your mass, weigh yourself. Calculate from that your weight (in *newtons*) and then your gain of P.E.

Then divide your gain of P.E. by the time you took to gain it. The answer is your USEFUL POWER, measured in *newton·metres per second*.

You know that a *newton·metre* is called a *joule* and that a *joule per second* is called a *watt*. Those changes of name are not things to test or discover by experiments; they are just dictionary-work, choices of shorter names. So you can say that your POWER in *newton·metres per second* is your *power* in *watts*.

How do you compare with a large horse? One horsepower is said to be 746 watts, nearly $\frac{3}{4}$ kilowatt. How many H.P. are you worth?

We call the gravitational P.E. that you gained *useful* because when you have climbed to the top of the stairs you could hold a rope that runs over a pulley to a load that almost balances you and then let your weight raise that load as you fall slowly down to the bottom of the stairs.

But there is also some USELESS POWER, because you develop waste heat. Assume that your body is, at best, 25% efficient. Calculate your USELESS POWER in that climbing—the power that went into warming you up.

Then calculate your TOTAL POWER: the rate at which you converted food energy to useful P.E. and waste heat together. Express that in watts.

For fun, also put your total power in the old units, horsepower. How many H.P. were you worth in total output?

Experiment 95
Measure your own useful power for an all-day job

Now suppose you had to go on climbing stairs all day, to earn your living. You certainly could not go on running upstairs like that. Time yourself climbing stairs very slowly and deliberately, as if you were carrying a load on your back. Climb as you would if you had to climb all through a working day of 8 hours. Calculate your useful power, in watts.

The USEFUL POWER of a large horse was measured and found to be about 746 watts. The USEFUL POWER of a human adult, working for many hours a day at jobs like hauling up loads with a pulley and rope, is about 90 watts. Compare *your own USEFUL POWER with that.*

When you know your USEFUL POWER, from the slow stair-climbing experiment, add three times that for waste-heat-production in your muscles.

Then multiply by 60 to find your useful output of energy in 60 seconds. Multiply by 60 again to find your useful output of energy in one hour.

Multiply by 8 to find your useful output of energy in an 8-hour working day, as if you kept up your slow stair-climbing all that time.

That is the extra energy you would need from your day's food, to do that day's work. The remainder of the 24 hours you might be resting—because you would be quite tired—and sleeping some of the time.

Even resting and sleeping would need some energy, to keep your heart working and your breathing going and your body warm, probably about 6000000 joules for 24 hours. Add that to your cost, in joules, for a day's work and find the total energy you would need to get from your daily food.

Food for 24 hours Different foods supply quite different amounts of energy from each kilogram that you eat and digest. In taking energy from food and using it in your muscles you convert the food as far as possible into carbon dioxide and water. Your body burns up the food, acting as a very-low-temperature furnace.

We can find the fuel values of different foods by burning them in a special container fed with the necessary oxygen. The results are expressed, nowadays, in *joules* of output heat from each 100 *grams* (or even each *kilogram*) of the foodstuff.

Since a kilogram is a large mass of food, we shall tell you here the energy values of food in *joules* for each *100 grams* of food digested.

For some time to come, you may hear of energy from food measured in the old units, Calories (or kilocalories) which we call thermal units. Those are the direct results of heating water in the special food-burning apparatus, so they necessarily emerge in kg-of-water × °C. Those measurements in thermal units are converted into values in joules by multiplying by 4200—since the results of the 'Court trial' in Chapter 9 show that one thermal unit is worth about 4200 joules. So we also tell you food values in old fashioned *thermal units for each ounce* of food digested.

See Table A of food values. Remember that these only show energy-values for muscular work and keeping warm. Other food materials, such as proteins, are needed for body building and repair. Those are extremely important for your health and growth, but they are *not* shown in the table of energy-values.

Table A

FOOD	ENERGY YIELD	
Special quantities (these energy supplies are for the amount stated, not for 100 grams)	*thousands of joules*	*'thermal units'**
Tea (1 cup)	0	0
(1 cup with milk)	42	10
(1 cup with milk and sugar)	210	50
Coffee (1 cup, black)	17	4
(1 cup with milk and sugar)	215	54
Chocolate with milk (1 cup)	760	180
Cola, (1 can—about $\frac{1}{3}$ litre or $\frac{1}{2}$ pint)	—	—
Soups (these vary greatly) (1 cup)	250 (?)	60 (?)
One egg (standard size)	380	90
Ice cream, Small cone or 1 scoop	670	160
Milk, 1 cup	670	160
One fish finger	216	54
Jam (2 teasp.)	300	70
Honey (1 tbsp.)	250	60

Table A

FOOD	ENERGY YIELD		FOOD	ENERGY YIELD	
	thousands of joules for each 100 grams digested	*'thermal units'* for each oz. digested*		*thousands of joules for each 100 grams digested*	*'thermal units'* for each oz. digested*
Fish			Currant buns	1380	93
Cod (fried in butter)	840	57	Fruit cake	1545	105
Cod, or any white fish			Jam tarts	1640	110
(steamed)	300	20	Rice pudding	600	41
Fish fingers	810	55	Peanuts (shelled and		
Sardines in oil	1200	80	roasted)	2460	170
			Oatmeal porridge	190	13
Vegetables					
Baked beans	390	26	*Dairy produce*		
Cabbage (boiled)	35	2	Butter	3100	210
Carrots	100	7	Cheese	1730	120
Cauliflower	100	7	Margarine	3200	220
Peas	200	14	Cooking fat or oil	3750	250
Peas (tinned)	390	26	Milk	270	18
Parsnips	200	14	Egg	670	45
Lettuce	50	3	Ice cream	840	57
Potatoes (boiled)	330	22			
(chips)	1000	68	*Meat*		
Tomatoes	60	4	Bacon	2000	135
Beans (haricot)	1080	73	Beef (corned)	940	64
(broad)	290	20	(roast)	1340	90
Lentils (dry)	1250	85	(stewed)	1020	70
Soya beans	1050	70	Lamb (roast)	1190	80
Onions	100	7	Liver (fried)	1160	78
			Pork (roast)	1710	115
Fruit			(chop)	2210	150
Apples	150	10	Ham (cooked)	1770	120
Bananas	320	22	'Luncheon meat'	1360	92
Oranges	150	10	Sausage (?)	1550	105
Sultanas	1050	70	Chicken	840	60
Tinned fruit	340	23			
Rhubarb	20	1	*Groceries*		
			Sugar	1660	110
Bread, cakes, etc.			Toffee	1850	125
Bread (white)	1060	72	Plain chocolate	2270	150
(wholemeal)	1010	68	Rice	1510	100
Corn flakes	1550	105	Spaghetti	1530	105
Crispbread	1340	91			
Apple pie	1260	85			

* 'thermal unit' is our name for 1 kg-of-water × 1°C, which used to be called 1 Calorie.

HUMAN ENERGY NEEDS

How much energy do we need to take from food in each 24 hours? The answer depends very much on the sort of people we are, particularly on our age and occupation. Table B gives some average figures for overall needs of energy from food.

Table B Human energy demands

Some needs are:

	thousands of joules per day		*thermal units* per day*	
BOYS AND GIRLS				
0–1 year	4200		1000	
2–6 years	6300		1500	
7–10 years	8400		2000	
TEENAGERS	BOYS	GIRLS	BOYS	GIRLS
11–14 years	11500	11500	2800	2800
15–19 years	14700	10500	3500	2500
ADULTS	MEN	WOMEN	MEN	WOMEN
Lying in bed all day	7400	6300	1800	1500
Working 8 hours per day:				
light work	12000	9500	2900	2300
heavy work	15000	12500	3600	3000
very heavy work	21000		5000	
PREGNANCY				
early months		10000		2400
later months		11500		2750
nursing the baby		12500		3000

* As well as the daily need in the modern units, joules, we also give rough estimates in thermal units, which are kg-of-water °C. Those were formerly called Calories or kilocalories.

ENERGY FOR SOME USEFUL JOBS

The following data were obtained by observing a coal miner, 32 years of age, height 175 cm (5 ft 9 in), mass 67 kg (148 lb), for a week: See Table C.

In general, the energy-transfer per minute by an adult man ranges from 53 000 joules for the heaviest work to 11 000 joules for the lightest work. Such estimates are, of course, only averages. Our muscle strength differs from one person to another and so does our efficiency; so energy needs may differ for the same job.

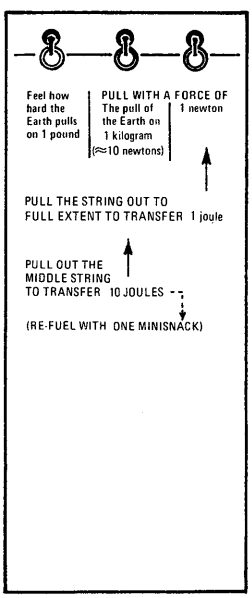
Table C

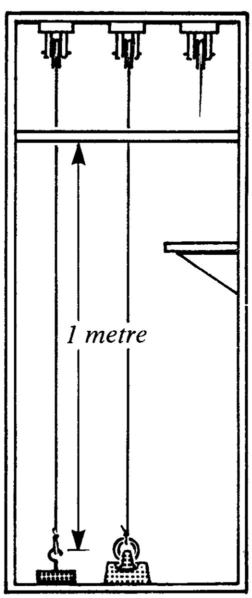
	thousands of joules per minute	*thermal units per minute*
Resting in bed	4	0.9
Washing, shaving, dressing	14	3.3
Walking	21	4.9
Standing	7.5	1.8
Cycling	28	6.6
Hewing coal	28	6.7
Loading coal	26	6.3
Walking (in mine)	28	6.7

In some parts of the World, the food that most people get provides only a little more energy than they need for resting and sleeping and keeping warm. So they can only do very light jobs of work; or, if they do heavy jobs, they can only work for a short time each day. If you believe in the conservation of energy, you cannot expect them to do more work just by trying harder. More work will need more food; and if someone is compelled to work faster than his food provides for, he must draw on some stores of fuel, in the form of fat in his body; and that may not last long. Even in hot climates, where little food-fuel is needed to keep a man's body warm, you cannot expect heavy manual labour on the small diet that many people get. Such people are not lazy but unfortunate.

Experiment 96
Energy-transfer box for power-transfer

To get a feeling for a joule of energy-transfer from your food-energy in muscles to another form, pull the cord marked '1 joule' on a forces-and-energy box. Inside the box the cord pulls a load of 0.102 kilogram up through a vertical height 1 metre.



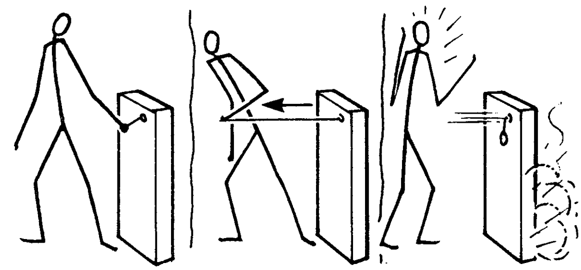


Then the *work* involved is:

$(0.102 \text{ kg}) \times (9.8 \text{ newton/kilogram}) \times (1 \text{ metre})$
$= 1$ newton metre of transfer *FROM* chemical energy (in your muscles) *TO* gravitational P.E.

That transfer is just 1 newton·metre, which we call 1 joule.

Each time you pull the cord out 1 metre, the transfer to gravitational potential energy is 1 joule; but your muscles are not very efficient engines. They use much more chemical fuel than is needed for the actual job, and convert the rest of the energy released from the fuel into heat. At their best, they are 25% efficient for rapid motion like that. So while you provide 1 joule of gravitational energy which could be useful, you also manufacture a good deal of heat, about 3 joules, which warms your arms and is later wasted to the air.



If you pull the cord all the way out once every second, you are transferring energy to heat at a rate, or POWER, of 1 watt when the load crashes on the floor in the box + 3 watts to waste heat in you.

Experiment 96X
More power

Work at a rate of 40 watts. Raise 1 kilogram 1 metre every second. That requires a force of 10 newtons and the power is 10 newtons × 1 metre/1 second, or 10 watts (which might be useful if you did not let the kilogram crash to the floor every second) + 30 watts, in producing waste heat.

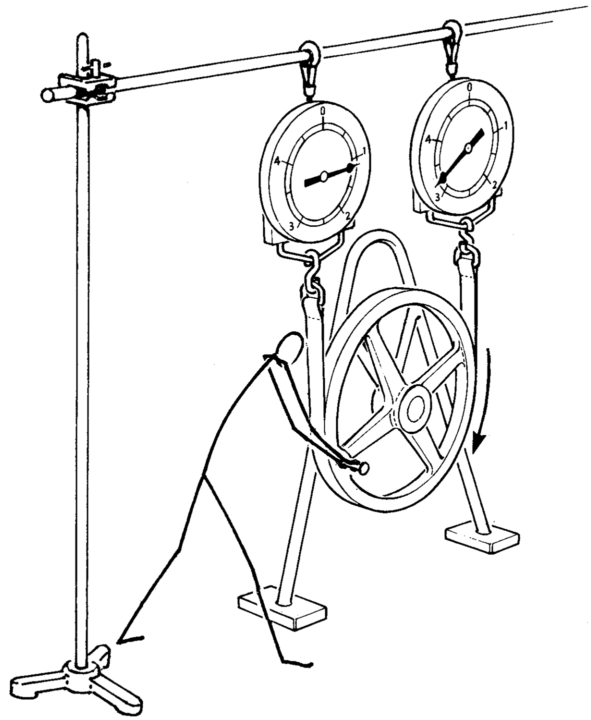
A minisnack Put a pinch of granulated sugar on the table. Select four crystals of average size (about $2\frac{1}{2}$ milligrams altogether). We call that, for fun, a minisnack. A minisnack will re-fuel you for raising a kilogram 1 metre; one grain for the energy transfer *FROM* your chemical energy *TO* P.E. of the load, and three grains for transfer to waste heat.

If you raise the kilogram 1 metre every second, you need 1 minisnack per second, about 10 grams of sugar per hour.

Optional extra experiment 97 Working against a band brake

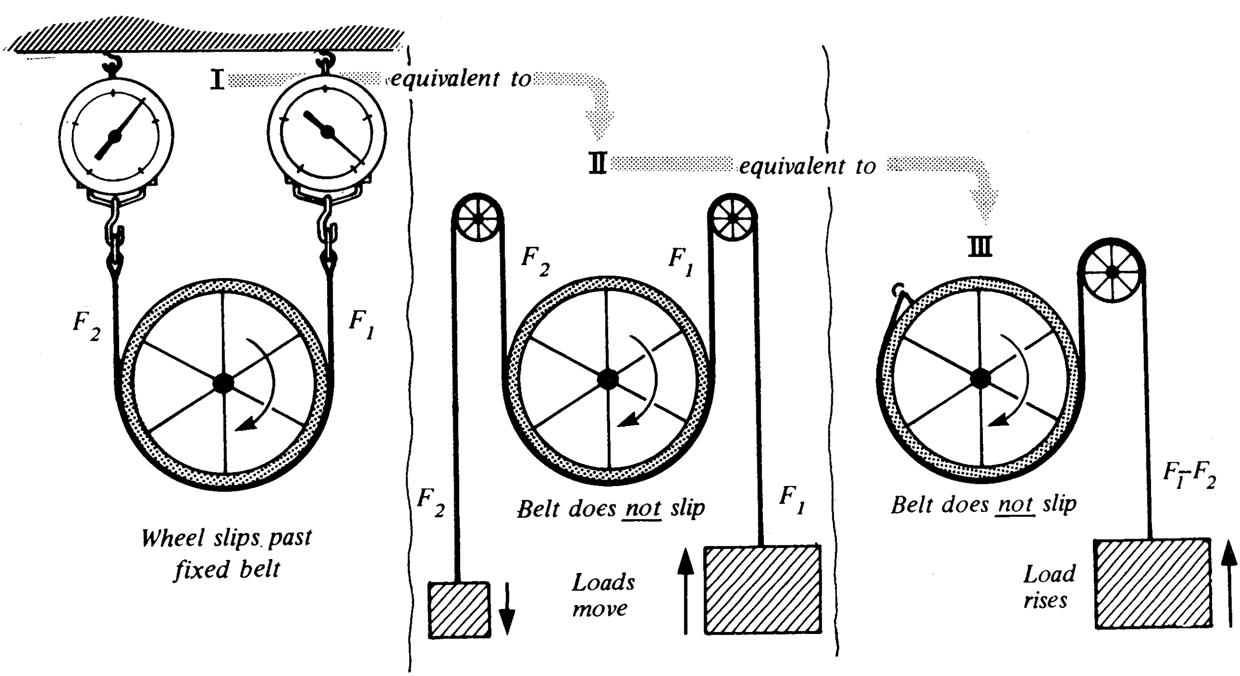
If your lab has a wheel with a band brake that you can use, you and your partner could run it and measure your transfer power *FROM* chemical energy in muscles *TO* 'useful' mechanical energy. In this case that useful energy is wasted as heat in the brake.

See the diagram which shows how you can calculate the *work*—and thence the *power* of the brake.



Optional home experiment 98
Output of power cycling up a hill

If you like, estimate your own (useful) power when bicycling up a hill. Think out the measurements you would need.



Progress Questions

1B. An electric motor lifts a load of 1 kg through a height of 1 metre.

a. What force in newtons is required?

b. How much work in joules is done in raising the weight?

c. It took 5 seconds for the weight to rise 1 metre. How much work was done in 1 second?

d. Another motor did the same work in 2 seconds. How much work was it doing in 1 second?

e. Which was the more powerful motor, the first one or the second one?

2. If you are buying an electric lamp for a room light, you might ask for a lamp of 40 watts power, or 60 watts, or 100 watts.

a. Which of these would give the most light?

b. Which of these would be the most expensive to run for the same time?

c. An electric fire could be 1000 watt (1 kilowatt) or 2000 watt (2 kilowatts). Which of these would give the most heat in the same time?

3. If an engine can work at the rate of 1 joule per second, we say its power is 1 watt.

a. Suppose an engine delivers 500 joules in 1 second, what is its power?

b. How many joules of heat is a 60-watt lamp giving each second?

c. How many joules of heat is a 60-watt lamp giving in a minute?

d. If an engine delivers 1000 joules in 4 seconds what is its power in watts?

4. The pull of the Earth on a 50-kilogram boy is 500 newtons. The boy climbs a flight of stairs with a height of 10 metres.

a. How much is the work of his energy-transfer while climbing the stairs?

b. He takes 20 seconds to climb the stairs. How much energy does he transfer each second?

c. What is his average power during this climb?

5a. What is your approximate mass in kilograms? (1 stone is about $6\frac{1}{2}$ kg.)

b. Estimate roughly in metres the height of a flight of stairs in your house or school.

c. How much potential energy (up-hill energy) do you gain in lifting yourself up this flight of stairs?

d. How long does it take you to run up as fast as you can—in seconds?

e. Copy and complete

When I go upstairs, I transfer . . ? . . joules to potential energy in . . ? . . seconds, so in 1 second I transfer . . ? . . joules. My power is . . ? . . joules per second or . . ? . . watts.

6a. When you run upstairs, using chemical energy, for every joule of useful mechanical energy you produce, your body also delivers 3 joules of heat. How many joules of chemical energy do you need to use if you wish to gain 1 joule of potential energy?

b. How many joules of chemical energy does the boy in Question 4 convert in running up the flight of stairs?

c. How many joules of chemical energy do *you* convert when you run upstairs, as in Question 4?

7a. When you eat sugar, it can provide energy. 100 grams of sugar can give you about 1 600 000 joules. If sugar costs 40p per kilogram, how much do those 1 600 000 joules cost you? How much for 1 million joules?

b. When you pay an electricity bill you are paying for the electrical energy you convert. The price is usually about 1.8p for 1 million joules. Is electrical energy more or less expensive than sugar energy?

c. A small electric fire takes about 15 minutes to convert 1 million joules. So it costs 1.8p for $\frac{1}{4}$ hour. How much will it cost for an hour?

d. When you burn gas in a gas fire or cooker, the cost of the heat is about 35p for 100 million joules (1 therm). Is gas cheaper or more expensive than electrical heating?

8. If a device with a power of 1 watt is used for 1 second, then 1 joule of energy is transferred in this second.

a. If a 1000-watt fire is used for 1 second, how much heat does it give, in joules?

b. How much heat energy does this fire give in 1 minute?

c. How much heat does this fire give in 1 hour?

d. In part **a.** we could write 1 kilowatt for 1000 watts. In 1 hour we say the energy transferred is 1 kilowatt·hour. How many kilowatt·hours of energy would a 2 kilowatt fire transfer in 3 hours?

(Your electricity bill at home is worked out according to the number of kilowatt · hours of energy transferred.)

9. 1 kilowatt·hour is the amount of electrical energy converted by a 1000 watt fire in 1 hour.

a. How long could you leave a 100 watt lamp on before it had converted 1 kilowatt·hour?

b. An electric fire is labelled '$2\frac{1}{2}$ kW'. How many kilowatt·hours of electrical energy would it convert if left on for an hour?

10. The energy provided by food is still sometimes measured in 'thermal units' (each equivalent to 4200 joules).

A slice of bread 'burnt up' in your body provides you with about 100 thermal units or 420 000 joules of chemical energy.

Use the table of food values to work out roughly how much energy you get from your own average daily diet.

Questions

11. Two pumps A and B are each capable of pumping water vertically up a height of 30 metres. Pump A takes 2 hours to pump up 600 kilograms of water. Pump B raises 600 kg in 20 minutes.

a. Which pump is the more powerful?

b. How much potential energy *(joules)* is gained when 600 kg are raised 30 metres? (take $g \approx 10$ newtons per kilogram).

c. What is the power (rate of working) in *joules per second.*
(i) of A; *(ii)* of B?

d. What is the POWER of each pump in watts?

e. What is the POWER of each pump in kilowatts?

12. A 50-kilogram boy races up a flight of 60 steps in 10 seconds. Each step is 20 centimetres high.

a. Calculate the rate at which he transfers food-energy to potential energy:
(i) in newton·metres per second
(ii) in horsepower (1 hp = 746 watts)
(iii) in kilowatts.

b. If his muscles are only 25% efficient, at what rate (in watts) is he actually transferring food energy?

c. What happens to the other 75% of food energy?

13. You are given a small 6-volt electric motor, and a 6-volt accumulator. The motor has an axle on which it can wind up string. Describe how you would estimate by experiment the power output of the motor, in watts.

14a. An electric lamp is marked '40 W'. Say exactly what this means.

b. Electric energy costs 6p per kilowatt·hour. How many hours could the 40-watt lamp be used, for £1?

15a. Joule, watt, kilowatt, kilowatt·hour. Which two of these are units of ENERGY, and which two are units of POWER?

b. If a kilowatt·hour costs 6p, how many joules can you buy for 1p?

16. A boy has to live in lodgings for a few weeks, while his parents are abroad. Each time he has a hot bath, the landlady charges him 25p. Is she charging him too much?

Data you will need:
Average hot bath takes about 90 litres of water (20 gallons).
1 litre of water is 1 kilogram of water
The water has to be heated from 10° to 55°C.
1 thermal unit (1 kg-of-water·1°C) = 4200 joules
1 kilowatt·hour = 3 600 000 joules
1 kilowatt·hour costs the landlady 6p.

17. Suppose your uncle has a car with 2 sidelamps, 2 rearlamps, and a lamp to light the rear number plate. Each of these lamps has a power of 6 watts. Also, there are two headlamps of 36 watts each.

a. How many watts altogether?

b. Your uncle sees your answer to **a.** 'Good gracious,' he says, 'if the engine has to supply all those watts, then at night time the car's speed will be much reduced and I cannot climb any very steep hills.'

Do you think he is right about this? The maker says that the engine's maximum power output is 45 kilowatts (60 horsepower). (Don't say that the power comes from the battery, and not from the engine. The engine drives a generator which is able to charge the battery with a small current even when all the lights are on.)

18. A crew of 8 men are rowing in an 'eight' (a light racing craft with four oars each side). We are going to calculate the power supplied to the boat. We estimate that they make 30 strokes per *minute*, and that the length of the pull at each stroke is 1 metre. The strength of each man's pull is 400 newtons.

a. How much is the WORK for 1 man making 1 stroke?

b. How much is the WORK for him per second?

c. How much is the WORK for the whole crew per second?

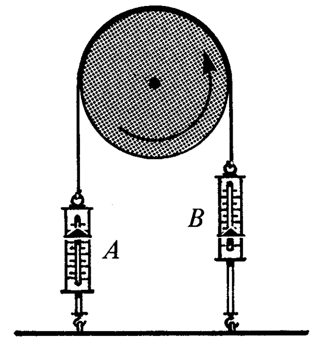
d. What is the power of the crew?

19. To see how strong the members of the crew were in the question just above, suppose that, instead of rowing, a crew man pulls on a horizontal rope with the same force, 400 newtons. The rope runs from him to a pulley, over and down to a load X kilograms, hung on the other end.

a. How big is X?

b. How many pupils in your class could hang on the rope just to replace X?

20. *(Advanced. Do not try this unless you have done the experiment or seen it done.)* The sketch shows a band-brake round a flywheel. The flywheel is rotated by an engine or electric motor whose output POWER is to be measured. The brake is attached to two spring-balances, A and B.



a. What can you say about the readings of A and B *before* the engine was connected. (The flywheel was at rest then, but free to turn.)

b. What happens when the wheel starts to rotate and increases to a final steady speed?

c. Which way, clockwise or anticlockwise, is the wheel in the sketch now rotating?

d. Suppose in an actual case, A reads 90 newtons, and B reads 300 newtons. The radius of the wheel is 0.20 metre, and it makes 50 revolutions per second.

e. What is the resultant force dragging the band, in newtons?

f. What is the circumference of the wheel, in metres?

g. How much energy is transferred to heat in the wheel and band, in one revolution of the wheel?

h. How much energy is transferred per second?

i. What is the power of the engine in watts?

CHAPTER 11

ELECTRIC CIRCUITS WITH VOLTMETERS

ELECTRICITY

VOLTAGE, CURRENT AND POWER

Now that you are well equipped to understand exchanges of energy and power, you can deal with electric circuits more scientifically and profitably.

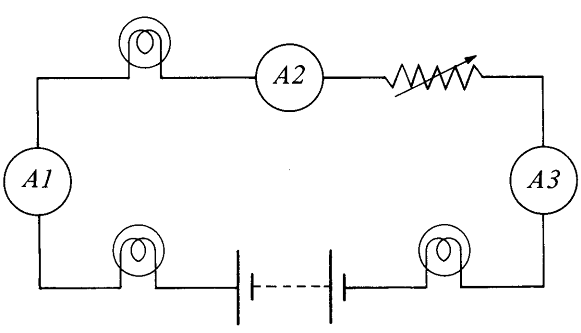
EXPERIMENTS FOR CATCHING UP

(marked†)

If you missed some of the simple early experiments with circuits you should see demonstrations now, to help you to catch up quickly. On the other hand, if you did those experiments yourself before, you should go straight on to new ones now—unless you like to see the catching-up demonstrations as quick reminders.

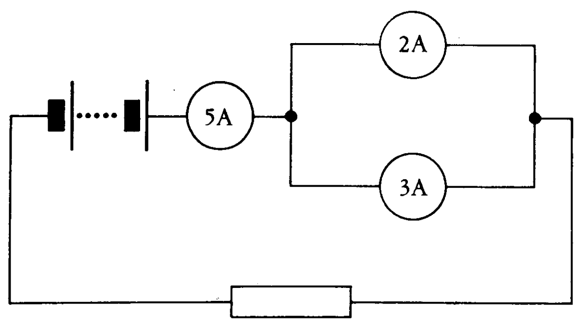
†Demonstration 99
Series circuits and branching circuits

a. A simple series circuit Look at the ammeters in the circuit sketched. *Does the current change as the electricity goes round the circuit?*

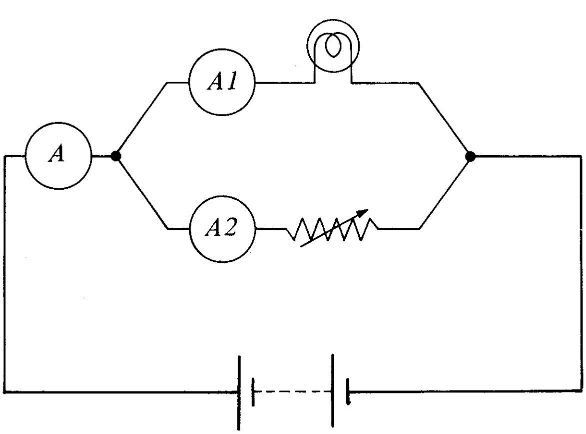


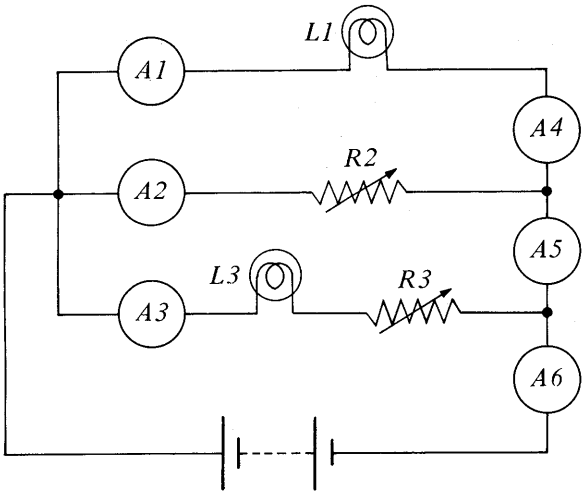
The answer is something very important to remember: a resistance in a circuit does NOT cut down the current and make less come out than went in.

b. Branching circuits The simple series circuit demonstration showed you that current does not get lost. Nor does it get lost when a circuit divides into branches which then re-unite—which we call a parallel arrangement.



The sketch shows 5 A in the main circuit dividing into 3 A in one branch and 2 A in the other. However, such a diagram only *illustrates* something that we find does happen. A diagram cannot *prove* that currents divide like that. You need to see a real experiment to show that, such as the one sketched here.





c. A complicated circuit. You may see a demonstration like the one sketched. If so, look at the ammeters carefully and see whether they tell the story you now expect.

A WATER CIRCUIT

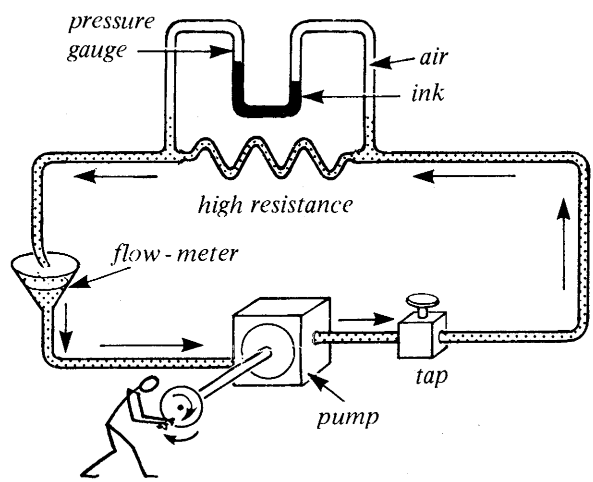
Water being pumped round a circuit of pipes behaves in much the same way as electricity in a circuit of wires. Water does not get lost on the way round—nor is more water suddenly manufactured; so flowmeters at various places in the circuit all show the same rate-of-flow. So do ammeters in an electric circuit.

When it was found that ammeters all read the same at different places in an electric circuit, scientists said, 'Just like water. There must (or may?) be *something* flowing round, like water.' And they called that *something* 'electricity', or 'electric charge'. That is how the word 'current' came to be used, because the experiments with ammeters led people to imagine a current of electricity—like a current of water—with its rate-of-flow measured in amperes*.

* It would be wrong science to turn the comparison with water-flow upside down and say 'We *know* that electricity flows like water; and therefore the electric current *must be* the same all round an electric circuit, *because* that is so for water. So we don't need all those ammeters: we needn't trouble to do an experiment.' That would be going back to the kind of unscientific argument that was popular four centuries and more ago, when people often made mistakes by quoting books without trying experiments.

Demonstration 100a
Model water circuit

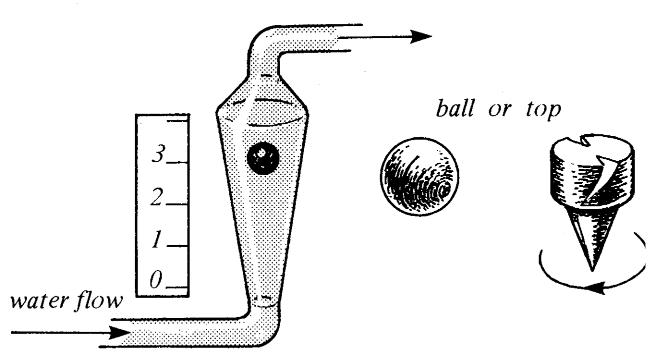
See the model sketched. This has only one flowmeter* because the model only illustrates the correspondence between an electric circuit and a water one. However you can imagine other flowmeters in the circuit.



Demonstration 100b
Water circuit with pressure gauge

One part of the water circuit has quite a high resistance—yet, once the flow is steady, water must flow out of that part just as fast as it flows into it. Suppose you wish to know how much pressure is being used to drive water through that part. See how a pressure gauge is connected for that.

* Flowmeters are often used for liquids and gases in industry and medicine. The usual commercial form is a vertical tapered glass tube in which the fluid flows upward. There is a light ball in the tube: and, the faster the flow, the higher the ball has to sit



to let that flow pass by. In some forms the ball is replaced by a little spinning-top whose motion makes it less likely that Bernoulli forces will jam it against one side of the tube.

To make the U-tube of ink indicate that pressure, you must connect its two ends to the ends of the resistance that you are investigating. Such a gauge always needs two connections: thus it measures pressure-difference rather than any absolute pressure. Most pressure gauges only measure *pressure-differences* between two places. And a voltmeter—which measures something like an electrical pressure-difference—is always connected to two places like that.

WHAT *IS* THE ELECTRICITY THAT FLOWS ?

We say that electricity flows round a circuit when there is a current. But what is the 'electricity' that flows? We cannot see it as we see coloured water flowing, or hear it as we hear coal flowing down a chute; so how do we know what it is? Perhaps we can never know fully what electricity is; although we can measure its rate-of-flow with an ammeter. Books may tell you a current is a stream of electrons—and sketches in books, or on television, may paint those electrons deceptively as sharp round coloured blobs. Yet scientists only know about electrons indirectly; and those pictures are only our teaching-models. So electricity must remain rather mysterious in science, partly real—known by experiments—and partly imaginary—talked of in a thinking model.

Coulombs For all that, we can *measure* electricity (electric charge) with an ammeter and a stopwatch. We measure it in coulombs (named after an early experimenter). One coulomb of electricity corresponds to, say, one litre of water in a water circuit. We can measure water flow in litres per second; and we measure electricity flow in *coulomb per second*, which are *amperes* (A).

If the current is 1 A, we say one coulomb passes each point in the circuit every second. One *ampere* is a name for a flow of one *coulomb per second.* That gives you a definition of a coulomb (C).

A current of 5 A means 5 coulombs pass each point each second. A current I, measured in A, means I coulombs pass every point in each second.

Progress Questions

1a. Water running from a tap fills a 100-cm^3 beaker in 2 seconds.
(i) What is the rate of flow in cubic centimetres per second?
(ii) How long would it take to fill a 1000-cm^3 beaker?

b. A girl fills 600 chocolate boxes in 2 hours.
How many does she fill in 1 hour?
How long does she take to fill 1200?
50 cars go past a counter in $\frac{1}{2}$ an hour.
How many go past in 1 hour?
How long for 25 cars?
4 coulombs of electricity go through a lamp in 2 seconds.
How many go through in 1 second?
How long does it take 40 coulombs to go through?

2. Electric current is flowing through a lamp at 2 amperes, which means 2 coulombs per second.

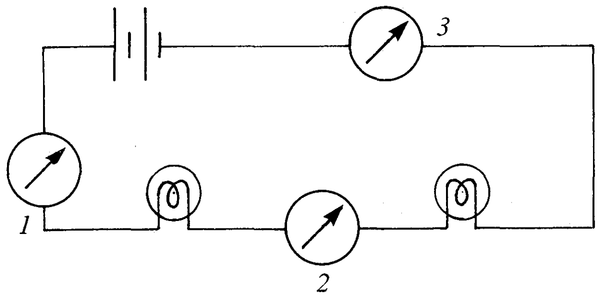
Copy and complete:

a. When the current is 2 A, . . ? . . coulombs flow in 1 second, . . ? . . coulombs in 2 seconds, . . ? . . coulombs in 5 seconds, . . ? . . coulombs in 1 minute.

b. If 15 coulombs flow in 5 seconds, we can say the current is . . ? . . coulombs per second, or . . ? . . amperes.

3. Copy and complete the table.

Current in amperes	Coulombs in 1 second	Coulombs in 5 seconds
2		
2.5		
	4.2	
	0.6	
		20
		12.5



4. The diagram shows a circuit containing three ammeters. Copy out the sentence below, filling in the blanks with some of the words from this list:

Electric current; *amperes*; *greater than*; *smaller than*; *the same as.*

An ammeter measures . . ? . . , which is measured in . . ? . . . The first ammeter's reading is . . ? . . the readings of the other two. The current in the second lamp is . . ? . . the current in the first lamp.

Question

5a. What is it that is measured in coulombs?

b. What is measured in amperes?

Two of the four statements below are *false*, and *two* are *correct*. Write out the two *correct* statements.

1 coulomb = 1 ampere for 1 second
1 ampere = 1 coulomb for 1 second
1 coulomb = 1 ampere per second
1 ampere = 1 coulomb per second

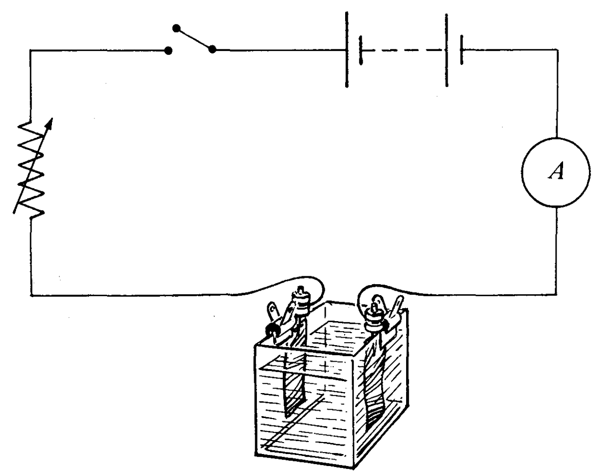
Counting coulombs by electrolysis If you pass a current through conducting liquids such as blue copper sulphate solution, or water with a little acid, the masses of the chemical products are proportional to CURRENT, and to TIME. So we can choose one chemical product and use its MASS to measure CURRENT × TIME, or ELECTRIC CHARGE. In your present work, we choose copper from copper sulphate solution and we find from experiment that each coulomb passing through copper sulphate solution deposits

0.000 000 329 kg of copper.

The experiment that gave us that number had to have an ammeter and a stop-watch; but once that is settled you can reverse the argument and use that number in testing your own ammeters in the lab.

That number can be sent on a postcard to a new lab elsewhere, and that is much easier than sending a delicate standard ammeter by parcel post! You may try using that number in an experiment to test an ammeter. Or you may see a demonstration.

Demonstration 101
Electrolysis of copper sulphate solution



In trial I, the circuit carries 1 A for 10 minutes. In trial II, it carries $\frac{1}{2}$ A for 10 minutes. In trial III, $\frac{1}{2}$ A for 20 minutes.

Look at the weighings of the copper carried across and deposited. Do they support the use of copper to measure CURRENT × TIME, which is ELECTRIC CHARGE?

Demonstration 102 *(OPTIONAL NOW)*
Electrolysis of water

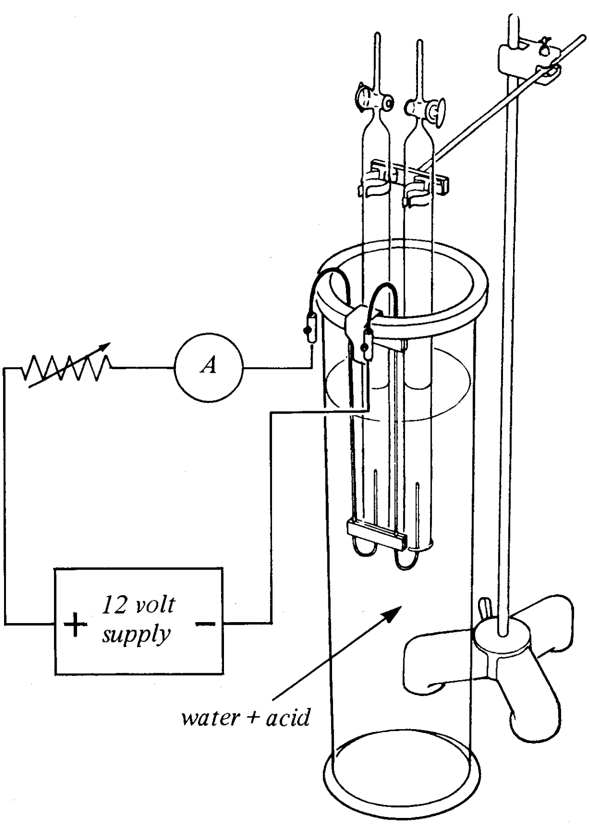
Hydrogen and oxygen emerge from water when a current is passed through it. A little acid has to be added to provide plenty of ions, but it is ultimately the water that is used up to yield those gases.

You may see a demonstration of that now, though it is not needed till Year 5, when we compare electrons with hydrogen ions. And you may well have seen the electrolysis of water in Chemistry. (See the sketch opposite.)

Ions: charged atoms You will soon meet Millikan's experiment which shows that electric charge comes in small 'atoms of electricity' all alike (as far as we yet know).

Millikan not only showed that, but also measured the *size* of the atom of electricity, the charge on one electron. And in modern atomic and nuclear physics, we usually reckon charges in those atomic units, electron charges. One electron carries a negative charge of 1.6×10^{-19} coulomb. So to make up one coulomb you would need about 6 000 000 000 000 000 000 electron charges.

Even without knowing the size of the electron charge, we can guess from the electrolysis of water and some knowledge of chemistry, that the charge on a hydrogen ion—a carrier in electrolysis of solutions, and probably in ionized gas too—is positive and the same size as one electron charge. So a hydrogen ion may be called H^+ and its charge $+e$, where an electron's charge is $-e$.

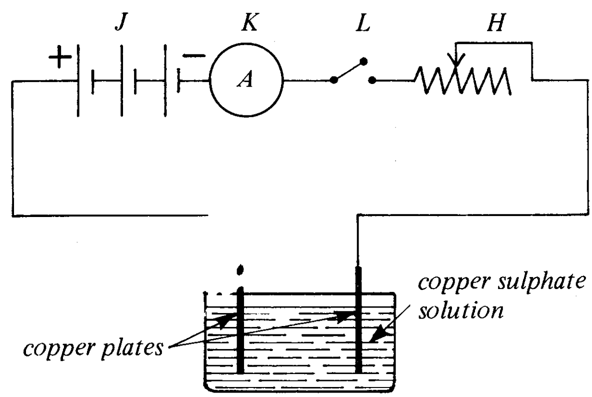


From simple chemical measurements, we know a copper atom is 64.5 times as massive as a hydrogen atom. So if copper ions are Cu^+ with charge $+e$ we should expect electrolysis of copper sulphate to deliver a mass of copper 64.5 times the mass of hydrogen delivered by the same CURRENT × TIME. In fact, we get only 32.2 times as much; so we guess (correctly) that copper ions are not Cu^+ but Cu^{++}, each with a double charge $+2e$.

You should not be surprised that copper ions make a blue solution instead of the usual brown colour of copper metal—that electric charge makes all the difference.

You may, if you like, picture electricity as riding across the copper-plating bath on blue horses of copper^{++}.

Progress Questions



6a. What are H, J, K, L?

b. How do you make the current 1 A exactly?

c. When current flows, copper gets deposited on one of the plates. How can you find out how much copper is deposited in 20 minutes?

d. How do you change the current to 0.5 A?

e. You let 0.5 A flow for 20 minutes. Will you get more or less, or the same amount, of copper as you got with 1 A?

7a. Ammeter A_1 reads 0.6 A. What does A_2 read?

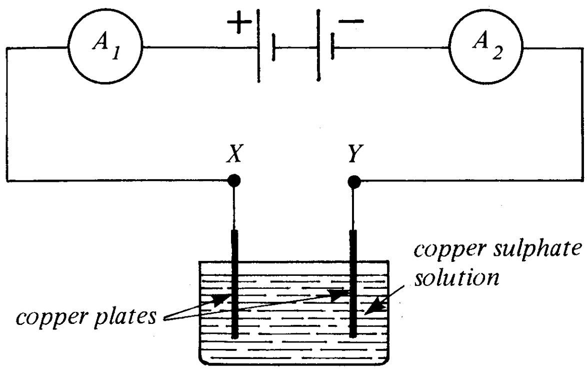
b. What current flows through the liquid?

c. How do we know there *must* be a current in the liquid?

d. One of the copper plates gets extra copper deposited on it. Which one?

e. Probably the copper in the solution carries charge across. Which plate does the copper move towards?

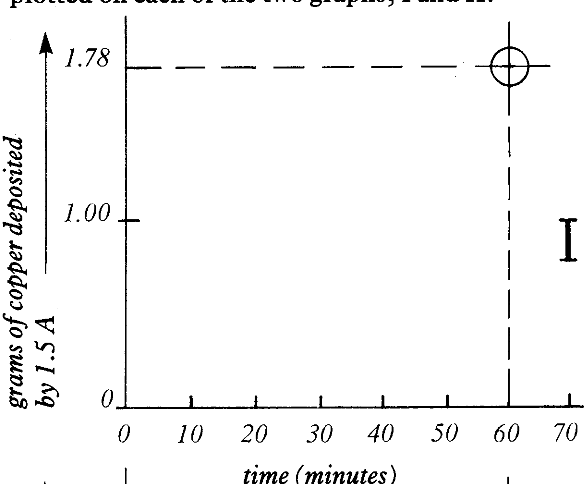
f. So do you think the copper in the solution carries positive or negative charge? Why?

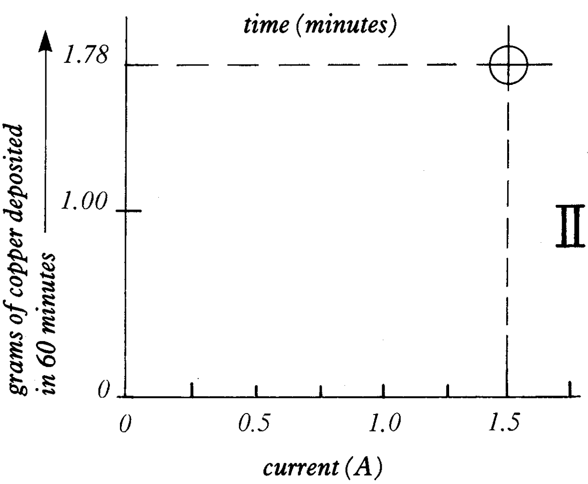


Questions

ELECTROLYSIS

8. A current of 1.5 A is passed for 1 hour through a solution of copper sulphate. At the end of that time, it is found that 1.78 g of copper has been deposited. This measurement gives one point to be plotted on each of the two graphs, I and II.





a. Copy graph I with that one point marked. Complete it by drawing a line through all the other measurements you can imagine. Draw that line to show how the mass of copper deposited by 1.5 A increases with time.

b. How long will it take for 1.0 gram to be deposited by 1.5 ampere? (Read the answer off your graph.)

c. What assumption about mass deposited and time elapsed have you made in drawing the graph?

d. Copy graph II and draw a line showing how you expect the mass deposited in 1 hour to increase with the current.

e. How much current is needed to deposit 1.0 gram in 1 hour?

f. What assumption about MASS DEPOSITED and CURRENT PASSED have you made in drawing the graph?

9a. How many coulombs are required to deposit 1.78 grams of copper? Calculate from the measurements given above at the beginning of Question 8.

b. How many coulombs are required to deposit half that much (that is, 0.89 gram)?

c. How many coulombs are required to deposit 1.0 gm of copper?

d. In working out your answers to (b) and (c) what did you assume about grams of copper deposited and coulombs of electricity passed?

e. Is that assumption (d) the same as, or different from, the assumption made in (b) and (d) of Question 8? Explain.

10. The same quantity of electricity (about 96 million coulombs) which sets free 1 kilogram of hydrogen in electrolysis also sets free 32 kgs of copper or 108 kgs of silver. The masses of the atoms of hydrogen, copper and silver are in the proportions

H :Cu :Ag 1 :64 :108

a. What do those numbers suggest about the electric charges carried by one atom of hydrogen and one atom of silver in electrolysis?

b. What do they suggest about the charge carried by one atom of copper compared with the charge carried by a single atom of hydrogen or a single atom of silver?

Note: Your arguments and conclusions here are simple but important. This was the first piece of evidence that suggested 'atoms' of electricity. This suggested there might be a 'least possible' quantity of electricity, namely, the quantity carried by a single hydrogen or silver atom (and some other atoms), in electrolysis. For example, we never find an atom carrying half as much charge as the hydrogen atom carries.

Charged atoms are called *ions* to distinguish them from ordinary uncharged atoms. (We choose that name because it means 'travellers' and charged atoms, or groups of atoms, do travel when an electric field is applied.)

11a. When an electric current passes through copper sulphate solution, copper is deposited on the plate joined to the negative terminal of the battery (cathode). We say that the copper atoms in the *solution* must carry an electric charge. Is that charge positive or negative? Give a reason for your answer.

b. Suppose your answer to (a) is 'positive'. Does that mean that there must be positive charge flowing from the cathode to the battery through the wire connecting them? Or is there another, alternative, explanation? If so, say what it is.

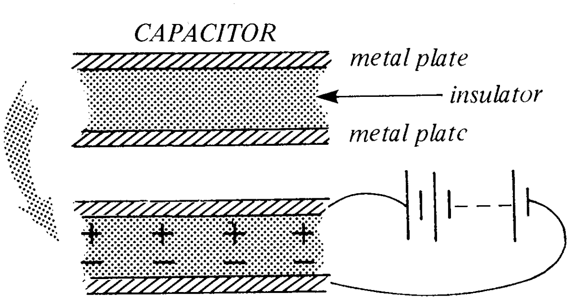
12a. The current through a copper sulphate solution is carried, at least in part, by copper atoms with a positive charge (see Question 11). Do you guess that negative charges are also being carried through the solution? Give a reason for your answer.

b. *If* the current in the solution is carried by both positive and negative charges, does this mean that the wires joined from the battery to the plates must *necessarily* be carrying both positive and negative charges? Explain the reason for your answer.

OTHER KNOWLEDGE OF ELECTRIC CHARGES: CHARGES AT REST

The same kind of things—electric charges that travel when driven in wires or in solutions or in some gases—can also sit at rest and show forces of attraction and repulsion and other effects. (These used to be called *electrostatic* charges but we now know they are the same as the moving electricity in circuits, so now we just call them electric charges.)

See electric charges being driven by a battery onto two insulated plates.



Storing up charges Two metal plates, separated by a thin sheet of insulator, form a *capacitor*.

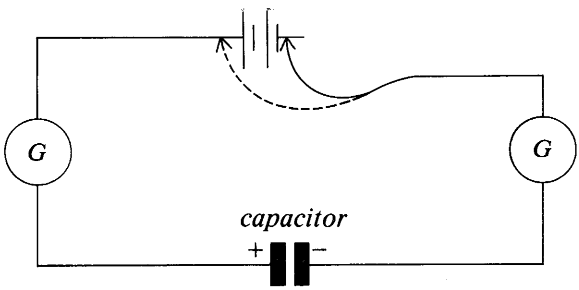
See capacitors being charged, and then discharged, by electricity from the supplies you use for currents: batteries and power-supplies. And see charged capacitors being discharged.

Then see the same things being done with charges from an 'electrostatic machine' such as a Van de Graaff generator. That machine gathers up charges in the same kind of way as you can gather small charges by rubbing a plastic pen on your sweater. But the machine does that on a grand scale; and the plastic pen would not make enough effects for you to see—though it might make tiny sparks in a dark room on a dry day.

Here are some experiments you may see:

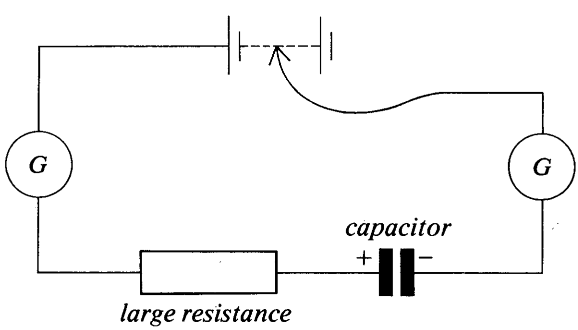
Demonstration 103
Experiments with capacitors

a. Charging a big capacitor When the switch is turned on, the two galvanometers show the tiny currents flowing for a short time onto the two plates. Then one plate holds + charge and the other plate holds − charge.



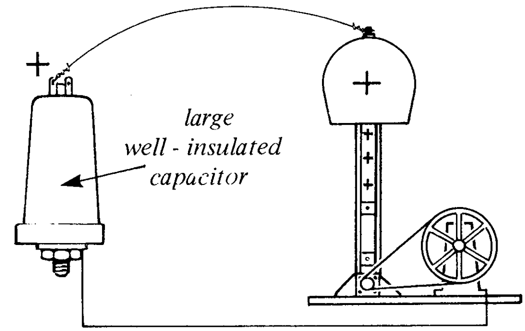
When the battery is taken out and the plates are joined through the two galvanometers, you see the stored charges running away again—and they neutralise each other.

b. Slower charging With a large resistance in series with the battery, the charging currents are smaller and it takes longer for the plates to acquire the same full charges.

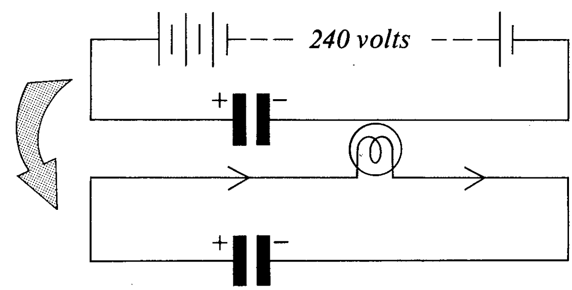


c. Charging to high voltage A smaller capacitor is connected to a 5000-volt supply. You must imagine tiny charging currents being driven onto its plates. Then see what happens when the capacitor is allowed to discharge. The spark is the same kind of thing as the spark made with charges from 'electrostatic' machines.

d. In fact you should watch experiment (c) being repeated with a Van de Graaff generator.



e. Discharging stored charges through a lamp Charge a large capacitor's plates by connecting to a 240-volt d.c. supply. Disconnect the supply and let the capacitor discharge through a lamp. *Why does the lamp stay alight for so short a time?*

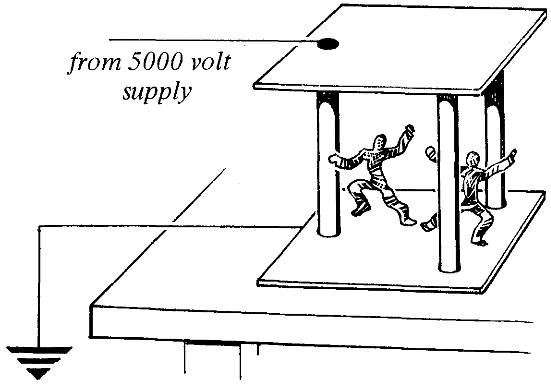


PREPARING FOR MILLIKAN

Millikan's experiment is one of the most important experiments in all modern physics. It is the only one we can offer you that shows individual electron charges. Unfortunately, it would take you and a partner a long time to adjust the apparatus and use it profitably. It is available in some schools and it is used in Nuffield A-level physics—so, if you are very keen and have time to spare, you might be able to try it. But, for the present, we suggest that all pupils should see a special film instead. As preparation for that film see a teaching model, then in Chapter 14 you will meet Millikan's experiment and its film.

Demonstration 104
The dancing man inside a capacitor

Instead of a capacitor with its plates and insulator all rolled up and housed in a box, arrange a capacitor with large horizontal plates separated by air as insulator. Give the plates + and − charges from a high voltage supply. Then place a



small, light metal object in the space between the plates. That may be a tiny figure of a man cut from aluminium leaf, or just a small scrap of leaf.

When a piece of metal leaf touches one plate, it gains a charge by sharing and is then repelled by the charge of that plate and attracted by the charge on the other plate.

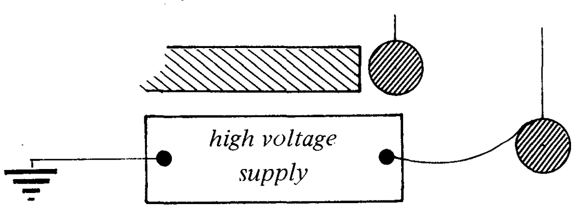
Watch what happens.

(In Millikan's experiment the apparatus is much smaller and the 'dancing man' is replaced by a tiny drop of oil (or a tiny ball of plastic) which is allowed to gain a few extra electron charges. That tiny drop falls slowly, delayed by air friction, and it rises slowly when the plates are suitably charged. The plate charges can even be adjusted to hold the tiny drop at rest, floating in air. Then the charge on the drop can be calculated.)

Progress Questions

13a. Where have you seen electric sparks
(i) from electric charge from rubbing?
(ii) from electricity from the mains?

b. *(i)* A rod of plastic is charged by rubbing. It is brought to touch a light plastic ball coated with metal. What do you expect to see?



(ii) A contact from a powerful electric supply touches the same uncharged ball. What do you see?

14. Usually you use current electricity from the mains or from a battery to
(i) light a neon lamp
(ii) move an ammeter needle.

a. How can you use a Van de Graaff machine to do both these jobs?

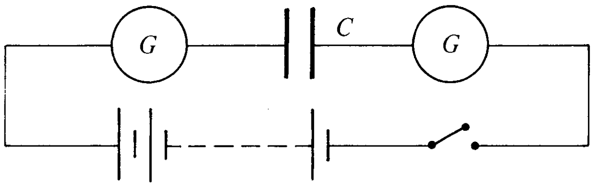
b. What sorts of things does a Van de Graaff machine usually do?

15a. Copy the table below and fill it in sensibly.

b. We talk about electric charge from rubbing, and electric charge flowing round a circuit from a battery. We think they are the same sort of thing. Is that fair? Give a reason for your answer.

	gives you sparks?	gives repelling effects?	lights a lamp?	moves an ammeter's pointer?
Electricity from the mains or battery:				
Electricity from rubbing (with rods, or a Van de Graaf machine):				

Question



16. In the diagram, C is a capacitor—two metal plates separated by a thin sheet of insulator. G and G are galvanometers which can indicate small currents.

a. What happens when the switch is turned on?

b. Re-draw the circuit without the battery so that the capacitor can lose its charges.

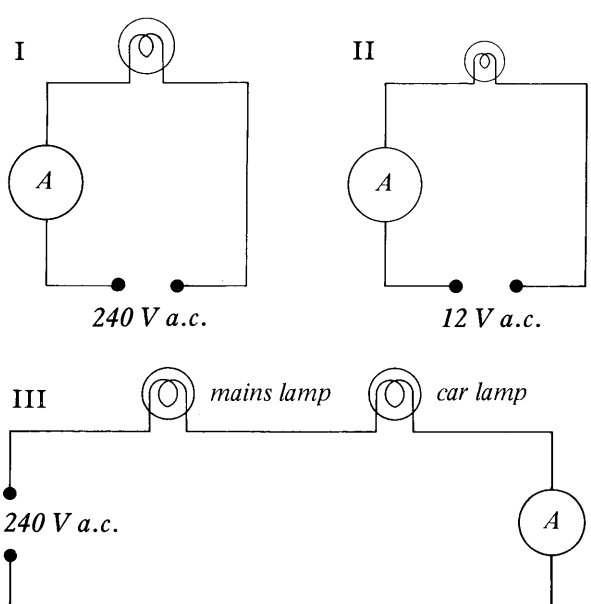
c. What happens in G and G when the capacitor loses its charges?

d. What could you do to show that the capacitor had charges on its plates other than the experiment of (b) and (c) above?

POTENTIAL DIFFERENCES: VOLTS

Both for electric currents and for charged capacitors, we need to know about something more besides *coulombs* of charge and *coulombs per second* or *amperes*. We need to know about volts. Look at an example of different voltages.

Demonstration 105
Comparing lamps

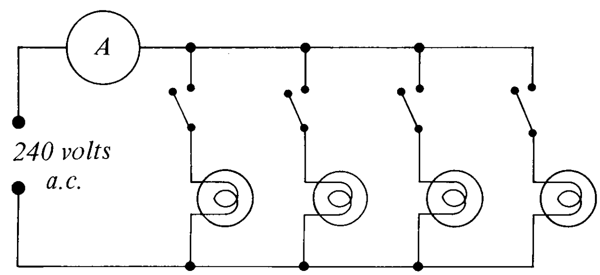


See the experiment sketched. In I and II each lamp is run on its proper voltage. In III both lamps are run in series, so the current *must* be the same in both. Is the light the same from both?

Of course it would be inconvenient to run the lamps in series for house lighting. Turning off one lamp would turn them all off!

They are run in parallel.

Demonstration 106
Lamps in parallel



See the demonstration sketched. Each lamp is supplied by the mains voltage, the same for all. But what happens to the total current as more lamps are switched on?

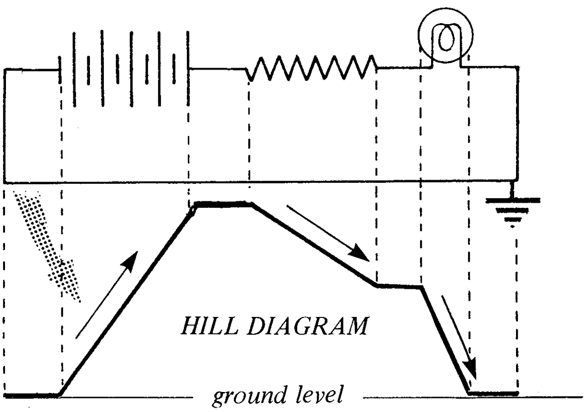
ENERGY SUPPLIED TO LAMPS ETC.

The longer you run a lamp, the more energy it takes from the supply, in direct proportion to the time, and the more energy it gives out as light etc. The more lamps you run in parallel, the bigger the current, in direct proportion; and the more energy the set of lamps takes in and gives out as light etc. The energy transferred in a given time is directly proportional to CURRENT and to TIME, that is to CURRENT × TIME or CHARGE.

But as you saw with the comparison of the two lamps, charge cannot be the only factor. You do need to know how many coulombs go through the lamp, but you also need to know *how many joules of energy each coulomb transfers FROM electrical form TO light etc, as it passes through the lamp.* The instrument which measures that is a voltmeter.

So for measurements of electrical energy or power you need a voltmeter: and you need to understand clearly what it measures.

Electricity 'falling through' a voltage We often speak of a coulomb 'falling through' so many volts and transferring so much electrical energy. That is rather like a 1-kilogram rock falling through so many metres. The rock can transfer more potential energy to other forms if it falls down the side of a 100-metre cliff than if it falls only 10 metres. In a similar way, a 1-coulomb charge of electricity delivers more energy from electrical form if it falls through 100 volts than if it falls through 10 volts. The rock falls through a 'height' in metres. The coulomb falls through a 'potential difference' in volts.



We can draw a hill diagram, showing how the battery pushes a coulomb up to a high level of energy in joules, so that it can then spend that energy as it runs down various hills to the bottom on its way round the circuit. The coulomb does not really have joules, like eggs in a shopping basket. It is pushed by electric field forces generated by the battery. Those forces grip it wherever it is in the circuit and drive it on round, delivering electric energy which comes ultimately from the battery.

You might picture a 6-volt battery giving 6 joules to every coulomb with the instructions 'remember you must spend all this energy on your way round the circuit and then you will get another load of 6 joules for the next round'.

In a way, a battery is like a moving ramp, such as the machine used to raise coal or gravel to the top of a tower for sorting it, or like a moving staircase for people. It raises electric charge, measured in coulombs, uphill to a higher level of electrical potential energy. Then as the electric charge travels round the rest of the circuit it is 'running downhill', changing electrical energy into heat, etc., as it makes some kind of collisions in the wires.

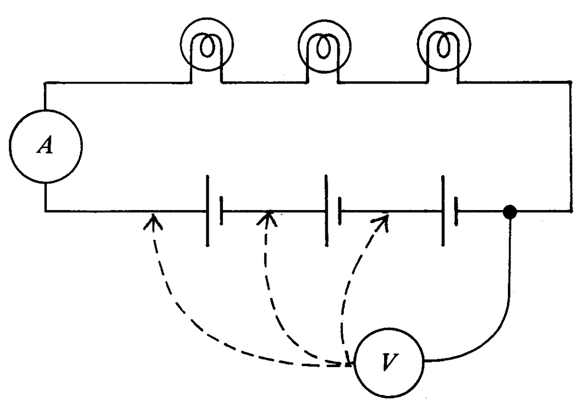
If it goes through a motor it pushes with catapult forces to raise a load and provide gravitational potential energy, etc. Then as each piece of electricity, each coulomb, reaches the battery again, it is raised up again with a new dose of energy, at the expense of chemical energy in the battery.

USING A VOLTMETER

At all costs you should learn how to attach a voltmeter to a circuit and how to use its reading in calculating power—even if you do not fully understand what the voltmeter is doing. That would be better than avoiding voltmeters altogether, which would bring your learning of electricity to a stop. So we suggest you should now try two experiments on using a voltmeter. Then we shall offer an explanation to help you understand voltage and voltmeters.

Experiment 107
The voltmeter as a cell counter

Set up a circuit with three cells and three lamps all in series, as in the diagram.



Attach two long, flexible wires ('leads') to the voltmeter.

Switch on the lamps, and keep them running.

Connect the voltmeter leads to one cell, then across two cells, then across three. Record the reading of the voltmeter each time.

How many cells are needed to light one lamp fully?

How many cells to light two lamps fully? Three lamps fully?

What does the voltmeter tell you? Scientific instruments count things. What things does your voltmeter count?

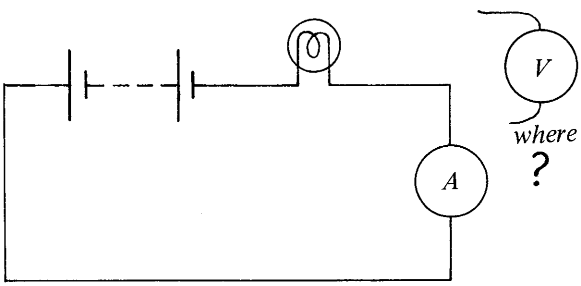
Is the voltmeter connected in series with the lamps or in parallel?

Is an ammeter connected in series with the lamps or in parallel?

What does an ammeter count?

Experiment 108
Using a voltmeter

Connect up a simple circuit of battery, lamp in its holder, ammeter and switch.



Switch on, to see the lamp light up. Note the current.

Where would you add a voltmeter to tell you the voltage for the lamp?

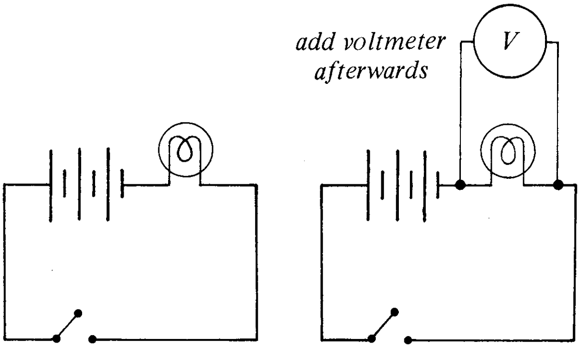
Carry out your suggestion: add a voltmeter. What happens? Discuss with your teacher.

You may have connected your voltmeter in a way that spoiled the lighting of the lamp. If so, think about the pressure gauge attached to the water circuit. That measured the pressure-difference used to keep water flowing through the high-resistance tube. Here you have a high-resistance lamp. Now, how should the voltmeter be connected? Try again.

If you are still not sure, ask your teacher for a private demonstration.

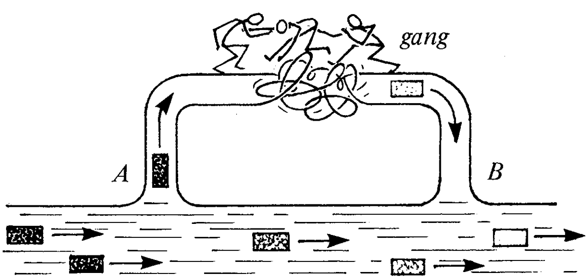
Demonstration 109
Connecting a voltmeter

It is always easier and safer to connect voltmeters if you first connect up the whole circuit without the voltmeter, and then add the voltmeter across the part of the circuit you are investigating.



A story It may seem strange that a voltmeter can find out how much energy every coulomb delivers, when it is connected in this way. Here is a story that may help you to see why voltmeters are connected in the way they are. Voltmeters make energy measurements. Think about a *money* measurement instead.

Imagine a stream of cars all driving the same way along a motorway. Suppose that every driver arrives at point A on the road with the same amount of money in his pocket as every other driver: and has spent all that money by the time he reaches point B.



To find out how much money that is, we do not hold up every car and examine the driver's finances—which would create a bad traffic jam. Instead, we arrange to divert just a few cars out on a side road at A, along a small lane and back to the main road at B. Somewhere on the lane there is a hold-up gang who empty the pockets of each driver in the small diverted stream; and then let him continue the loop to rejoin the motorway at B. That is a rough model of the way a practical voltmeter works.

WHAT IS VOLTAGE?

Now that you can use a voltmeter, connect it *across* the part of the circuit you want it to measure. You could just be told how to use its measurement:

multiply voltage by current and that gives the power, the rate of transfer of energy *FROM* electrical form *TO* heat, etc, in the region the voltmeter covers.

But if you want to understand *why* that tells you power, you need to know what voltage *is*. The voltmeter measures the energy-transfer made by each coulomb of charge passing through the region where the voltmeter is applied. It measures the transfer, in joules, made by every coulomb of charge. That *is* voltage.

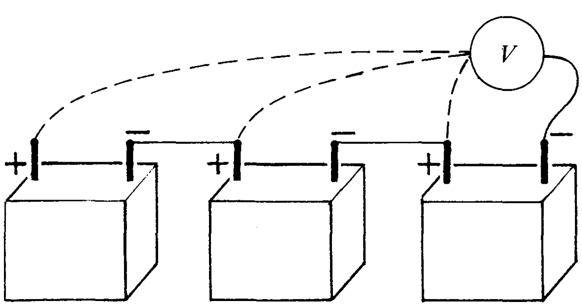
A voltmeter measures joules for each coulomb, or *joules per coulomb*: and we give one *joule per coulomb* a shorthand name, one *volt* (V).

There are several names for that energy-transfer for each coulomb: voltage is the common name: potential difference is the formal, official, name: and we often shorten that to p.d.

You should give your voltmeter a simple test to see whether it is sensible to think it measures energy-transfer. The test is like the cell-counter experiment, but the way you treat it is different.

Experiment 110
Does your voltmeter measure what it is supposed to? A test

Either use a car battery which lets you use 1 cell, 2 cells, or more as you choose, or connect up several 1.5-volt cells in series and use them.

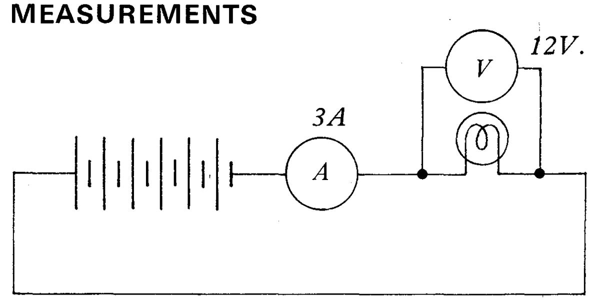


Think about the chemical changes in each cell when you let your battery drive a current. Inside the battery, the same current passes through each cell in turn: so that each cell should deliver the same amount of energy to a coulomb—a transfer *FROM* chemical energy *TO* electrical energy. Therefore, if voltage is energy-transfer per coulomb, two cells in series should provide twice the voltage of one, and three cells three times the voltage of one.

Try that on your battery. Connect your voltmeter across just one cell, then across two cells, then three, four, five and six cells.

Do your voltmeter's readings support the general idea of its use?

VOLTMETERS AND POWER MEASUREMENTS



Now you are ready to use your voltmeter in practical measurements. Suppose you have already done that and find, in the circuit sketched, that the lamp is taking 3 A and the voltmeter reads 12 volts. Then you should 'unroll'* those statements as follows:

The current is 3 A: this means that 3 coulombs pass through the lamp in each second.

The p.d. is 12 volts : this means that each coulomb delivers 12 joules in passing through the lamp.

Then you can calculate the power, the rate-of-transfer of energy in the lamp.

$$\begin{aligned} \text{Power} &= 3 \textit{ coulombs per second} \times \\ &\quad 12 \textit{ joules per coulomb} \\ &= 36 \textit{ joules per second} \\ &= 36 \textit{ watts.} \end{aligned}$$

You will find experiments and questions about such measurements in the next chapter.

---

*Unrolling statements of current and voltage like that will make calculations easy and clear. You should do that with the data in each question you answer about volts, amperes and watts.

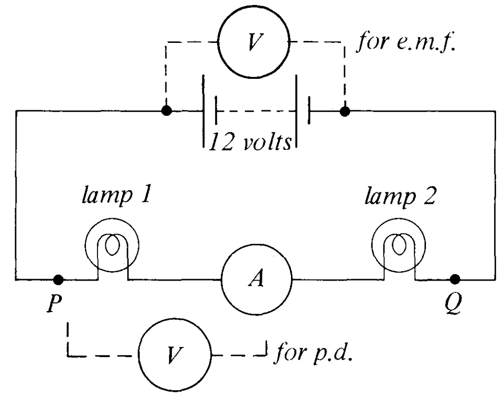
If a statement of watts is given, you can unroll it like this: *The power is 36 watts : this means that 36 joules are delivered every second* (FROM electrical form TO heat, etc., in the lamp).

THE BATTERY'S VOLTAGE: e.m.f.

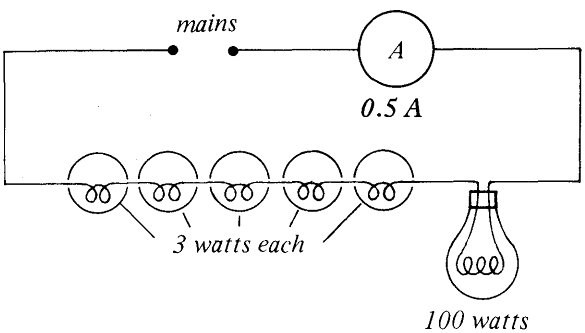
A voltmeter connected across a lamp or motor tells you the energy-transfer made by each coulomb FROM electrical form to heat, or mechanical energy. What does a voltmeter connected across a battery tell you? It must tell the energy-transfer made by each coulomb passing through the battery FROM chemical form TO electrical form—the other way round this time. We call that the battery's e.m.f., electro-motive force.

A similar story holds for the e.m.f. of a dynamo.

Demonstration 111
p.d. and e.m.f.



Progress Questions



17. In this circuit, a current of 0.5 A goes through each lamp. Each small lamp is '3 watts', and the mains lamp is '100 watts'.

a. How much energy does *one coulomb* transfer to heat and light in each small lamp?

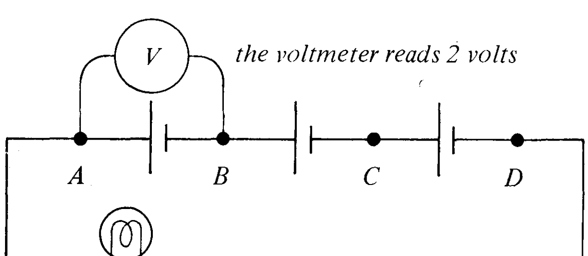
b. How much energy does *one coulomb* transfer to heat and light in the mains lamp?

c. What is the p.d. across the five small lamps?

d. What is the p.d. across the mains lamp?

e. What is the p.d. of the mains?

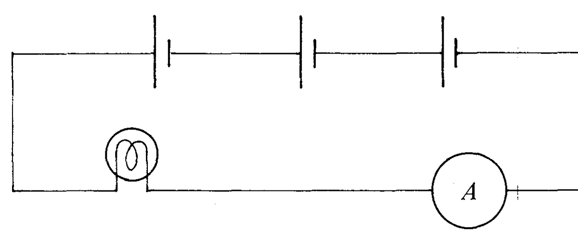
18a. The voltmeter's wire to B is moved to C.



(i) Draw a new circuit diagram to show this.
(ii) What will the voltmeter read now?

b. The voltmeter is joined across all three cells.
(i) Draw a circuit diagram to show this.
(ii) What will the voltmeter read now?

c. The voltmeter is moved down below and joined across the lamp.
(i) Draw a circuit diagram to show this.
(ii) What will the voltmeter read now?



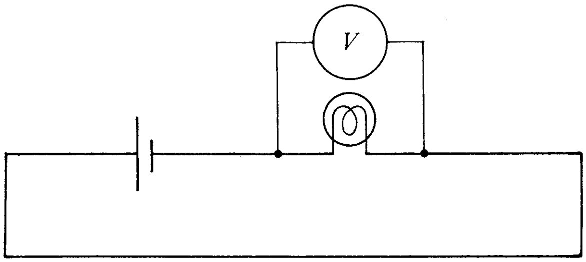
19a. Draw *three* circuit diagrams to show how you would connect a voltmeter to measure
(i) the voltage across the battery.
(ii) the voltage across the lamp.
(iii) the voltage across the ammeter.

b. Which of those three voltages would you expect to be biggest?

c. And which of the three the smallest?

20a. Copy and complete:
In the lamp, electrical energy changes to . . ? . . energy.

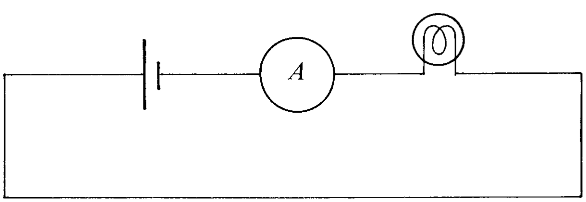
b. The voltmeter reads the voltage across the lamp. It reads 1 volt.



That means *every coulomb* of charge gives up to 1 joule of energy in the lamp.
(i) How many joules do you get when 2 coulombs pass through the lamp?
(ii) How much energy from 60 coulombs?

c. You join a second cell in series with the first.
(i) Draw a circuit diagram.
(ii) What will the voltmeter read now?
(iii) Copy and complete:
The voltmeter reads . . ? . . volts. That means every coulomb of charge gives up . . ? . . joules of energy in the lamp.
(iv) How many joules for 2 coulombs?
(v) How many joules for 100 coulombs?

21a. Copy the diagram and add a voltmeter to read the voltage across the lamp.

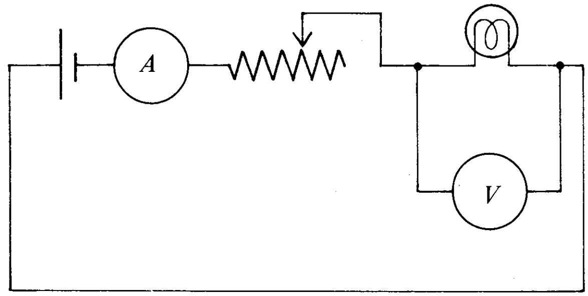


b. The voltmeter across the lamp reads 3V. How many joules do you get for each coulomb?

c. The ammeter reads 1 A. How many coulombs go through the lamp each second? (1 *A* = 1 *coulomb per s.*)

d. So how many joules (are charged to heat) in 1 second?

e. How many joules in 1 minute?



22. The voltmeter reads 2 volts and the ammeter reads 0.5 amps.

a. How many joules does each coulomb deliver in the lamp? (1 *volt* = 1 *joule per coulomb*.)

b. How many coulombs go through each second? (1 *ampere* = 1 *coulomb per second*.)

c. So how many joules per second are delivered in the lamp?

d. So what is the power, in watts? (1 *watt* = 1 *joule per second)*.

The rheostat is adjusted, to make the current bigger. Suppose the voltmeter reads 3 volts, and the ammeter reads 0.8 A.

e. How many joules are delivered in 1 second?

f. How many joules in 1 minute?

23. A voltage of 12 V drives 3 A through a lamp.

a. How many joules for every coulomb?

b. How many coulombs in every second?

c. So how many joules every second?

d. So what is the power, in watts?

e. Can you see a quick way to work out the power from the voltage and the current?

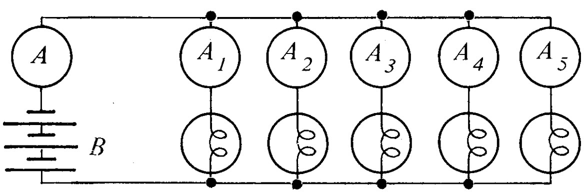
Questions

24a. What is meant by 'potential difference'?

b. And what does a 'potential difference of 1 volt' mean?

25. An electric current is sometimes compared with flow of water. Flow of water might be measured in litres per second (or in cubic metres per second or in gallons per second). What is the corresponding unit for flow of electricity?

The water itself might be measured in litres (or in cubic metres or in gallons). What is the corresponding unit for electricity?



26. The diagram shows five bulbs for car sidelamps joined in parallel to a battery which lights them at normal brightness. Each lamp is correctly marked '3 watts'. Each of the ammeters A_1 to A_5 reads 0.5 ampere.

a. If all the ammeters are accurate, what does the chief ammeter A read?

b. How many joules of electrical energy are used in each second by each 3-watt lamp?

c. How many joules are delivered in each second by all five lamps together?

d. How many coulombs pass in one second through each lamp?

e. How many coulombs pass in one second through all five lamps together?

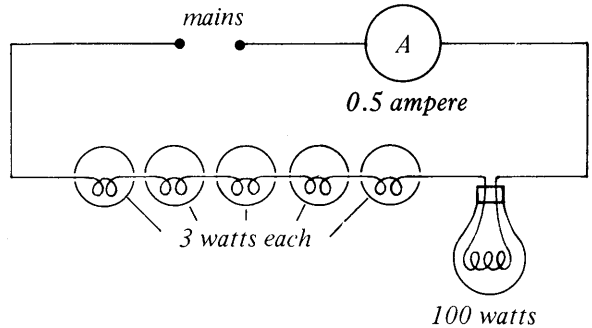
f. What can you say about the way in which (quantity of electrical energy converted to other forms) depends on (quantity of electricity passed)?

27a. How many coulombs pass through each small lamp in the diagram in one second? How many per second through the large lamp?

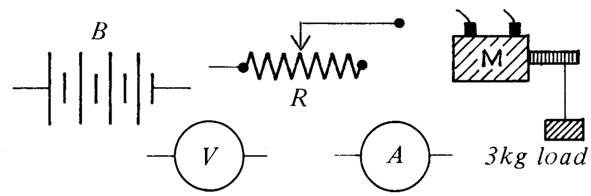
b. How many joules of electric energy are converted by each small lamp in 1 second?

c. How many joules are used by the mains lamp in 1 second?

d. We know that the energy converted (joules)



varies directly with the electricity passed (coulombs). But now, for the same number of coulombs (answer **a** above) we have very different numbers of joules converted in the sidelamp bulb and the mains bulb (answers **b** and **c** above). The amount of energy converted depends on something else besides the quantity of electricity. What else?



28. In the diagram M is a small electric motor that runs on a 6-volt supply. B is an 8-volt battery, R is a rheostat, A is an ammeter and V is a voltmeter.

a. Draw a diagram showing these items joined in a suitable circuit. Include the ammeter to measure the current when the p.d. across the motor is 6 volts.

b. How would you make sure that the p.d. across the motor is just 6 volts?

c. A 3-kg load is attached to the axle of the motor and can be raised as the motor turns. How would you find the electrical energy in joules supplied to the motor while the load is raised 1 metre? What other measuring instrument do you require besides a voltmeter, an ammeter, and a metre stick?

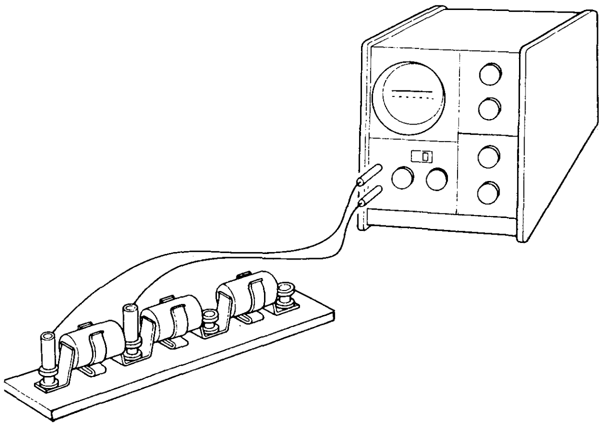
29. In the circuit of Question 26 each lamp takes '3 watts, 0.5 ampere'.

a. How many joules of energy are 'delivered' in each lamp by each coulomb passing through it?

b. What, then, is the voltage of battery B?

A DIFFERENT KIND OF VOLTMETER: OSCILLOSCOPE

An oscilloscope, in which a thin beam of electrons makes a spot which draws a graph, can be used as a voltmeter. Apply the p.d. to be measured to the pair of plates which make the spot move up or down. The vertical rise of the spot indicates the voltage applied.

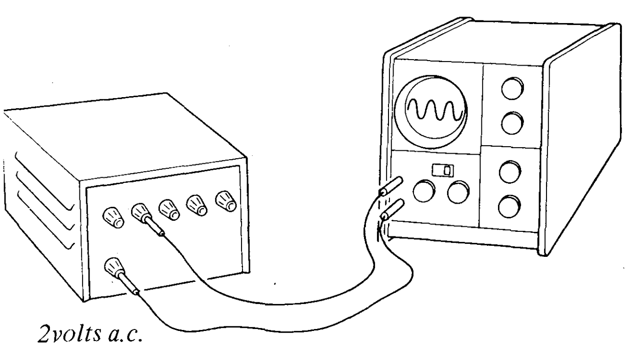


Since the oscilloscope takes practically no current from the circuit under investigation, it is in some ways better. (The ordinary voltmeters that you use in the lab use a small trickle of current—in that, they are unlike the pressure gauge in the water circuit, which steals none of the water flow.)

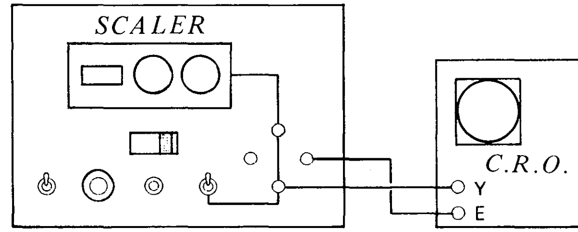
You can also make the spot move sideways at a steady rate and thus draw a time-graph of the voltage.

Now, or in Year 5, you should use an oscilloscope for several things such as:

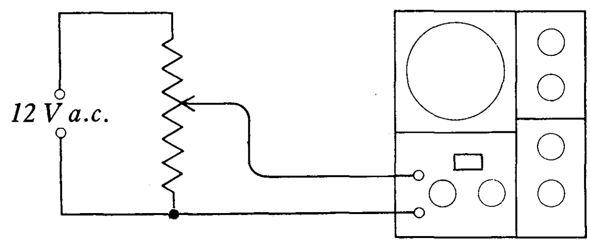
(a) as a modern voltmeter
(b) to show the wave-form of the mains a.c.

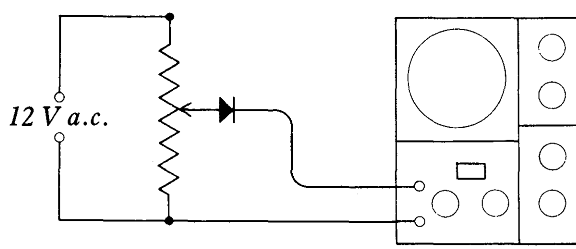


(c) to exhibit the wave form for the 1000 Hertz pulses from the scaler

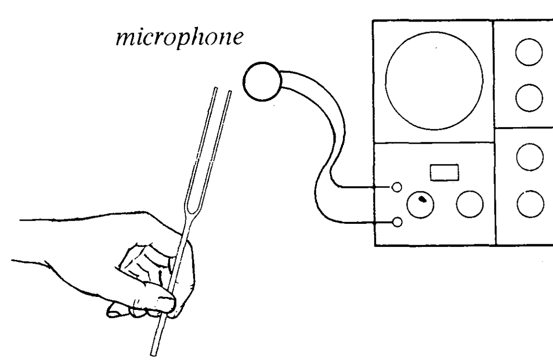


(d) to measure the speed of sound
(e) to illustrate the rectifying action of a diode



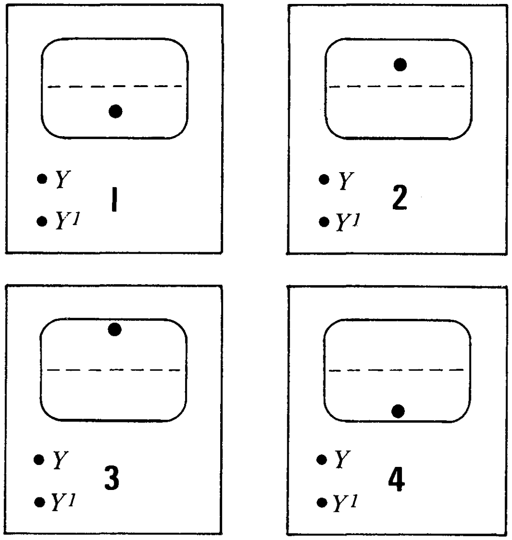


(f) as a sound-wave-mirror, to see the wave forms of your own voice or of any musical instrument that you play.



Questions

OSCILLOSCOPE



30. Diagram 1 shows an oscilloscope screen. The spot is stationary and nothing is joined to the input terminals Y and Y^1. Diagram 2 shows what you see when one $1\frac{1}{2}$ V cell is joined across Y and Y^1.

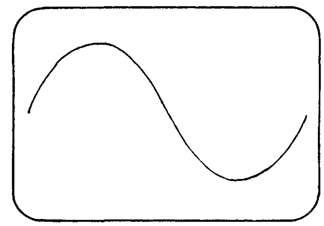
a. In diagram 3, what is joined across Y and Y^1?

b. In diagram 4, what has been done now?

31. An alternating voltage (changing direction many times a second) is connected to the YY^1 terminals of an oscilloscope. What do you see on the screen:

a. if the spot was standing in the middle of the screen to start with?

b. if the spot is being swept across the screen?



32. The time base makes the spot cross the screen from left to right in 1/50 of a second. The sketch shows what we see when an alternating voltage is connected to the Y plates.

a. How many times a second does the voltage alternate?

b. An alternating voltage of frequency 200 hertz is applied instead. Draw what you expect to see.

CHAPTER 12

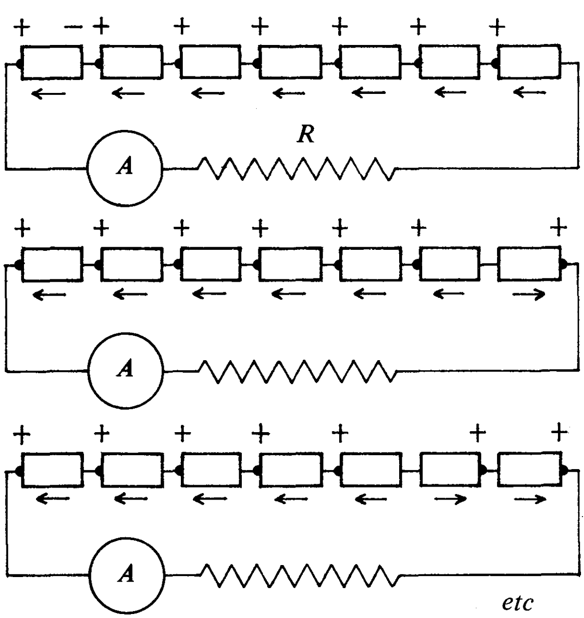
OHM'S LAW AND OTHERS

VOLTS, AMPERES, AND OHMS OF RESISTANCE

This is a chapter of measurements of electric circuits. It should help you to understand the behaviour of lamps and house wiring, hunting for faults in cables—and, in the next chapter, the working of electric power lines and measurements of electric power.

First investigate the way CURRENT and VOLTAGE are related for several materials and electrical devices. Then put that knowledge to work in various applications.

See a demonstration which will show you the kind of behaviour you are going to investigate in your own experiment on Ohm's Law.



Experiment 112
Ohm's Law: a direct, simple approach—without a voltmeter

You will see the circuit shown in the diagram. The ammeter shows the current which the battery of cells drives through the resistor, R. All seven cells are kept in the circuit throughout the experiment, so that the total resistance stays the same.

First the current is read with all seven cells driving it. Each of the seven makes its contribution of energy to every coulomb passing through.

Next, one of the cells is reversed. Then each coulomb receives the usual share of energy (from chemical supply) in six of the cells: but in the reversed cell it is to pay back one share from electrical form to chemical form. (We assume that the action of the cell can be reversed like that—not exactly true but quite close to true if current is not driven through the cell backwards for much time.)

Read the current. That is the current driven by six cells minus one cell, an effective batch of *five cells*.

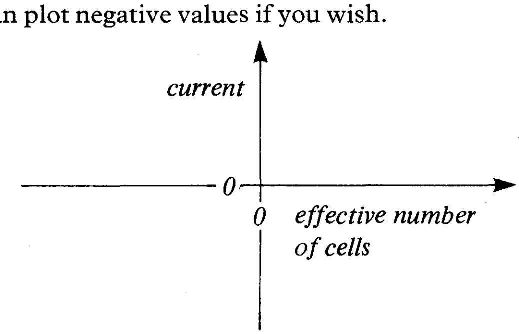
Reverse one more cell and read the current for an effective batch of *three cells*.

Reverse one more cell and read the current for an effective batch of *one cell*.

Reverse one more cell. What can you do now?

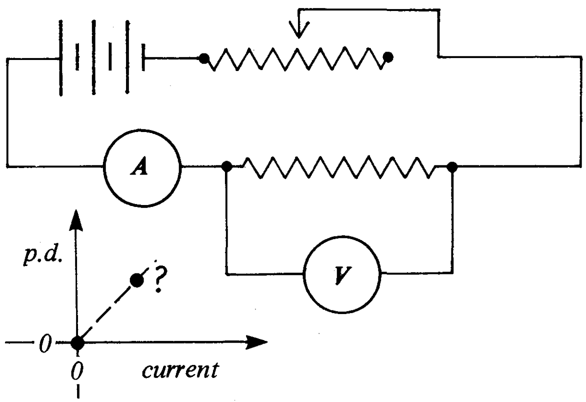
Continue as far as you can.

Plot a graph of current upwards against effective number of cells along. You should put the origin (0,0) in the centre of your paper so that you can plot negative values if you wish.



Experiment 113
Ohm's Law: How are p.d. and current related for a metal wire?

Set up the circuit shown.



Obtain a series of pairs of readings of the CURRENT through the sample of alloy wire and the VOLTAGE across it. Three or four pairs will be enough, but they should spread from 0 to the largest value your instruments can take.

How do current and voltage seem to be related, for your wire?
(i) First guess, by looking at your measurements. Then test your guess by arithmetic: divide p.d. (voltage) by current.
(ii) Plot a graph of p.d. (upwards) against current (along). *What does your graph tell you?*
(iii) We call P.D./CURRENT the RESISTANCE of the sample. Calculate the resistance of your sample from your arithmetic in *(i)*.

Your answer will be in $\frac{\text{volts}}{\text{amperes}}$ or *volts per ampere*. We name one *volt per ampere* one *ohm*—this is just dictionary-work to be economical, like naming one *sea-mile per hour* one *knot*.
(iv) Also calculate the resistance from measurements of your graph. *In what way does the graph give you a better estimate?*

We call the simple relationship you have now seen, (for such a wire), Ohm's Law.

Some oil engineers speak of Ohm's Law for a pipe-line. What do they mean?

Ohm's work One hundred and fifty years ago, G. S. Ohm, a German schoolmaster, set out to find a relationship between current through a wire and voltage between its ends. He already had an idea of the wire offering *resistance*, much as a pipe offers resistance to water-flow.

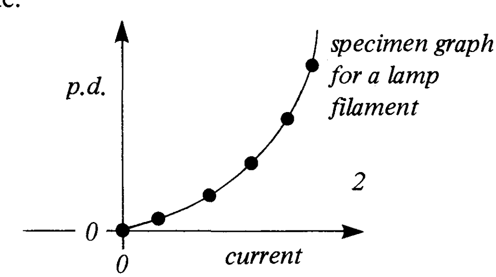
He was the son of a locksmith, so he knew how to draw metal wires of different sizes for his experiments. (At that time, wires were not available in shops as they are now in our electrical age.)

Ohm tried different lengths, different thicknesses, different metals, and even different temperatures. His instruments, and even his voltage supply, were very primitive; but Ohm extracted a 'law'—P.D./CURRENT is constant for a wire. That constant value was the wire's RESISTANCE which he had dreamed of. And he found rules for the way resistance depends on the length and thickness of the sample.

Ohm hoped for rewards of fame and promotion for his discovery but the authorities scorned his work; and it was only when it became known and honoured outside Germany that he was made a professor—to his great happiness.

Ohm's Law is a very useful link between current and voltage. It has helped in the design of telegraph lines, telephones, motors, power lines, . . . the whole development of electrical equipment through the last century and on into this century.

Nowadays we also know of materials whose behaviour does not follow Ohm's Law; and those now play essential parts in many of the most important modern devices: rectifiers, transistors, etc.



If you made measurements of volts and amperes for a lamp filament your graph would not be a straight line through (0,0).

Is that because the pure metal of the filament does not 'obey' Ohm's Law or is it only because the filament gets hotter and hotter with more current?

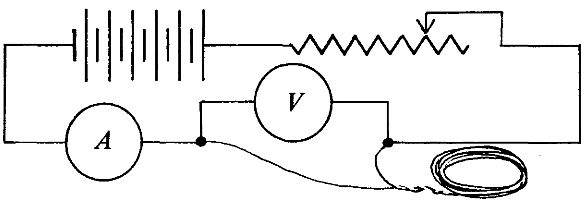
Try a quick experiment which may settle that question.

Experiment 114
Temperature change and resistance

a. Set up a simple series circuit with long leads, joined to the loosely wound coil of insulated copper wire.

Adjust the rheostat to give a current about 4.5 A through the coil. Then switch off.

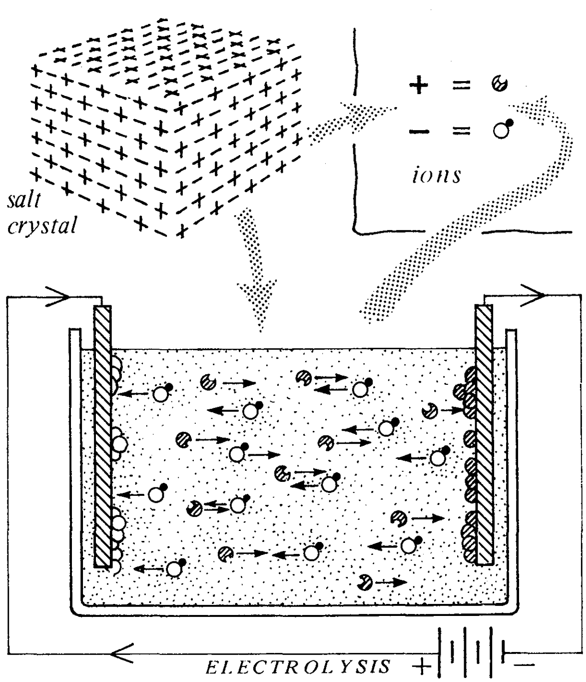
After a minute or so (for cooling) switch on and read the ammeter and voltmeter during the next half-minute or so. Watch the changes.



b. Repeat the experiment with the coil suspended in water in the container. Keep the water very well stirred.

CONDUCTION IN LIQUIDS AND GASES

In liquids, the current is carried by ions—atoms or atom-groups carrying electric charges. This is called electrolysis. In some cases the atoms are already charged ions in the solid crystals: for example sodium chloride, illustrated below.

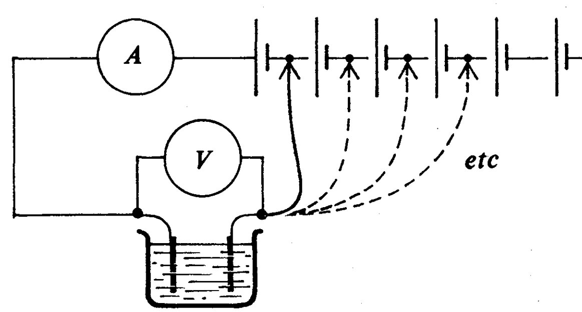


Demonstrations 115, 116, 117
Relationship between p.d. and current for (a) copper sulphate solution; (b) water; (c) neon gas

See (a) and (c). You may see (b), but it is optional now, and will become important in Year 5. Here are some notes:

a. In blue copper sulphate solution the current is carried by positively charged copper atoms, Cu^{++} ions, and negatively charged sulphate ions, SO_4^{--}.

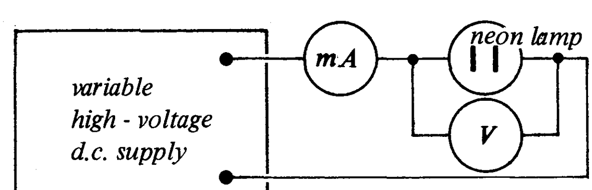
The Cu^{++} ions give the solution its blue colour. They drift very slowly across. The SO_4^{--} ions drift very slowly across, the opposite way. Although the ions drift slowly the current starts as soon as the battery is connected, because the whole liquid is full of a dense population of ions, which start drifting at once. Thus, although an individual ion takes a very long time to drift across from one plate to the other, the current appears to run fast.



Does the liquid seem to 'obey' Ohm's Law?

b. In electrolysis of water (which you will see again next year) a little acid is added to provide plenty of hydrogen ions, H^+, but it is the water that produces the gases—the original acid remains.

c. In neon gas a large voltage is needed to pull an electron of some neon atoms. Then flying electrons make more ions in collisions.



FURTHER EXPERIMENTS

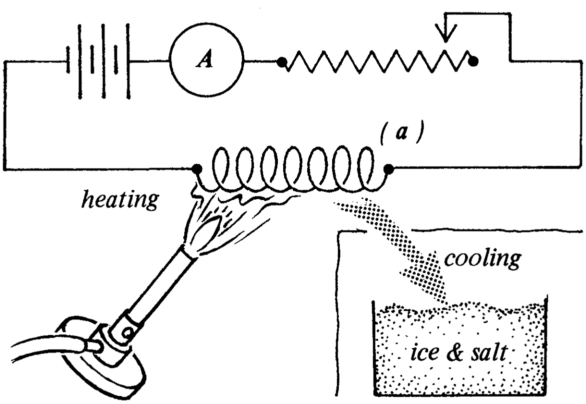
Try some more experiments on conduction: effects of heating; materials that do not 'obey' Ohm's Law; and devices such as transistors which go far beyond and away from Ohm's Law behaviour.

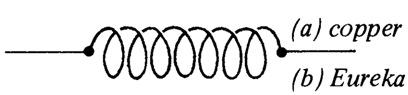
Such non-Ohm's Law things are of great importance in modern electronics.

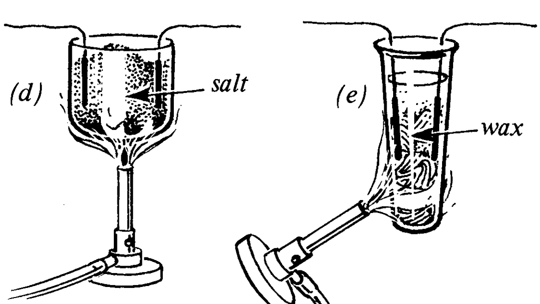
Experiment 118
Effect of temperature changes on conductivity

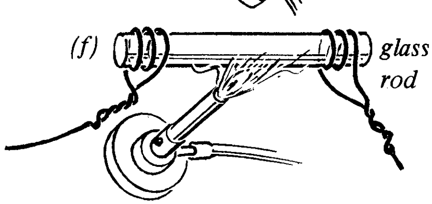
Try the effect of heating on some materials which may conduct a current.

Set up a circuit with battery, rheostat, ammeter and the specimen. Heat the specimen gently with hot water or even a small flame. (If you like, try the effect of cooling with ice.) Try some of the following specimens.









a. Thin bare copper wire—about 1 metre made up into an open coil.

Adjust the rheostat or the battery connectors to make the current about 0.8 A. This will need only a small voltage.

Then warm the copper coil *very gently* in a low bunsen flame. Watch the ammeter.

If you like, extend the experiment by placing the coil in a mixture of ice and salt, or in some solid CO_2.

(*Warning*. The coils may touch each other; then a short-circuit may mask the proper current-change.)

The resistance of copper clearly increases as the temperature is raised. *What use might be made of this effect?*

b. Replace the copper coil by a coil of alloy wire (Eureka: 60% copper, 40% nickel). Repeat the experiment. You will need a greater voltage.

Interesting optional extensions

c. Try a 'thermistor' instead of the coil. Warm it gently.

d. Put a block of salt in a crucible. Dip two pieces of thick bare copper wire into the salt and connect them in the circuit, in place of the coil. Heat the crucible *gently*. Watch the ammeter.

e. Embed two pieces of thick copper wire in paraffin wax in a test tube. Make sure they do not touch. Connect them in the circuit.

Heat the tube *gently*. Watch the ammeter. (*HINT*. Remember that 0 is a perfectly proper number among measurements!)

f. Try a glass rod about 10 cm long. Wind two or three turns of thick, bare copper wire round the glass rod, near each end. Connect the wires in the circuit. Heat the rod *gently*. Watch the ammeter.

(You may see a glass rod being heated much more strongly in a demonstration with a large mains voltage across it. If it is hot enough it will behave differently.)

Demonstrations 119, 120, 121, 122
Effects of strong heating

See the effects of heating on some of the following:

Common salt This is melted in a crucible. Does the molten salt carry a current? Salt is sodium chloride and if you could make a current pass through it, you might be able to obtain sodium, a very active metal.

Paraffin wax This melts easily. Does it conduct, when melted? Its molecule is a long chain of carbon and hydrogen atoms; and both its ends are quite inactive, unlikely to carry electric charges.

Glass A rod of common soda glass is heated in a flame until it is beginning to soften. The glass contains sodium ions, among other things. These ions, Na^+, could carry a current if they were not held tight in the solid glass. When the glass is hot and soft, those ions *can* move. A large voltage can then drive a current. Since the glass still makes motion difficult for the ions, the rod has a large resistance and any current develops a lot of heat, perhaps enough to melt the glass.

Thermistors These are made of a mixture of metal oxides, such as those of copper, manganese, nickel. We describe them as 'semi-conductors'. Unlike pure metals they decrease in resistance when heated.

Germanium This is a type of semi-conductor which behaves just like an insulator when cold but suddenly becomes a conductor when heated. (Most ordinary insulators become conducting when heated very strongly—but only when that brings them to a much higher temperature than the threshold for germanium.)

Semiconductors These materials which do not fit with Ohm's Law seemed at first to be oddities as likely to be a nuisance as useful. But now they are manufactured in a variety of forms and put together as transistors—which are of enormous use in electronics.

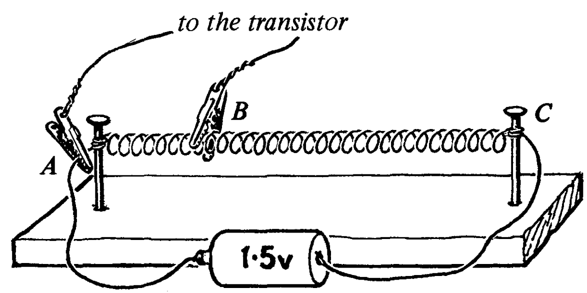
Nowadays, a group of tiny transistors, resistors, capacitors, can be assembled (usually by a photographic process) in a minute, complete device—for example an amplifier. We call such devices 'integrated circuits'.

TRANSISTORS

The transistor was a marvellous discovery. It has replaced fragile vacuum tubes that needed hot filaments, so that radios, amplifiers and many other electronic devices are now made with transistors.

Try for yourself the amplifying behaviour of a small transistor.

What is a voltage-divider? When you experiment with a transistor you will need to apply a very small input voltage; not 12-volts from a battery, not 1.5 volts from a dry cell, but only a few tenths of a volt. We do not have a battery which supplies such a small voltage directly. So we have a problem like that in a bakery which has only a very long loaf and the customer wants just a short loaf. The baker can slice off a fraction of the loaf's length with a large knife (as you may see a baker do in France). A voltage-divider lets us slice off a fraction of a cell's voltage with a sliding crocodile clip.



a home-made voltage divider

The diagram shows the simple voltage-divider that you may use in the next experiment. A long coil of resistance-wire is stretched between two posts A and C (it is a coil of nichrome wire for repairing electric heaters). A 1.5 volt cell is connected to A and C and a crocodile clip, B, can grip the wire wherever you wish.

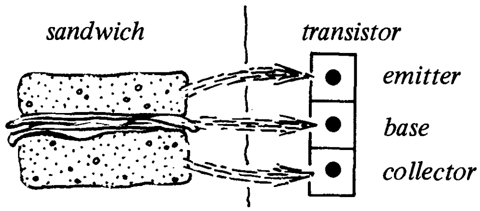
If the clip B is near A, the voltage between A and B is only a fraction of the whole 1.5 volts.

Example In the sketch, AB is about one-fifth of the total length AC. So we expect the voltage between A and B to be about one-fifth of the whole 1.5 volts; that is, 0.3 volts.

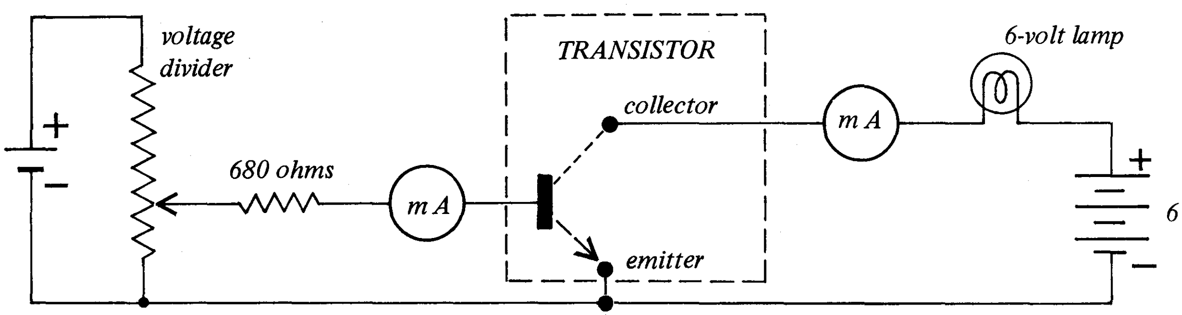
Experiment 123 Transistor

A transistor is a tiny chip of semi-conductor materials. It is rather like a sandwich of a slice of ham between two slices of white bread.

The transistor's emitter corresponds to a THIN SLICE OF BREAD.
The transistor's base corresponds to the HAM.
The transistor's collector corresponds to a THICK SLICE OF BREAD.



In your transistor, a minute current in the base-emitter circuit is used to control a *much* larger current in the collector-emitter circuit.



Arrange the circuit as in the sketch. Connect the voltage-divider across the $1\frac{1}{2}$-volt cell.

Connect the movable clip to the fixed resistance of 680 ohms, one milliammeter (range about 100 milliamperes) and the *base* terminal of the transistor.

Connect one end of the voltage divider to the *emitter* terminal of the transistor.

Connect the *collector* terminal of the transistor to the other milliammeter (range about 100 milliamperes), the small lamp and the 6-volt battery, and back to the *emitter* (which is already connected to the voltage-divider).

Try the following experiments:

(i) Leave the *base* circuit open, with no connection to the *base*. You will see no detectable current in the *collector* circuit.
(ii) Join up the *base* circuit. The voltage for a suitable base current is less than 1 volt. Start with no voltage from your voltage-divider and increase the voltage until the lamp in the collector circuit glows. Read the milliammeter in that circuit.

Then look at the other milliammeter, in the base-emitter circuit. *Is any current flowing to the base?* If there seems to be *no* current try switching the supply on and off, and see whether the milliammeter's pointer moves at all.

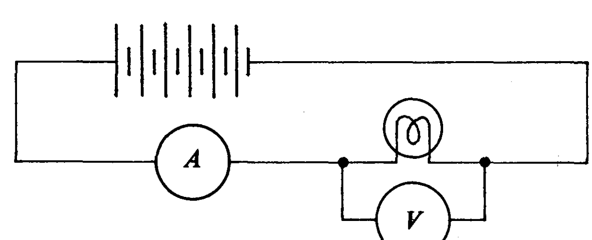
Your transistor is amplifying current. Comparing the two milliammeter readings gives you an idea of the amplification.
(iii) Increase the *base current* a little, causing an increase in *collector current*. The ratio of the two currents will remain approximately constant.
(iv) The collector current will level off at about 60 milliamperes, which is the limit imposed by the lamp in the circuit. Any further increase in the base current will have no further effect.

MEASUREMENTS

Measure various resistances and see some demonstrations.

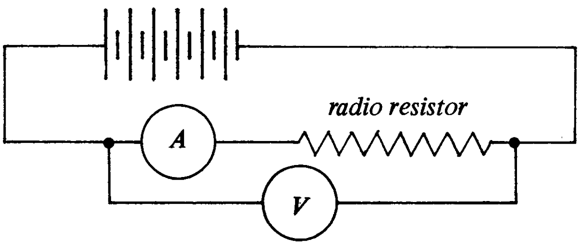
Experiments 124 and 125
Measuring resistance with a voltmeter and an ammeter

(i) Resistance of a lamp Set up a circuit as shown.



Take one pair of readings of the ammeter and voltmeter. Calculate the resistance of the lamp *at its running temperature.*

(ii) Resistance of radio type resistor. Replace the lamp in the circuit by a radio resistor. (Beware of including the voltmeter's current in the ammeter's measurement.) Repeat the measurements and calculation.



(iii) Resistance of heating element of an electric fire. Repeat the experiment with a radiant heater element. Use 12 volts.

Then see some demonstration measurements.

Experiment 126
Measure the resistance of your voltmeter *(OPTIONAL)*

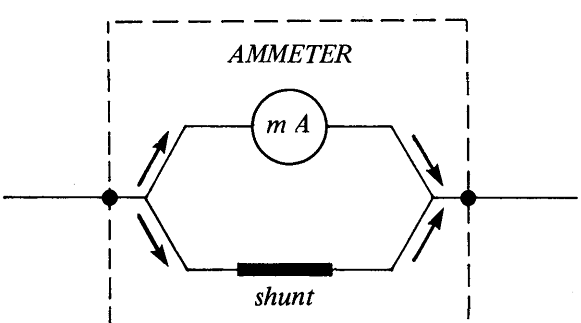
This is a puzzle. Try it, if you like.

APPLICATIONS

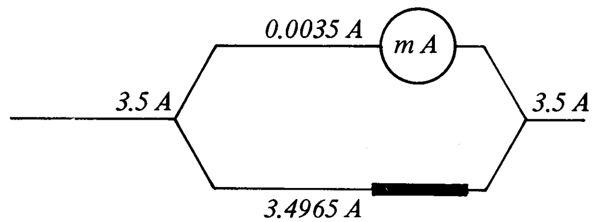
Put Ohm's Law to some uses.

Experiment 127
Making an ammeter *(OPTIONAL)*

Your galvanometer is arranged to measure small currents of a few milliamperes. Suppose you wish to use it to measure much larger currents, say 3.5 A at the end of its scale. When the pointer is there, the current through the little coil which moves with the pointer must be the same as ever, say 3.5 mA (or whatever your milliammeter is built to measure there).

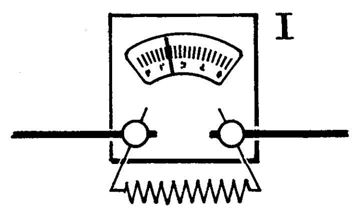


So, if you want to use it for a large current, the rest of that large current (3.5 A minus 3.5 mA, for example) must travel by an alternative route, a loop line in parallel.



shunting a 3.5 mA meter to make a 3.5 A ammeter

For that loop line or *shunt,* connect a short piece of alloy wire across the terminals of your galvanometer, as in diagram I. See diagrams II and III for the safe arrangement.*



Start with a very short shunt, straight across from terminal to terminal. Make a very rough test of that by connecting in series a lamp, your shunted galvanometer, a commercial ammeter (for comparison) and one 1.5-volt cell—just for a safe first trial.

* If, when adjusting the shunt, you let the whole big current go through the galvanometer, even momentarily, you might damage the galvanometer badly. Avoid the arrangement of

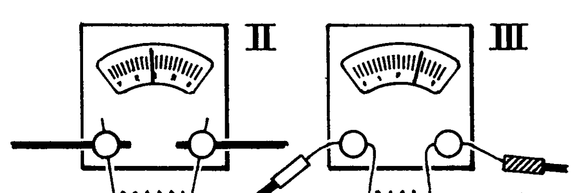
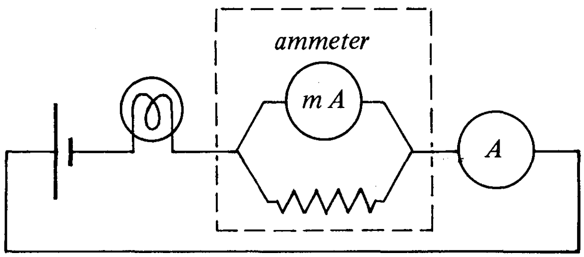


diagram II, which might do that; use the safe arrangement of diagram III where there is no danger because the large current always goes through the shunt-wire, even when it is off the galvanometer's terminal.



Switch on the current just for a moment to see whether the pointer moves much too far or much too little.

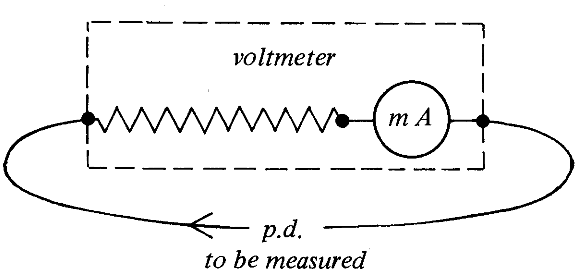
Adjust the length of shunt by trial and error. Shorten or lengthen the shunt until your home-made ammeter seems to read roughly what you want it to read.

Then change the battery in your test circuit to 12 volts instead of 1.5 and adjust the shunt more carefully till you have a good ammeter.

A commercial ammeter is constructed like this. It is a milliammeter with a shunt. Sometimes the basic instrument has several removable shunts to make it an ammeter with a choice of several ranges—as in the case of the demonstration meters in your lab.

Experiment 128
Making a voltmeter *(OPTIONAL)*

The ordinary commercial voltmeter that you use in lab is really a 'trickle meter' that measures the tiny trickle of current that the applied voltage drives through a high resistance inside the voltmeter's case. Your galvanometer *is* a trickle meter. It measures small currents, up to 3.5 mA when the pointer is at the end of the scale.



To convert your galvanometer to a voltmeter reading, say, 3.5 volts when the pointer is at the end of the scale, you must add a large resistance in series, as in the diagram.

(If you like making calculations, you could ask: 'what is the total resistance if 3.5 volts applied to the whole instrument drives 3.5 mA through it?' ANSWER R = P.D./CURRENT = (3.5 volts)/(3.5 mA) = (3.5 volts)/(0.0035 A) = . . ? . .

Then you know the total resistance needed. The makers of the galvanometer tell us it has resistance 10 ohms. So most of the resistance you have calculated has to be added).

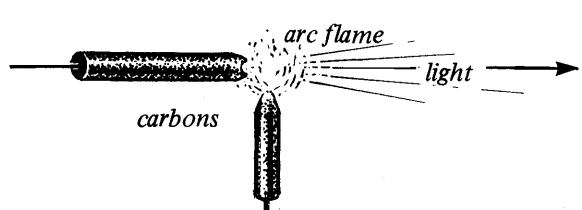
But you need not calculate. You can discover the right resistance to add by trial. Choose the largest high resistance you are offered. Connect it in series with the galvanometer and connect to a 1.5-volt cell, just for an instant. Does your voltmeter read 1.5, as you wished? If it reads more, you do not have enough resistance in it: add more. If it reads too little, try less resistance in it.

When you have adjusted the resistance, try your voltmeter on two 1.5-volt cells connected in series. Also test those with a commercial voltmeter to make sure yours now reads as you wish.

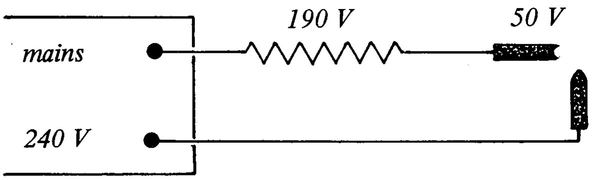
If you like, convert your voltmeter to one with twice that range, 0–7 volts; and try that on a 6-volt battery.

Experiment and Demonstration 129
Making an electric arc work from the mains

An arc is one of the earliest forms of electric lighting. It gives an intensely bright light from a white-hot rod of carbon. The arc itself is a flaring flame in the gap between two carbon rods. The flame is like a 'plasma' composed of ions from the air, together with ions of carbon and carbon compounds and electrons. Their bombardment keeps one rod (or both) white hot.



A very small arc will run at 4 to 5 A with a gap of $\frac{1}{2}$ to 1 cm between carbons. There will be about 50 volts across the arc, *but a resistor in series is necessary for stability*. Can you guess how that resistor helps? The striking voltage is about 70 volts, but the arc will then run on 50 volts.



The calculation The arc needs about 50 volts between the two carbons, but it is to run on 240-volt mains. The rest of that supply voltage must be taken by a resistor in series with the arc. Calculate the resistance needed if the current is to be 5 A, as follows:

Voltage across the resistor = 240V − 50V
= 190V

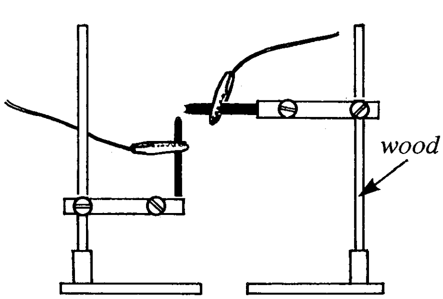
Assume Ohm's Law applies

$\therefore R$ = P.D./CURRENT = . . ? . ./. . ? . .
= . . ? . . ohms

That resistor must get rid of a lot of heat; so it must be carefully mounted and protected.

A measurement When you have finished the calculation, ask for a group of several 500-watt radiant heater elements already connected in parallel. Measure the resistance of that group with a battery and voltmeter and ammeter. If your result agrees reasonably with the resistance you calculated, your teacher can use the group of resistors to make an arc run.

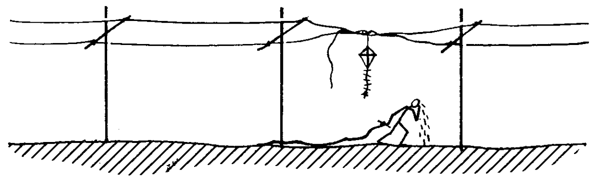
Demonstration The arc carbons are held in *wooden* stands, and connected as in the sketch.



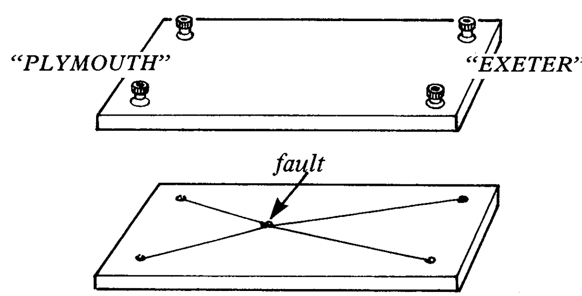
There must be a shield to prevent direct light reaching your eyes, because the arc is too bright for them. But you can see the arc by using a lens to project a real image of it on the wall.

Experiment 130
Fault finding *(OPTIONAL)*

Pretend a pair of overhead telephone wires, the lines from Exeter to Plymouth, have developed a fault. At some unknown place on the way one wire has sagged across the other and made a short-circuit which prevents telephone calls.



Act as a telephone engineer and find out where the fault is. You have a battery and ammeter and voltmeter with which you can make tests at the Exeter end. Then take them to the Plymouth end and make tests there.



under-side of the board

When you have worked out where the fault must be, uncover the wires and see if you are right.

Progress Questions

1a. How many amperes does 1 volt drive through 1 ohm of resistance?

b. How many amperes will 6 volts drive through 1 ohm of resistance?

c. How many amperes will 6 volts drive through 2 ohms of resistance?

2. The mains voltage connected to an electric heater is 240 volts. The heater takes 4 amperes. What is its resistance?

3. A lamp is marked 240 volts, 120 W. It is run on the 240-volt mains with an ammeter in series. The ammeter reads 0.5 A.

a. Calculate the resistance from that information.

b. If you measured the resistance of the lamp with a 1.5-volt cell, and an ammeter and a voltmeter, would you expect to get the same result as your answer to (a)?

c. Give a clear reason for your answer to (b).

d. Describe an experiment (that you saw or did) which supports your answer to (c).

4a. If there is a voltage of 2 volts, and 600 coulombs moves through a wire, how much energy is transferred?

b. If this energy simply raises the temperature of the wire, what kind of energy has been produced?

c. If this energy makes a motor turn, what kind of energy has been produced?

5. A current of 2 A is driven by a voltage of 12 volts for 1 minute.

a. How many coulombs are moved round the circuit?
(Reminder: *coulombs* = *amperes* × *seconds*)

b. How much energy in joules is transferred?

c. How much energy is transferred *per second*? (That will be in *joules per second*, which means *watts*.)

Questions

6a. How much current is taken from 240-volt mains by a 60-watt lamp?

b. A rheostat is marked '200 watts'. This means that 200 watts is the maximum rate at which the whole of its winding can safely transfer energy to heat. The rheostat is also marked '10 A'. This means that 10 A is the maximum safe current through any or all of its windings. With larger currents the windings may overheat and loosen or break. What is the largest p.d. that can safely be put across the terminals of this rheostat?

c. When a p.d. of 12 volts is connected to an electric lamp, it takes 3 A. How much power does the lamp take?

7. What does 'Ohm's Law' say? When or where is it likely to be useful?

a. What current does a 6-volt battery supply when joined to a 2-ohm resistance?

b. When a 200-ohm resistance is joined to the mains, the current is 1.15 A. What is the mains voltage?

c. A 2-volt accumulator is joined to a resistor and an ammeter which reads 0.25 A. What is the resistance of the circuit?

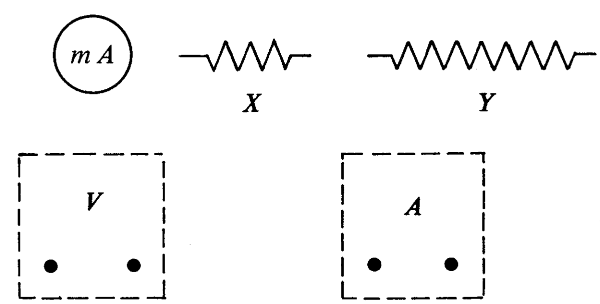
8a. What current would a 2-volt accumulator supply when joined to resistances of 4 ohms and 6 ohms in series?

(OPTIONAL EXTRA QUESTION)
b. If the resistors were joined in parallel, what current would then be supplied?

9a. What is the resistance of a 12 V 36 W car headlamp bulb?

b. If you measured the resistance with a 1.5-volt cell and a milliammeter, you would *not* get this result. Explain why.

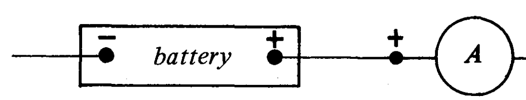
10. The sketch shows a milliammeter (mA), and two resistors, X a very low resistance of thick wire, Y a very high resistance; also two boxes, one labelled V for voltmeter, the other A for ammeter, with terminals to receive wires of a circuit.



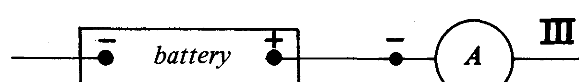
Draw the two boxes larger and draw in them the things from the sketch that would make a voltmeter and an ammeter. Label the things you put in each box, and show how they are connected.

11a. Sketch I shows a battery. Copy it and label the + end.


I



II



III

b. Sketches II and III show a circuit with a battery and an ammeter each with the + terminal marked. Which is the correct way to connect the ammeter II or III?

12. In your experiment with a transistor, a tiny current was amplified to a much larger current. Did your transistor also amplify POWER, produce more power from nowhere? If so, does that fit with Conservation of Energy? If not, where did the extra power (if there was any) come from?

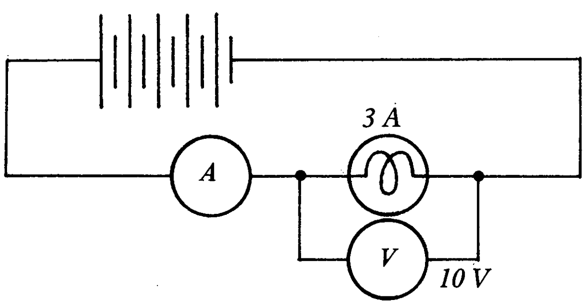
CHAPTER 13

POWER IN ELECTRIC CIRCUITS

POWER IN A CIRCUIT

Now that you are familiar with voltmeters you can measure electrical POWER. That is the rate at which energy is transferred between electrical form and other forms (chemical, mechanical, heat . . .).

For example, in the circuit sketched the voltmeter connected *across the lamp* shows the energy-transfer *in the lamp* for every coulomb passing through it.



Suppose the ammeter reads 3 A. The current through the lamp is 3 A. What does that mean? *That means 3 coulombs pass through the lamp each second.*

Suppose the voltmeter reads 10 volts. What does that mean? *That means each coulomb passing through the lamp delivers 10 joules.*

How fast is energy being delivered to the lamp? Try multiplying:

CURRENT × VOLTAGE = POWER

$$3\frac{\text{coulombs}}{\text{seconds}} \times 10\frac{\text{joules}}{\text{coulombs}} = 30\frac{\text{joules}}{\text{seconds}} \text{ or } 30\text{watts}^{*}$$

* We call a *joule/second* a *watt*, just as a shorthand name. No experiment is needed to show that 100 *watts* is the same as 100 *joules per second*. Watts is merely a name for joules per second.

Dictionary

AMPERES	*coulombs per second*
VOLTS	*joules per coulomb*
WATTS	*joules per second*
OHMS	*volts per ampere*

Cancelling units Current is measured in *amperes*, which are *coulombs per second*.*

One ampere means 1 coulomb passes in each second, or 2 coulombs pass in 2 seconds or 10 coulombs pass in 10 seconds. And 5 amperes means 50 coulombs pass in 10 seconds. Then just divide:

$$\frac{50 \text{ coulombs}}{10 \text{ seconds}} \text{ brings us back to } \frac{5 \text{ coulombs}}{1 \text{ second}}$$

or 5 coulombs per second.

So coulombs per second are calculated by dividing $\frac{\text{coulombs}}{\text{seconds}}$

Use that form in cancelling units:

3 amperes × 10 volts

= 3 coulombs per second × 10 joules per coulomb

$$= 3\frac{\text{coulombs}}{\text{seconds}} \times 10\,\frac{\text{joules}}{\text{coulombs}}$$

$$= 30\frac{\text{joules of total energy-transfer}}{\text{seconds of total time}}$$

= 30 joules per second

Cancelling units will often help you to make sure you have done a calculation the right way. Multiplying the units as well as the numbers gives a check of what you are doing. The units must

* Note that 'per' (or the sign /) means 'in each' or 'for every', as well as 'divided by'.
Examples: the PRICE of eggs *50 pence per dozen*; the SPEED 50 *kilometres per hour*.

cancel down to the proper unit for the thing you are calculating—if not, you are making a wrong calculation.

Here is an example for fun.

Suppose a big block of flats is supplied with bread by a number of bakers' men each delivering several loaves. Suppose we know the number of bakers' men passing through the block of flats per day—that is the current in men per day. Suppose we know the amount of bread delivered by each man, in loaves per man—that is like the potential difference. Now we multiply the two together and we have, for example, [6 loaves per man] × [10 men per day], which is

$$6\frac{\text{loaves}}{\text{men}} \times 10\frac{\text{men}}{\text{days}} = 60\frac{\text{loaves}}{\text{days}}$$

so 60 loaves are delivered to the flats each day.

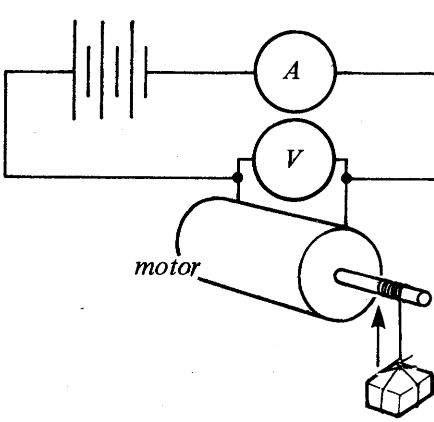
If we make a mistake and divide instead of multiplying, we have

[6 loaves per man] ÷ [10 men per day]
= 0.6 loaf·days per square man

which warns us by its nonsense.

Power for a lamp In a lamp run by a battery the energy-changes are *FROM* chemical energy *TO* electrical energy *TO* heat and radiation. Readings of current and voltage give the POWER, *the total rate of transfer* from electrical energy to heat and radiation.

Power for a motor With an electric motor, you can make two estimates: INPUT POWER by multiplying measurements of VOLTAGE and CURRENT; and OUTPUT POWER by multiplying measurements of WEIGHT and SPEED of a load that the motor is raising.



If the motor is just spinning without any load being raised the *useful* OUTPUT POWER is zero; then the INPUT POWER has a disappointing fate: it is all going to fan the air and thus warm it a little! If the motor is brought to a stop by too heavy a load, its *useful* OUTPUT POWER is again zero. Between those extremes, a motor has a wide range of adjustable behaviour with good OUTPUT POWER.

Experiment 131
Power transferred in a lamp

Arrange a suitable circuit with a voltmeter across to the lamp to show the energy-transfer (measured in joules) for each coulomb that passes through the lamp.

The ammeter shows how many coulombs of electric charge pass through the lamp during each second.

Record your readings of the meters.

Calculate the energy (in joules) transferred *during each second FROM* electrical energy *TO* heat and radiation.

If you write your record in the following way you will find the calculation clear as well as easy:

Specimen record

Current . . . A. This means that:
. . . coulombs pass through the lamp in each second

p.d. across motor . . . V. This means that:
each coulomb transfers . . . joules *FROM* electrical energy *TO* radiation and heat energy in the lamp

Therefore . . . coulombs pass through in one second, each delivering . . . joules.

Therefore the power is . . . $\frac{\text{coulombs}}{\text{seconds}} \times \frac{\text{joules}}{\text{coulombs}}$

. . . joules per second
. . . watts

‡ **Calculations in answering questions** If you always write out descriptions like those above, which begin with
'This means that . . .'
you will make your answers to questions about voltages, power, resistance, etc. very clear.

It is worth the extra trouble to write out these 'rigmaroles' every time, because then you will get your answers right, and at the same time you will show how you arrived at them.

FORMULAE FOR POWER

Now express the rule for power differently. Start with POWER = (p.d.) × (current) = $V.I.$

Then use Ohm's Law in the form:

P.D./CURRENT = a constant, called RESISTANCE; $V/I = R$

POWER = $V \times I = RI \times I = RI^2$

POWER = V^2/R

Such 'formulae' should appear on the front of your examination papers, so there is no point in making a special effort to learn them by heart. You will almost certainly learn them through use.

Experiment 132
Power transferred in a motor

Measure the electrical power taken by an electric motor. Supply the motor from a 6- or 12-volt battery.

Draw a suitable circuit; then connect it up.

Measure the current the motor takes, and the p.d. across it. Then calculate the INPUT POWER for the motor.

If you write your record in the following way you will find the calculation clear as well as easy:

Specimen record

Current . . . A. This means that:
. . . coulombs pass through the motor in each second
p.d. across motor . . . V. This means that:
each coulomb transfers . . . joules *FROM* electrical energy *TO* mechanical energy in the motor.
Therefore . . . coulombs pass through in one second, each delivering . . . joules.

Therefore the power is . . . $\dfrac{\text{coulombs}}{\text{seconds}} \times \dfrac{\text{joules}}{\text{coulombs}}$

. . . $\dfrac{\text{joules}}{\text{seconds}}$

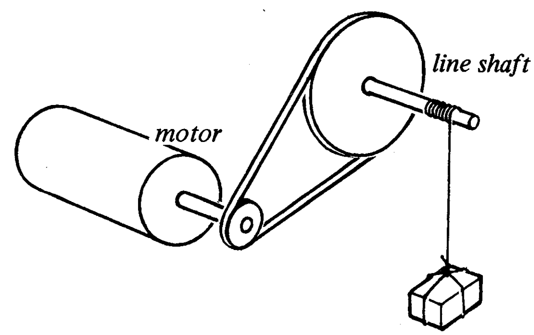
. . . watts

That is all wasted power if your motor is running light with no load. *Where does the energy go?*

Try loading the motor by applying friction with a card or a gloved finger.

Experiment 133
Further experiments with a motor
(OPTIONAL)

(i) Make your motor haul up a load Use the same electric circuit as in Experiment 132 but arrange your motor with a belt to drive a line shaft which winds up a cord to raise various loads ($\frac{1}{2}$ kg, 1 kg, . . .).



Watch the change of input current as you change the load.

(ii) Measure your motor's efficiency Choose one load (e.g. 1 kg) and estimate the efficiency of your motor; that is

$$\frac{\text{mechanical output POWER}}{\text{electrical input POWER}}$$

Multiply that by 100 to express it as a percentage.

To measure the output POWER multiply the WEIGHT of the load (measured in newtons), by the DISTANCE the motor hauls it up *in 1 second.*

Where does the rest of the input power go?

A load to be raised makes a demand on a motor. An electric motor can adjust to such demands over a wide range of loads. What is the useful OUTPUT POWER of your motor when it is asked to raise *no load at all?* What is its OUTPUT POWER when it is asked to raise such a *huge load* that it stalls?

Find, by trial and error, the load that seems to make your motor give its *maximum* OUTPUT POWER.

Maximum power Make a rough estimate of that maximum OUTPUT POWER and compare it with the INPUT POWER for the same load.

Animals and human beings are adjustable like that motor: they can adjust their output FORCE over a wide range, and their OUTPUT POWER behaves rather like that of an electric motor (though for a different reason). Think about your own OUTPUT POWER in raising various loads with a rope and single pulley. Can you prove, even without trying it, that there must be some load for which you can put out *maximum* power?

(iii) Make your motor drive a dynamo which lights 1, 2 or 3 small lamps in parallel.

Measure the INPUT POWER for the motor as before.

Then move the ammeter and voltmeter to measure the OUTPUT POWER from the generator to the lamps—or borrow another pair of meters.

Watch the current and the motor's speed as you turn on more lamps—you are running a miniature power station with your motor taking the place of a steam engine.

Can you estimate the efficiency of the motor-generator combination? It is:

$$\frac{\text{output POWER of generator}}{\text{input POWER for motor}} \times 100\,\%$$

(iv) Let your motor drive a massive flywheel Watch the power input to the motor while the flywheel is accelerating; and again when the flywheel is spinning at constant speed.

When the flywheel has reached constant speed, where is the energy going?

How can you get the energy that is now stored in the spinning flywheel back into electrical form? Try that.

Demonstration 134
Power of a fractional horse-power motor

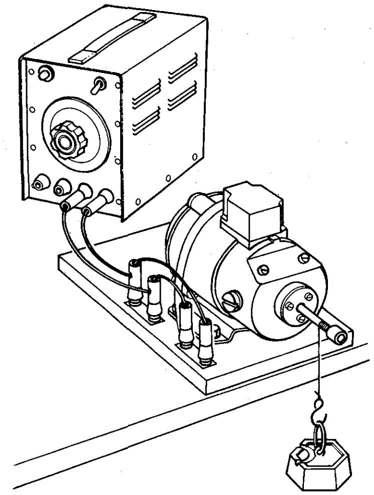
You may see practical measurements on a commercial motor.

If so, calculate:
its INPUT POWER, from electrical measurements;
its *useful* OUTPUT POWER, by

$$\frac{\begin{bmatrix}\text{the FORCE it uses}\\ \text{in raising a load}\\ \text{(WEIGHT of load)}\end{bmatrix} \times \begin{bmatrix}\text{HEIGHT through}\\ \text{which load is}\\ \text{raised}\end{bmatrix}}{\text{TIME taken}}$$

and its overall efficiency by

$$\frac{\textit{useful}\ \text{OUTPUT POWER}}{\text{INPUT POWER}}$$



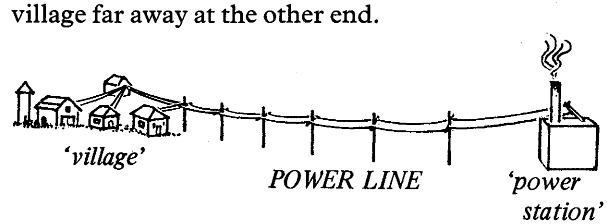
POWER LINES

Electric power is carried across the country from power stations (near coal mines, or shipping ports for oil, or a waterfall) to homes and factories far away. We do not want to waste much of the energy on heating the transmission wires. On the other hand we do not want to make the wires very thick so that supporting them would be an expensive engineering business.

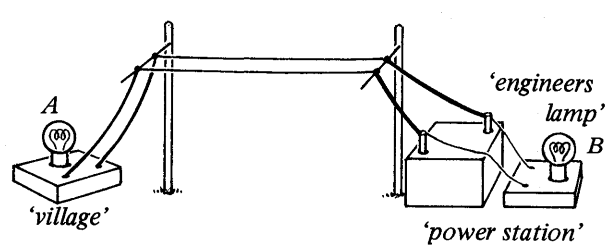
Experiments with the model power line will show you how we solve the problem.

Experiment 135a
d.c. Model power line

Take a battery to represent a power station connected to one end of a power line which feeds a village far away at the other end.



Set up your power line with its thin wires stretched between two tall stands. The wires are made of high-resistance metal to imitate the resistance of a very long, real power line.



Connect a lamp A at the far end of your power line from the power station. That lamp represents the village.

Connect the 12-volt supply direct to the terminals at the near end of the power line.

Also install a lamp B connected straight to the 12-volt supply which represents the power station. That lamp is the power station engineer's reading lamp.

Run your electric power grid and see how well it supplies the lamps. Why does the village lamp suffer?

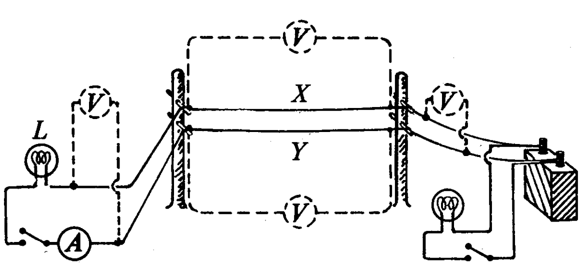
If you like, install an extra lamp at the village, parallel with lamp A. How well does the power system supply those two?

Then see the same model power line run on a high-voltage supply. Since the mains voltage can be dangerous, that is a demonstration.

Demonstration 135b
Model power line at high voltage

Measurements of power line By connecting a voltmeter across various parts of the model power line, you could estimate the power supplied by the 'power station' and the power taken by the 'village' and thence the efficiency of the system.

Experiment 136
Measurement of power in model power line
(OPTIONAL)



Make measurements with a voltmeter across:

the power station
each of the two power-line wires
the village

Calculate the power supplied by the power station, the power taken by the village, and the power wasted on the power-line wires.

Calculate the efficiency of the system, which is:

$$\frac{\text{power taken by village}}{\text{power supplied at power station}}$$

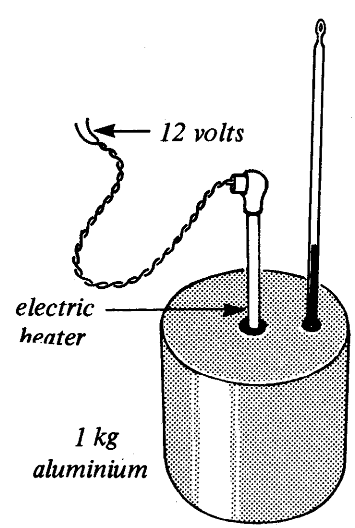
Then see the measurements repeated with a high voltage supply, and again calculate the efficiency.

Specimen Record Table

PART OF CIRCUIT UNDER INVESTIGATION	CURRENT THROUGH PART amperes	P.D. BETWEEN ENDS OF PART volts	POWER DELIVERED IN PART watts
village			
power wire X			
power wire Y	*SPECIMEN*		*Do not write on this table*
power system (village and power wires, by one direct measurement)			
check: total of village $+ X + Y$			
(this table should then continue for the experiment with high voltage)			

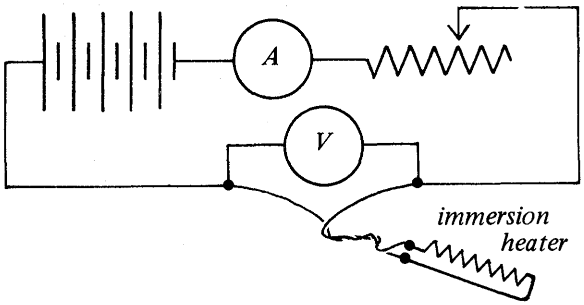
Experiment 137
Electrical measurement of the specific heat capacity of aluminium

(OPTIONAL; an alternative form of the measurement in Chapter 9, which did not use a voltmeter but made a comparison with water instead)



Connect up the circuit as the diagram. The heater is designed to run on a 12-volt supply and deliver 40 to 60 watts. Keep it switched off, until you are ready.

Switch on, and adjust your rheostat quickly to make the current 3 or 4 A. Switch off again as soon as you can.



Before switching on for the main experimental run, wait for 5 minutes to let the block reach a uniform temperature.

Take the temperature, and record it. Switch on and start the clock.

Keep the heater running for a measured time, say 5 minutes.

Switch off. Watch the thermometer and record the *maximum* temperature reached.

Weigh the block to find its mass (measured in kilograms).

Calculate the electrical energy supplied. That will be measured in:
volts × *amperes* × *seconds* (for the time the current ran) or (*joules*/*coulomb*) × (*coulombs*/*second*) × (*seconds*), that is, *joules*.

To calculate the specific heat capacity, divide that energy by the mass of aluminium and by the *maximum* temperature-rise.

That will tell you the energy (measured in joules) needed for each kilogram for each degree rise of temperature. That is called the specific heat capacity of aluminium.

Specific heat capacity of water If you like, repeat this measurement with a saucepan of water instead of the aluminium block. (See the picture on page 174). That will give you the specific heat capacity of water—the energy (in joules) needed for each kilogram of water for each degree rise of temperature. From Chapter 9, you might expect a value about 4200; but your measurement is unlikely to agree closely. (Why?)

Then you can calculate the comparison-number, c-n, for aluminium by dividing specific heat capacity of aluminium by specific heat capacity of water. (Very careful measurements yield 0.22).

Progress Questions

1. Copy the table and fill it in.

Appliance	*Power in watts*	*Energy taken in 12 hours in kilowatt·hours*	*Cost for 12 hours at 6p per 'unit'*
1-bar fire	1000 W		
2-bar fire	2000 W		
Bright lamp	100 W		
Dim lamp	25 W		
Fridge	100 W		
Immersion heater	3000 W		

Note: The Electricity Board calls 1 kilowatt·hour 1 'unit'.

2a. Copy the table below and use WATTS = VOLTS × AMPERES to calculate each current. All these things work off the mains, at 240 volts.

Appliance	*Power*	*Current*	*Fuse needed*
Small fire	1000 watts		
Big fire	2000 watts		
Table lamp	60 watts		
Bright lamp	100 watts		
Fridge			
Hair dryer			
T.V.			
Electric iron			
Kettle			
Immersion heater			

b. You have fuses for currents of 3 A, 5 A, 13 A. In the fourth column in the table, fill in the *smallest*, and therefore the *safest* fuse you would need.

3. Look at the electrical appliances in your house and find out the POWER of each one. Make a chart like the one in Question 2, and fill it in. (*Note* 1000 watts is the same as 1 kilowatt.)

4. When you use a 1000-watt (1-kilowatt) fire for one hour, you get what is called '1 kilowatt·hour' of heat energy.

a. How much heat energy in kilowatt·hours do you get when the fire stays on for 2 hours?

b. How much heat energy in kilowatt·hours do you get when a 2-kilowatt fire stays on for 3 hours?

c. What is 1 kilowatt·hour in joules?

5. When you plug two or more things into one socket, extra current has to flow through the supply wires that go to the socket.

a. Copy Table 1 and use the information in Question 2 to fill it in.

b. Supply wires to sockets are designed to carry a certain amount of current, perhaps 2A in a lighting circuit, or 13A in a ring circuit. It is dangerous to 'overload the circuit'—to have more than the right amount of current. Why?

c. Sometimes a plug becomes very hot in use. Suggest a cause.

6. When you pay for electricity you pay for the number of kilowatt·hours you use. The Electricity Board calls 1 kilowatt·hour '1 unit'.

Copy and complete Table 2.

7a. Table 3 is a sample electricity bill. Copy it and fill in the columns:

b. Ask to see an electricity bill at home. Copy it out, and check the costs.

8. Use [watts = volts × amperes] to find the power in watts of the following.

a. A desk reading lamp, voltage 240 volts, current $\frac{1}{4}$ A?

b. A vacuum cleaner running steadily, 240 volts, 2 A?

c. An electric bell running steadily, 6 volts, $\frac{1}{2}$ A?

Table 1

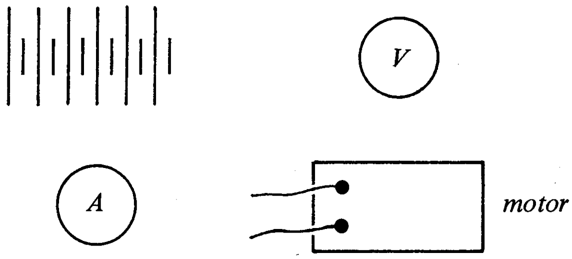
Appliances plugged into one socket	*Total current*	*Will 3 A fuse blow?*	*Will 5A fuse blow?*	*Will 13A fuse blow?*
Small fire, table lamp Big fire, bright lamp, TV Big fire, iron, hair dryer Fridge, iron, kettle				

Table 2

Appliance	*Power*	*Time it is on*	*No. of kilowatt·hours ('Units') used*	*Cost, at 6p per unit*
Small fire	1000 watts = 1 kilowatt	1 hour 10 hours $\frac{1}{2}$ hour		
Immersion heater	3 kilowatts	1 hour $\frac{1}{2}$ hour		
Bright light	100 watts	10 hours		
Table lamp	40 watts	10 hours		

Table 3

Meter readings (units)	*Number of units used*	*Standing charge*	*All units at 6p per unit*	*Total*
987642 987810		£5.30		



9. Here are the pieces of apparatus needed to find the electric power used by a motor.

$$\text{Power (in W)} = \text{Voltage (in V)} \times \text{Current (in A)} = VI$$

So we need to measure V and I.

a. Draw a circuit to show how you would connect the pieces.

b. Now draw another circuit, including a variable resistance, so that you can vary the voltage across the motor.

c. Suppose the motor is marked '12 V'. You wisely arrange for the voltage across it to be 12 volts.

As the motor is lifting a kilogram weight the current reads 0.5 A.

What is the electrical power put in to the motor?

10. You find that the motor in Question 9 takes 5 s to lift the kilogram up through 1 metre.

a. What is the downward force on the kilogram in newtons?

b. So how many joules of energy are needed to lift the kilogram?

c. So how many joules of energy per second does the motor give out in lifting the kilogram?

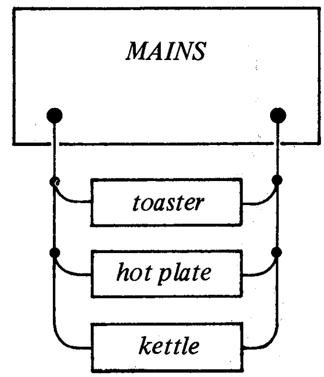
d. 1 joule per second = 1 watt. What is the power given out by the motor in watts?

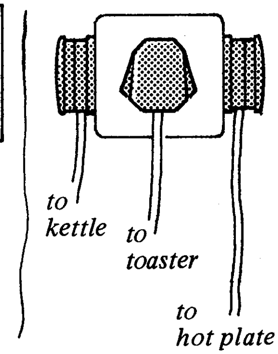
11. You have probably found that for the motor in Questions 9 and 10 the electrical power input is much higher than the mechanical power output. Suggest one or two places where the electrical power put in is wasted as heat.

12. Mr Smith from the Electricity Board called to give advice on the refitting of a kitchen. He saw one wall point connected through a fused adaptor to

a 1.5 kW toaster,
and a 2 kW hot plate,
and a 2 kW fastboiling kettle.

These three appliances were in parallel.





a. If all three appliances were used at the same time, what would the total power consumption be?

b. Electrical power (in watts) = Voltage × Current.

The supply voltage is 240 volts.

What current would be drawn from the mains when all three appliances were being used?

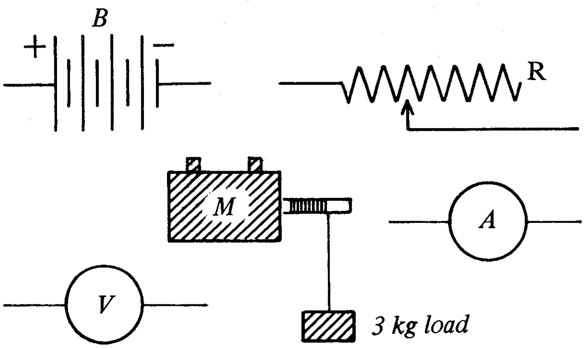
c. Do you think the 13 A fuse in the adaptor would have broken?

d. What advice do you think Mr Smith gave the house-owner?

13. You have an electric immersion heater, which works on a 12-volt supply.

How could you do an experiment to find out the power of this heater (i.e. how many joules per second the heater gives)?

14. M is a small electric motor that runs on a 6-volt supply, B is an 8-volt battery, R is a rheostat, A is an ammeter and V is a voltmeter.



a. Draw a diagram showing these items joined in a suitable circuit. Include the ammeter to measure the current when the p.d. across the motor is 6 volts.

b. How would you ensure that the p.d. across the motor is 6 volts?

c. A 3-kg load is attached to the axle of the motor and can be raised as the motor turns. How would you find the joules of electrical energy supplied to the motor during the time the load is raised 1 metre?

d. What other measuring instrument do you require besides a voltmeter, an ammeter and a metre stick?

15. In an experiment done with the apparatus of Question 14 the motor raises the 3-kg load 1 metre in 8.0 seconds. At the same time, the voltmeter reads 6.0 V and the ammeter reads 2.5 A.

a. How much mechanical energy was transferred in raising the 3-kg load through 1 metre? (Take g = 10 newtons per kilogram.)
b. How many coulombs flowed through the motor in 8 seconds?
c. What does '6 volts' mean? (Explain using joules and coulombs.)
d. How many joules of electrical energy were transferred when the load was raised 1 metre?
e. The 'efficiency' of a motor can be written:

$$\text{efficiency} = \frac{\text{output of mechanical energy}}{\text{input of electrical energy}} \times 100\%$$

Calculate the efficiency of this motor.

What happened to the rest of the transferred electrical energy, which did not appear as mechanical energy?

16. A p.d. of 1 volt means that 1 joule of energy is transferred FROM electrical form energy TO heat, etc. for every coulomb of electricity flowing through or, in short,

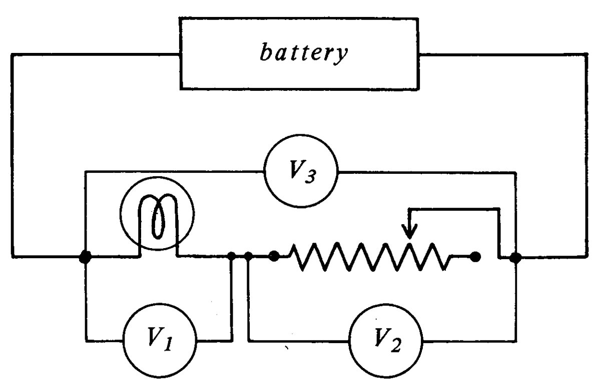
one volt is a name for one *joule per coulomb*

By definition, 1 *watt* means a rate of energy transfer 1 *joule per second.* Also, 1 *ampere* means 1 *coulomb per second* rate-of-flow-of-charge. Use these three definitions, of volt, watt and coulomb, to show that 1 *volt* × 1 *ampere* is the same as 1 *watt.*

17. A factory at the end of a power line takes 200 kilowatts (200 000 watts).

a. The power station at the other end delivers 208 kilowatts to the power line. What happens to the 8 kilowatts difference?

b. Another factory starts work too, taking 200 kilowatts. So the power line has to deliver 400 kilowatts for the two factories.
(i) Is the current in the power-line wires the same as before, or doubled, or what?
(ii) Is the heat wasted from the power-line wires the same as before or doubled or what?
(iii) How did you work out your answer to *(ii)*?



18a. What does V_1 tell you?

b. What does V_2 tell you?

c. The reading of V_1 is 1.2 volts and the reading of V_2 is 2.8 volts. What will the reading on V_3 be?

d. What does V_3 tell you?

e. You move the slider on the rheostat so the current in the lamp gets bigger. V_3 reads the same. V_1 then reads 2.2 volts. What will V_2 read?

19. Mr X lives in a small flat, with no central heating, in a cold part of England. He likes to 'take the chill off' the main room of his flat. So he keeps a 1-kilowatt electric heater running day and night from the 1st October to the 1st June.

a. How much does it cost him, at 6p per kilowatt·hour?

b. For a party, he attaches several more heaters to the same socket. The circuit has a 30 A fuse in it. How many 1 kW heaters can he have (including the original one) without blowing a fuse?

c. When he is running only his original heater, he turns on ten 100-watt lamps. What is the effect of the lamps on the heating of the room
(i) if he has pulled dark curtains over all the windows?
(ii) if there are no curtains (but the windows are shut)?

20. A battery produces a current of 0.6 A when the external resistance is 2 ohms, and 0.2 A when the external resistance is 12 ohms. Find the e.m.f. of the battery. (*Hint.* There is probably some resistance in the battery itself.)

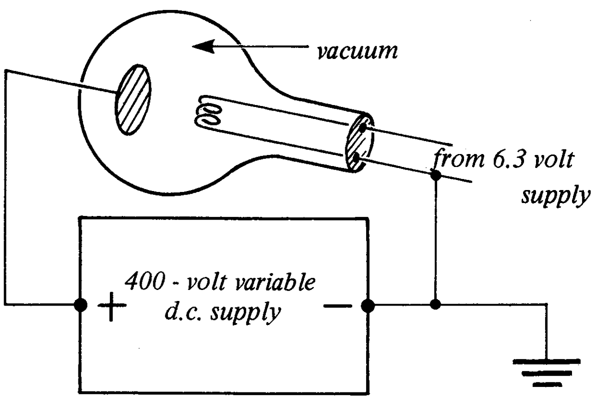
21a. How much current is taken from 240-volt mains by a 60-watt bulb?
b. A rheostat is marked '10 A, 200 W'. This means that 200 watts is the maximum rate at which it can safely dissipate energy (i.e. lose in the form of heat), and that the current is then 10 amperes. What is the largest p.d. that can safely be put across the terminals of this rheostat?
c. When a p.d. of 12 volts is joined across an electric lamp, it takes 3 amperes of current. How much power does it use?

CHAPTER 14

ELECTRONS

CURRENT THROUGH A VACUUM

Can you drive a current through a vacuum? Not unless there are carriers which have electric charges that can be shot across empty space. Try to drive a current across the vacuum in a glass bulb that has been very well pumped out.



Demonstration 138a
The diode as an electron gun

See this device in action. In earlier designs for electronics many small versions of this were used—often a tube a few cm high and a few cm wide, though very large tubes were used in radio transmitting stations.

Take a wire from a high voltage supply to one piece of metal in the bulb, and a wire from the other terminal of the supply to another metal plate in the bulb. Look for a current by inserting a milliammeter.

Now try heating one piece of metal in the bulb. That piece should be a tungsten filament (as in a lamp) which you can heat by sending current through it from a separate battery. Again try to drive a current across the vacuum.

Such a device is called a *diode*. Try applying small, medium and large driving-voltages to the diode when it is in a state to provide carriers. Try reversing the voltages you apply.

The carriers probably come from the heated filament. If so, decide by looking at your milliammeter whether the carriers have *positive* charges or *negative* electric charges. Argue out that decision with your teacher.

We have other evidence which suggests that those carriers are already freely moving about in metals. But they cannot escape until the metal is made very hot, in which case they are able to 'evaporate'.

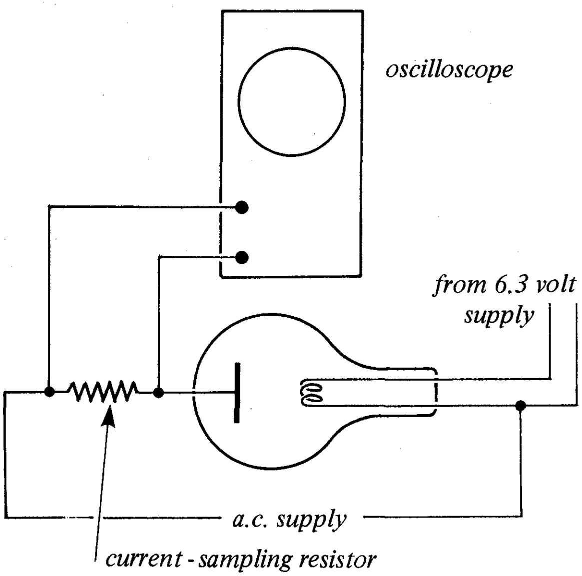
A valve? A diode is sometimes called a 'valve', which is something that lets things through one way, and stops them going through in the reverse direction— for example, valves of a steam engine or a car engine, or the valves in your own body that prevent blood from flowing backwards. Later on, you will put another type of diode to good practical use as a valve.

Demonstration 138b
The diode as a rectifier, shown on the oscilloscope

Heat up the filament, connect the diode and a resistor in series to a low voltage a.c. supply.

When the supply succeeds in driving a current through the diode there will be a p.d. between the ends of the resistor. So the resistor can act as a sampling resistor to show the current on an oscilloscope screen. Run leads from the sampling resistor to the vertical input terminals of the oscilloscope.

Before you see what the diode does, just look at the a.c. wave-form on the screen. Then try to guess what the wave-form will look like when the diode is there, acting as a 'valve'.

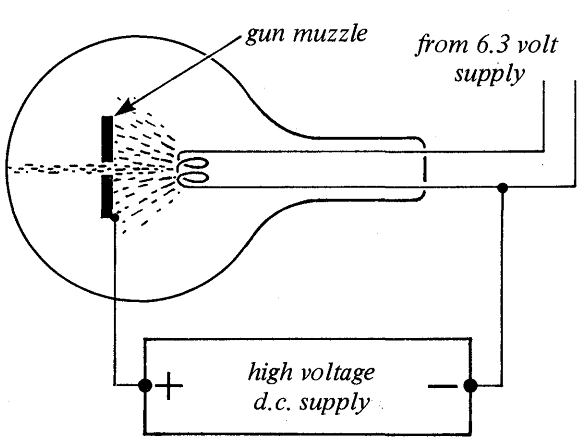


Then see the wave-form with the diode in action.

We say the diode acts as a 'rectifier' because it straightens out the backwards-and-forwards current to a series of one-way humps straight ahead. That bumpy product could be used to charge a car battery: ordinary a.c. could not.

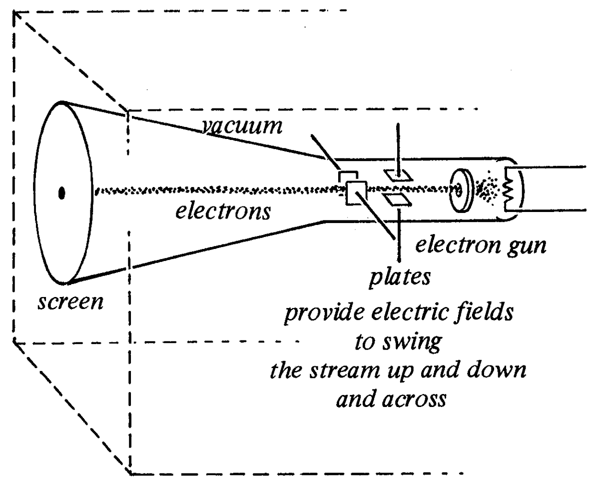
If you like, you could carry this one stage further and make a 'full-wave rectifier' arrangement with four diodes.

A gun? Suppose you drilled a hole in the cold receiving plate in a diode. Then some of the carriers would reach the hole instead of hitting the plate, and they would have to go straight on through. Then you would have a gun which would make a stream of these carriers come out through the hole in the plate.



THE IDEA OF AN ELECTRON GUN

Your TV picture tube has just such a gun, to fire the electrons straight out to the screen in the tube. There the electrons make a bright spot by exciting a glow in the screen. But on their way they can be pulled up or down and left or right by electric or magnetic fields.

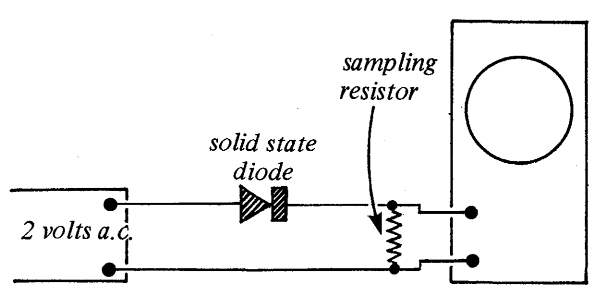


In the oscilloscope that you use, electric fields move the electron stream. In television tubes that is done by magnetic fields.

Modern diodes We still have electron guns, in TV picture tubes and oscilloscopes, with a hot metal cathode emitting electrons. But, for most other purposes, the hot metal is now replaced by a semiconductor: the diode has become a small cool element like a transistor. See an experiment with such a solid-state diode, or, if possible, try it for yourself.

Experiment 138c or d
Solid-state diode as a rectifier

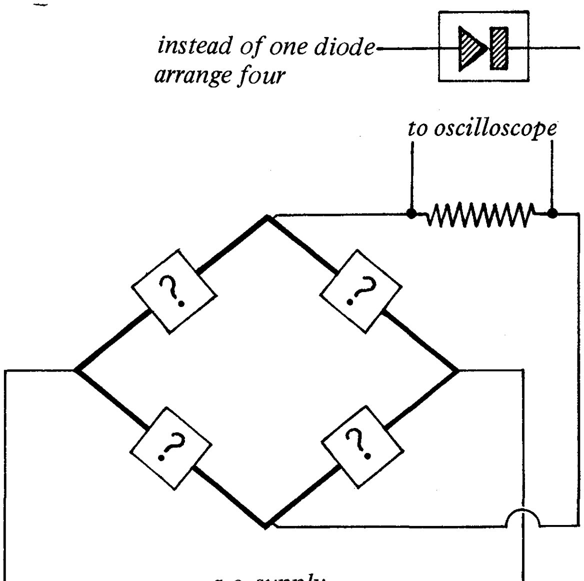
Connect the diode to the transformer and the



sampling resistor (1500 ohms) as in the diagram. Take leads to the oscilloscope.

Experiment 138e
Full-wave rectifier *(OPTIONAL)*

Arrange a 'bridge' circuit as in the diagram. Think about the way to arrange the four diodes so that in the course of a cycle of the a.c. supply current will go through in *each* half cycle and make humps in the same direction. The sketch does not show you which way each diode must point. You need to decide that.

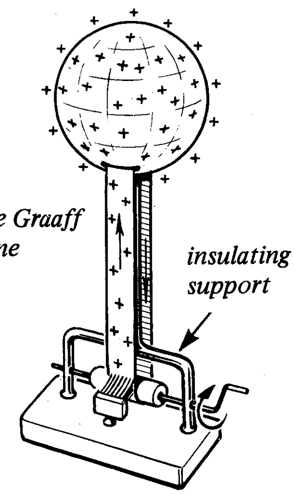


†COULOMBS AT REST: EXPERIMENTS FOR CATCHING UP

† If you saw experiments with electric charges at rest, pushing and pulling each other, you are ready to understand Millikan's experiment on electric charges. It is one of the most important experiments in all modern physics; and you should go straight ahead now and see a film of it; and discuss the evidence.

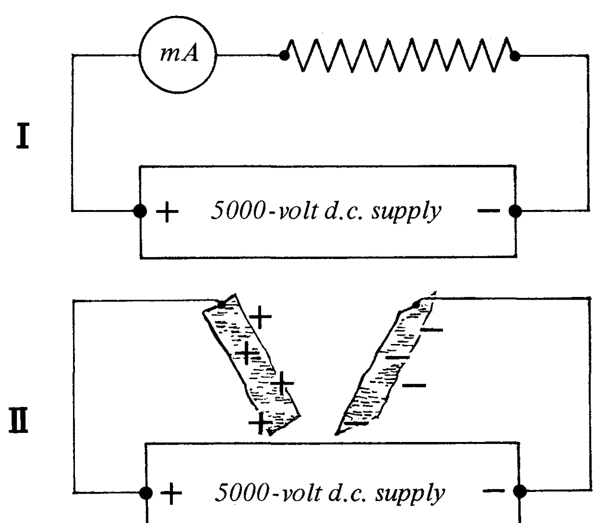
If you missed all experiments with charges at rest, see some of the quick demonstrations described below; but do not let them take much time, because the only point of seeing them now is to prepare for Millikan's experiment. See them then go straight ahead to Millikan's experiment. It prepares for atom models next Year; and postponing it would hurt your progress in modern physics.

Coulombs at rest (We had better say **micro-coulombs at rest**; because the charges we command in these experiments are only a few millionths of a coulomb at most. Yet they are the same kind of things, charges of electricity, as the coulombs that travel in electric circuits.)



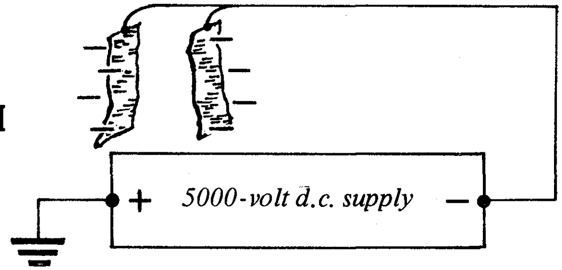
Demonstration 139a
'Battery' makes current or stores charges: compare with Van de Graaff

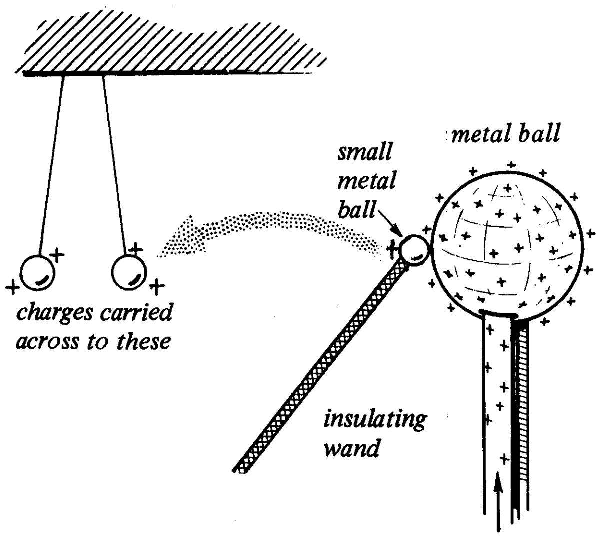
A power supply (equivalent to a big battery) can continue to drive a current (diagram I) *or* it can drive momentary currents onto flexible sheets of thin metal and store + and − charges there.

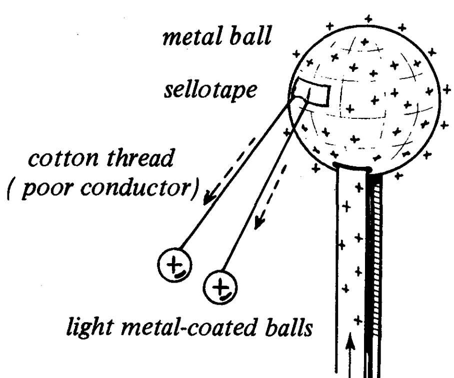


See those 'opposite' charges *attract* (diagram II).

III



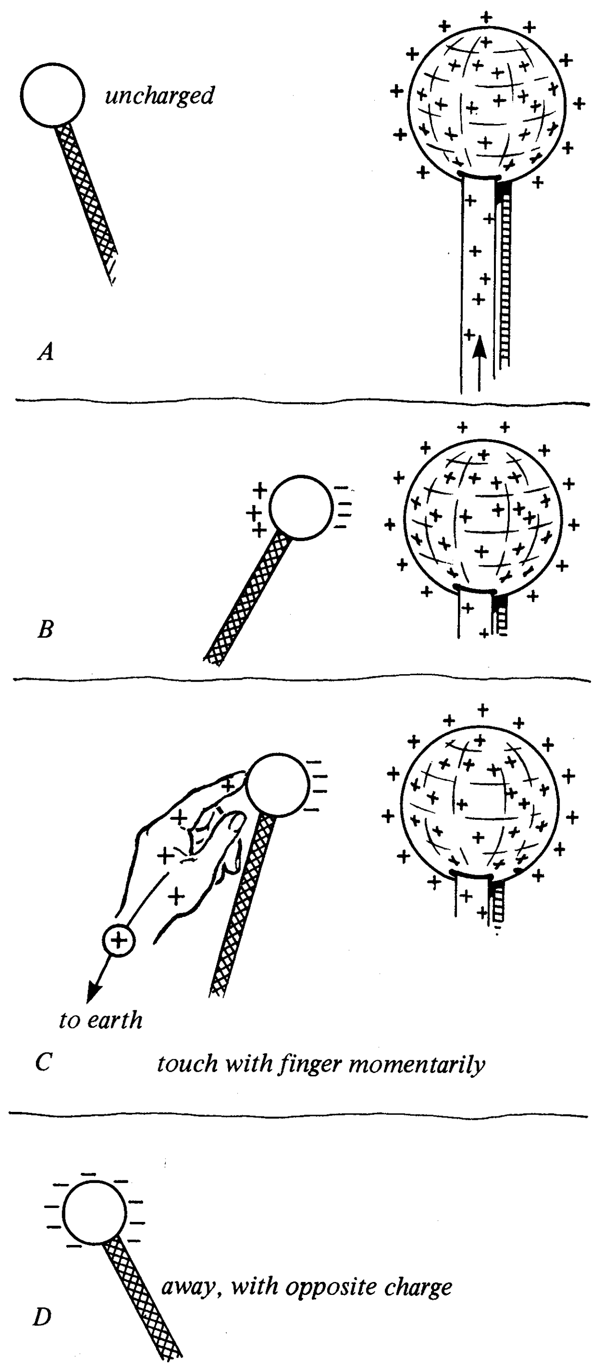




Also see two lots of 'like' charge *repel* (diagram III).

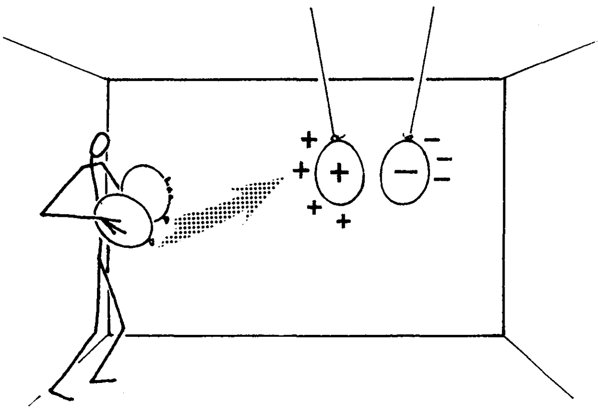
With larger charges from a big store on a Van de Graaff machine the repulsion is easier to see.

By a special trick, we can obtain an opposite charge from a Van de Graaff store: bring an uncharged metal ball *near* to the store so that the store pulls an *opposite* charge and pushes a *like* charge away on the ball. Touch the ball and let that like charge run away to earth; then bring the ball away with the remaining *opposite* charge on it. See how that attracts another ball with a sample charge direct from the store.

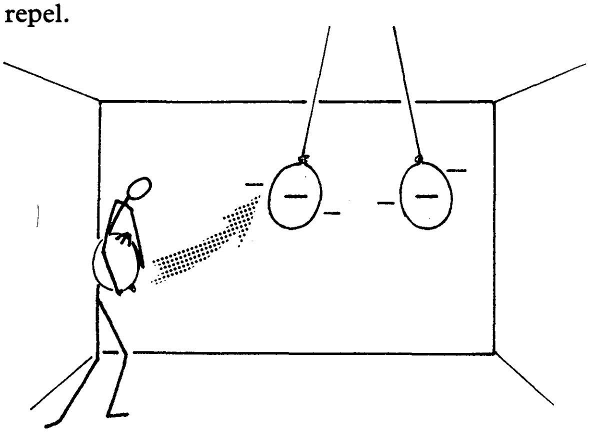


Demonstration 139b
Scraping charges off atoms

Rub two balloons against each other. One will scrape a little extra charge off the other. Then with opposite (‘*unlike*’) charges the balloons attract.



Rub each of two balloons on your sweater. Each scrapes some of the same kind of charge off the fabric. See those balloons (with ‘*like*’ charges) repel.

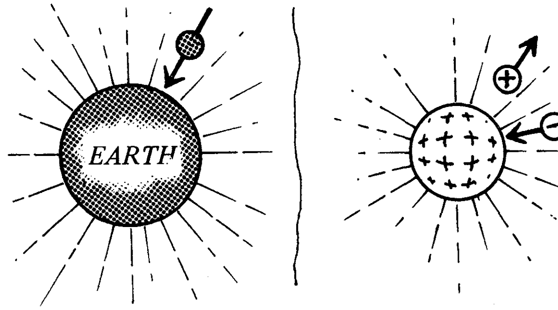


Summary For those tiny charges of micro-coulombs, you can sum up this behaviour:

LIKE CHARGES REPEL
UNLIKE CHARGES ATTRACT

Patterns of electric fields We say there is an ‘electric field’ that spreads out from any electric charge, ready to grip on any other charge and exert a force on it. That is much like the gravitational field that spreads out from the Earth (or Moon or any other mass) ready to grip on another mass and pull it.

You can see the pattern of the Earth’s gravitational field by letting small objects fall: vertical straight lines towards the Earth. Now see some electric-field patterns—if you missed seeing them before.



field, ready to pull on any mass

electric field ready to push or pull any charge

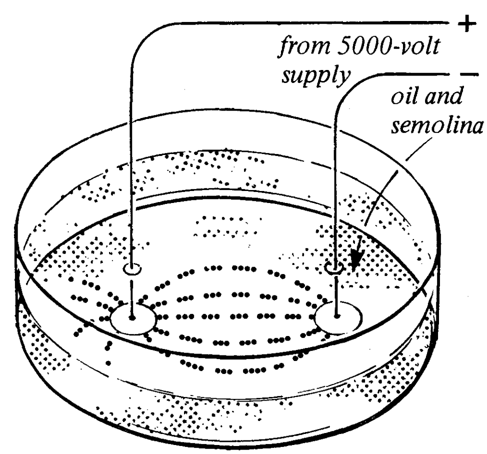
Demonstration 139c
Electric field patterns

Drive charges onto small metal plates immersed in insulating oil.

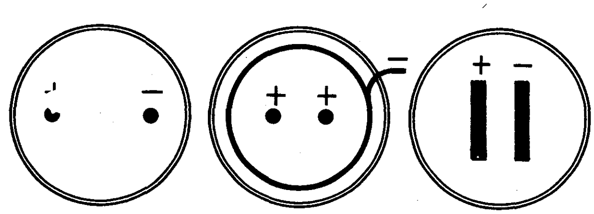
Grains of semolina cereal behave like electric compass-needles and gang up into lines that show the direction of electric field forces.

See three patterns which illustrate forces—just as magnetic-field patterns do for forces between magnets:

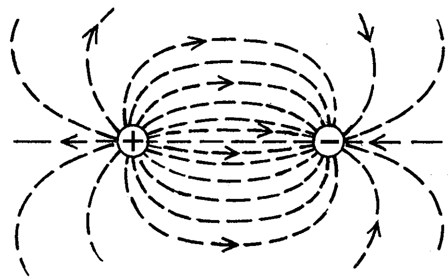
A + and − charges attract
B + and + charges repel

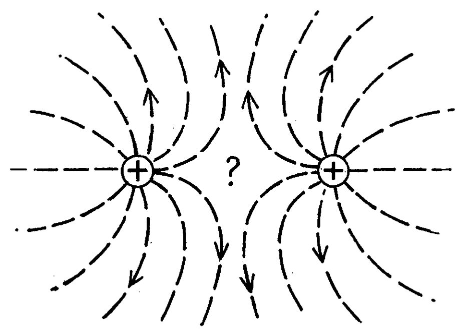


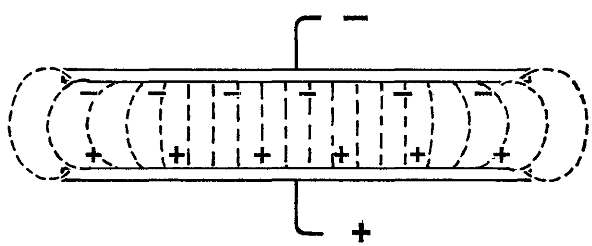
patterns made by grains of semolina



A *B* *C*







C wide plates with + and − charges show a 'uniform' field in the space between them. We use such a field in Millikan's experiment.

A stream of electrons See an electron gun in action, with a special arrangement to make the stream visible.

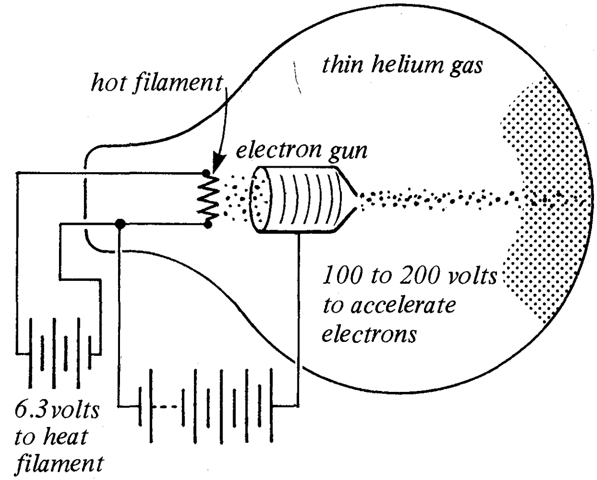
Demonstration 140a and b
Fine beam tube

A little, very dilute gas in the globe makes the stream visible. Electrons bombard that gas and excite a faint glow as the damaged gas atoms recover.

Description. At one end of the tube there is a little cone-shaped 'gun'. In that gun a starting plate is heated by a tiny electric grill.

The plate has a special surface that lets electrons loose rather easily. Electrons boil off that plate. They are speeded up in the gun by a large voltage between that starting plate ('cathode') and the gun muzzle ('anode').

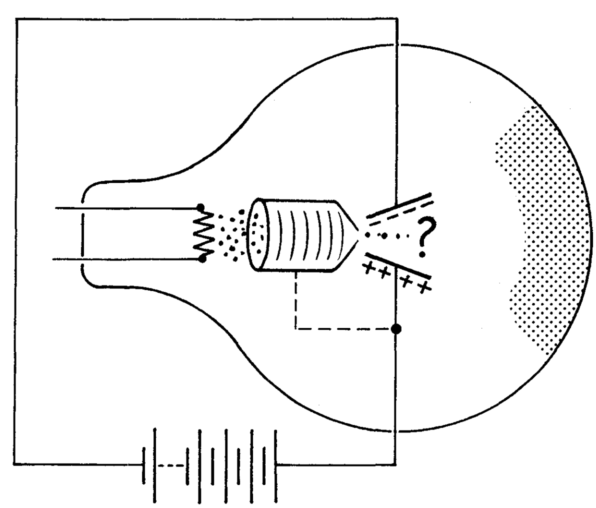
Electrons come out at high speed through a tiny hole in the cone-shaped muzzle.



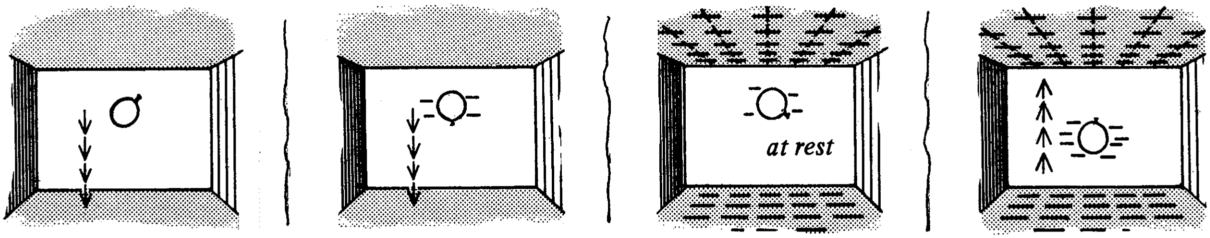
(We can calculate their speed from some measurements. It is more than 5 000 000 metres per second (more than 20 million kilometres per hour or 12 million miles per hour!)

The electrons continue at that constant speed to the end of the tube and make a bright spot where they crash against the mineral screen.

This is like an oscilloscope tube, but naked so that you can see inside. The tube in a cathode ray oscilloscope or a TV picture tube has an electron gun just like that: but here the stream from the gun muzzle is made visible. This glass globe has been pumped out to a very good vacuum to remove air, which would soon slow electrons down by collisions. But then a *very little* helium gas is let in, because the helium atoms give out a green glow when hit by electrons.*



*A similar tube of another make has a thin atmosphere of hydrogen, which makes a faint blue glow, instead of the green glow of helium.



The electron stream. So you can see the path of the electrons as a thin line of glow. Look at that carefully. You are seeing the path of electrons flying through thin helium, almost a vacuum, all by themselves, with no wires there.

Pulling the electrons aside. Use a battery to put + and − electric charges on the small plates just outside the gun muzzle. Those pull and push the electrons upward (or downward) and you can see the stream making a bend there. This is how the stream is deflected in an oscilloscope.

What would you expect to see if we applied an alternating voltage to the plates?

THE BASIC ELECTRIC CHARGE: ARE ALL ELECTRONS THE SAME?

Does electric charge—electricity—always come in tiny packages, all the same, one electron charge? If so, here is another case like atoms, of something packaged in unsplittable units*—knowledge of this has changed all our thinking-pictures in modern physics.

We have other evidence that there are electrons. We can measure their mass, and their momentum and kinetic energy when they are moving. We can even register their passage through air and see their tracks in a cloud chamber or count them with a Geiger counter or a more modern equivalent. We know that each carries a negative charge. But are all those charges the same size**; and do they set a limit of the smallest charge we can have?

How do we know the tiny basic charges are all the same? See a film of Millikan's experiment which gave scientists that assurance. Here is a general preparation and explanation for that.

The floating balloon: a thought experiment Imagine an ordinary balloon, blown up and released in the lab. It will float slowly down to the floor (because its total WEIGHT is greater than the BUOYANT FORCE due to surrounding air). Now imagine you have given the balloon a negative charge of electricity. It would still float down to the floor as before, because the charge on it would not experience a strong new force.

But now imagine the ceiling is covered with a huge positive charge and the floor covered with a huge negative charge—a vast pair of parallel plates, charged + and −. Now the balloon will be pushed upwards by the charges on the floor and pulled upwards by the charges on the ceiling. You *could* adjust the charges on floor and ceiling to be just the right size to hold the balloon poised, at rest in the middle of the room. Then the upward force due to those electric charges, acting on the balloon's charge, must just balance the net pull of gravity downward.

But if you then change the charge on the balloon it will no longer be poised. Suppose you double the balloon's charge: it will float *upward.* You could stop that by changing the floor and ceiling charges. Halve them; then their force on the balloon's doubled charge will again poise the balloon at rest.

In our form of Millikan's experiment, we poise a very tiny 'balloon' in the space between two plates (like floor and ceiling). In every case we make the upward force balance the downward pull of gravity on the tiny 'balloon'.

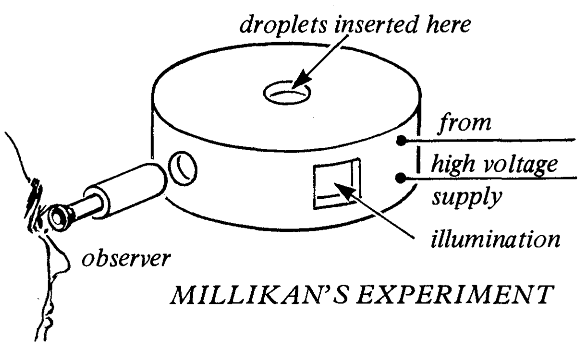
* Are electron charges unsplittable? For a long time we have believed they are. But you may now hear of tiny particles called 'quarks' with fractional charges like $\frac{1}{3}$ of the electron charge *e*. The quark was a theoretical guess to help in making 'thinking-pictures' of atoms. Perhaps it is only imaginary; but experimenters have set out to look for real quarks.

** As a warning, note that for many years chemists and physicists were sure that all atoms of chlorine must be exactly alike. But now we know that ordinary chlorine is a mixture of two kinds of atom, Cl^{35} and Cl^{37}, the rarer kind 6% more massive—yet both have the same chemical properties. On the other hand, a search for different sizes of electron charge has yielded no success, except for the recent suggestion of quarks.

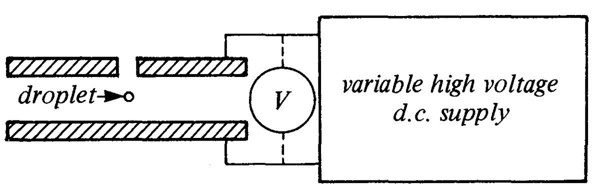
That is what you see in the Millikan film. The 'balloon' is not a real toy balloon full of air. It is a very tiny ball of solid plastic, which you, or the camera, can just see with a small microscope. In Millikan's original work, it was not a plastic ball but a tiny drop of oil from a spray. So we shall speak of it as 'the droplet' although in the film it is a plastic ball. (Tiny balls of plastic are more convenient for the film because many can be manufactured all the same size—then if the experimenter loses one from his field of view he can pick up another and use it to continue the experiment.)

Film 141
Are there electrons? The Millikan experiment

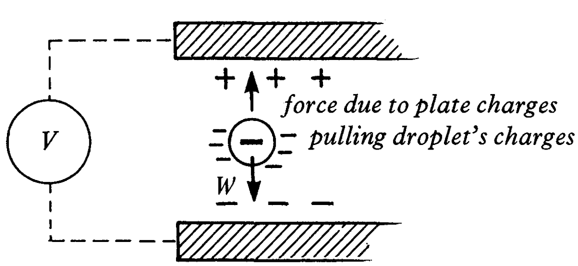
Watch the film, if possible in short stretches, viewing some parts of it several times.



MILLIKAN'S EXPERIMENT



In the film, the droplet starts with a small electric charge, gained by chance collisions with ions in the surrounding air. The voltage between the plates is adjusted to hold the drop poised; and the voltmeter reading is recorded.



Then the charge on the droplet is changed. Ions are made in the air near it (by X-rays or by radium) and the droplet picks up a further charge in a collision. It is poised again, and the new voltage recorded.

The argument for the film Here is how the droplet is poised. Suppose it has a negative charge. The battery drives equal and opposite charges on to the two plates, + above and − below. Those charges on the plates together push and pull the droplet upward (while gravity pulls it down).

Two batteries in series, with *twice* the voltage, will drive twice as much charge onto the plates. Then the upward force on the droplet will be twice as big.

The voltmeter tells us how much charge we are putting on the plates, how big the force on the droplet will be.

There are two factors which affect the upward force:
(a) The charges on the plates, which we can estimate by the voltage V that we apply to the plates;
(b) the charge carried by the droplet (which we want to find out about).

We multiply those two factors to find a measure of the upward force; and the result must *always be the same* if the upward force always balances the droplet's net weight (VOLTMETER READING, V) × (DROPLET'S CHARGE) = same answer every time
∴ DROPLET'S CHARGE = (constant) × $(1/V)$

For several different charges on the droplet, we read the voltmeter each time and calculate the value of $\frac{1}{V}$. Then we look at the whole series of values of $\frac{1}{V}$ for successive (unknown) charges on the droplet. We ask the key question, 'Does this record show signs of there being one basic, unit, charge?

On the next page there is a question that may help you to understand the argument:

Question

1a. Mr X has several paper bags of eggs. They are sealed up and he does not know how many eggs there are in any of the bags. To find out, he weighs each bag of eggs:

One bag weighs 350 grams
another weighs 300 grams
others weigh 450, 200, 250 grams.

Guess how much each egg weighs.

b. Explain how you got your answer to (a).

c. If you are right about the weight of an egg, how many eggs are there in each of the five bags?

d. Suppose Mr X has one more bag of eggs, and, when he weighs it, he finds it weighs 325 grams. You would now have to alter your guess for the weight of an egg—to what? Otherwise you would have to suppose that the last paper bag had an odd half egg in it, and paper bags do not hold half eggs!

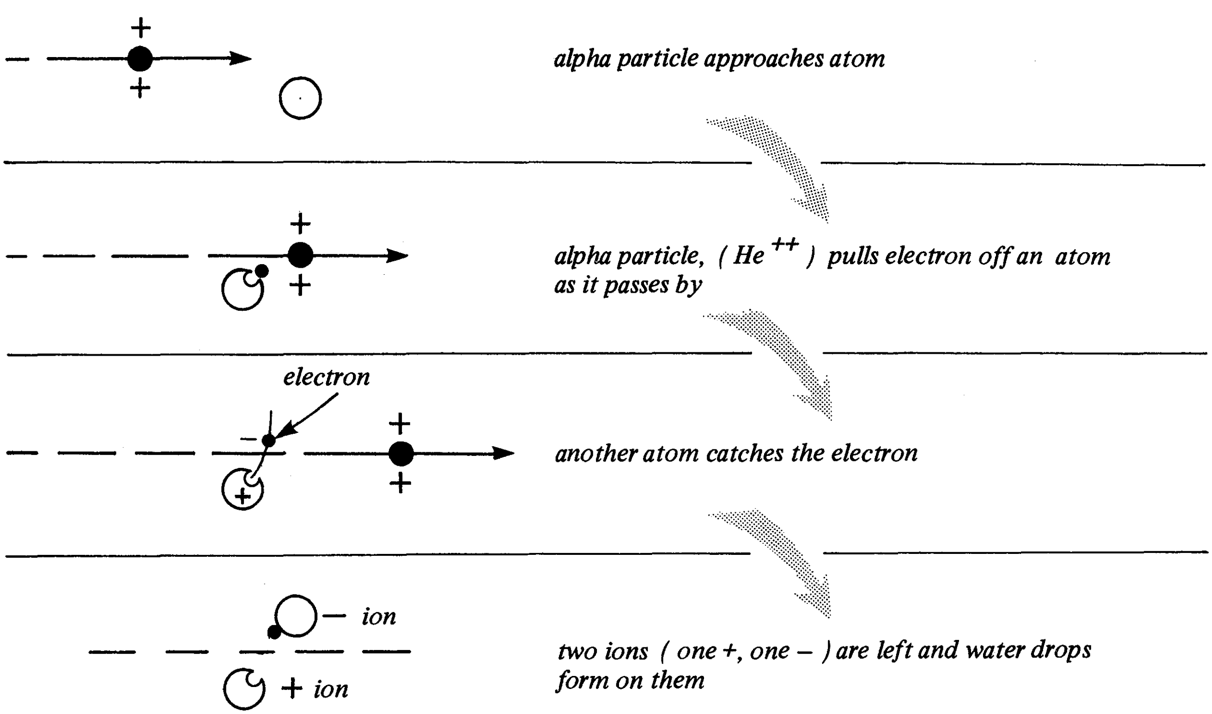
(But Mr X did not have a bag weighing 325 grams, so you can keep your previous estimate of the weight of an egg—realising all the time that you might be wrong. You would feel much more certain about it if he weighed many more bags and never found anything different from 50, 100, 150, 200 grams.)

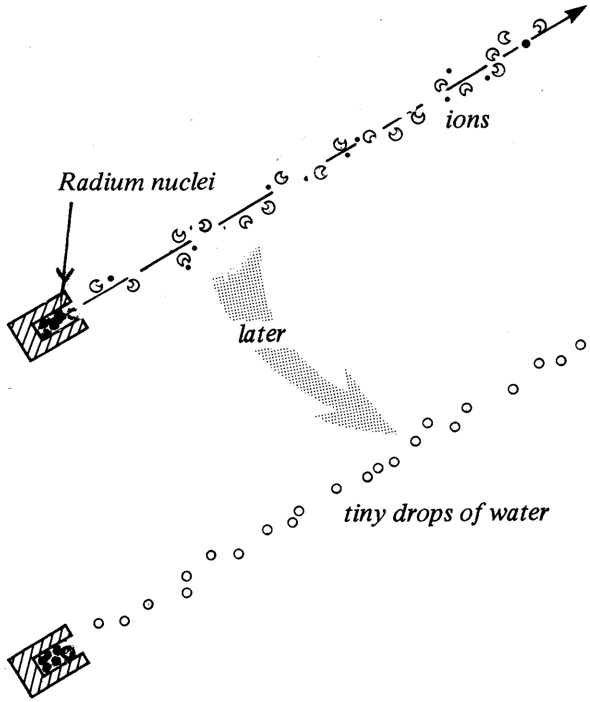
Like Millikan's original experiment, the film suggests that there *is* a basic charge, which we call the electron charge, *e*. For your present knowledge, that is a more important idea than a measurement of the actual size, in coulombs, of that charge *e*. The film goes on to show that measurement. Watch that part too, if you like, but it is optional.

IONS IN AIR

You have seen the faint glow of excited gas in the fine beam tube. Bombarding electrons have 'damaged' some atoms of gas and the glow is emitted as the atoms recover. In many cases of damage, an electron belonging to an atom is pushed out by a bombarding electron. The remainder of the atom is then a positive ion. (An ion just means a traveller. Charged atoms travel when an electric field is applied.) The ejected electron wanders away and is soon caught by some neighbouring neutral atom which then becomes a negative ion.

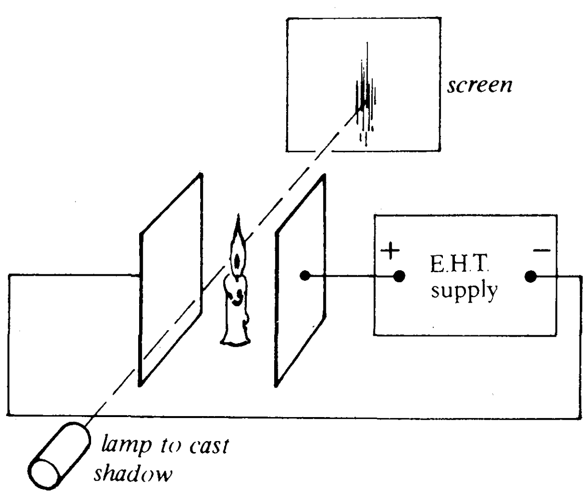
You have already heard of such ions in electrolysis. Those are ready-made. Even in a solid crystal of salt, the Na^+ ions and Cl^- ions are there waiting to travel and carry currents when they are let loose in water. But here, in gases, ions are made by bombarding neutral atoms or molecules.





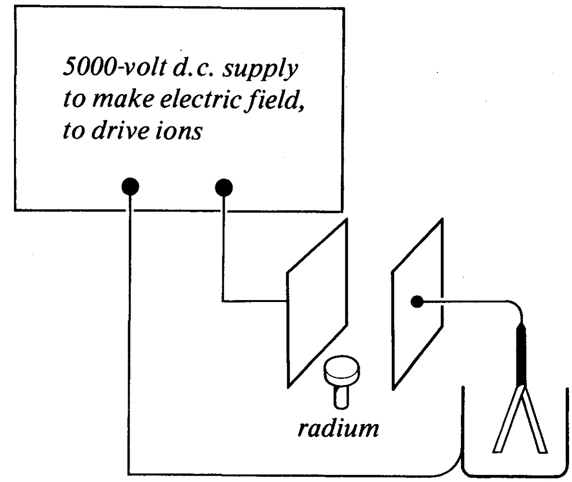
Nuclear 'bullets' from radioactive atoms make the tracks in a cloud chamber. They hurtle through wet air, detaching an electron from atom after atom, leaving a trail of ions in their path. Then drops of water are made to condense on those ions, making the path visible. (See figure on preceding page.)

Demonstration 142
Ions in a candle flame, driven by an electric field



See the demonstration sketched. Flames are rich in ions.

Demonstration 143
Radium makes ions in air



See the demonstration sketched. A small, safe sample of radium does not make enough ions for the battery to drive a current of them that you could see on a galvanometer. We have to show the ions are there by letting them carry charge to an electroscope.

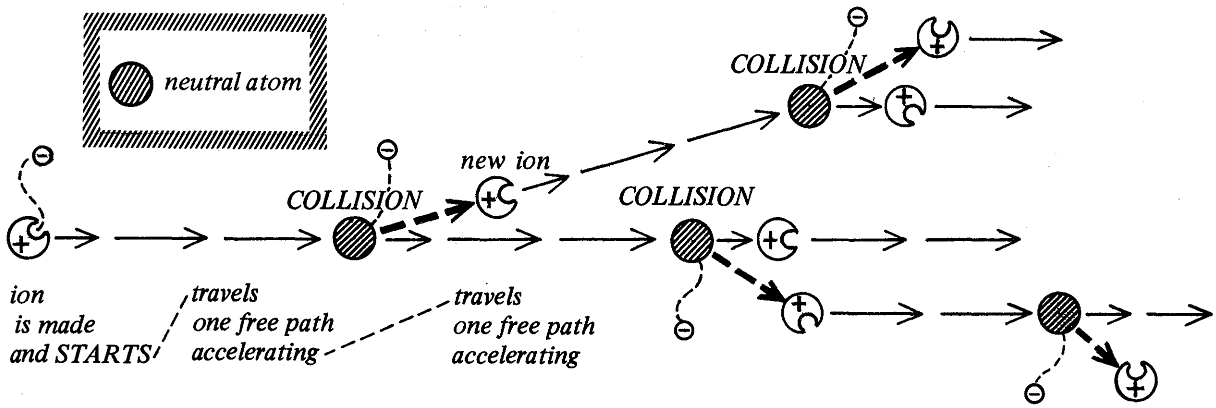
MULTIPLICATION OF IONS: SPARKS

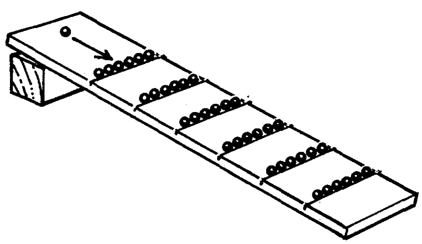
If we apply a large voltage and make a very strong electric field we can drive an ion so hard that when it next hits a plain air molecule it has enough energy to knock an electron off that molecule. Then we have gained a pair of ions. Those ions in turn can gain enough energy to make another pair, and so on in a cascade, a chain-reaction. That *is* a spark.

Do not expect that to happen when air molecules collide in the atmosphere around you. They need far more energy to make ions, and a strong electric field is needed for that.

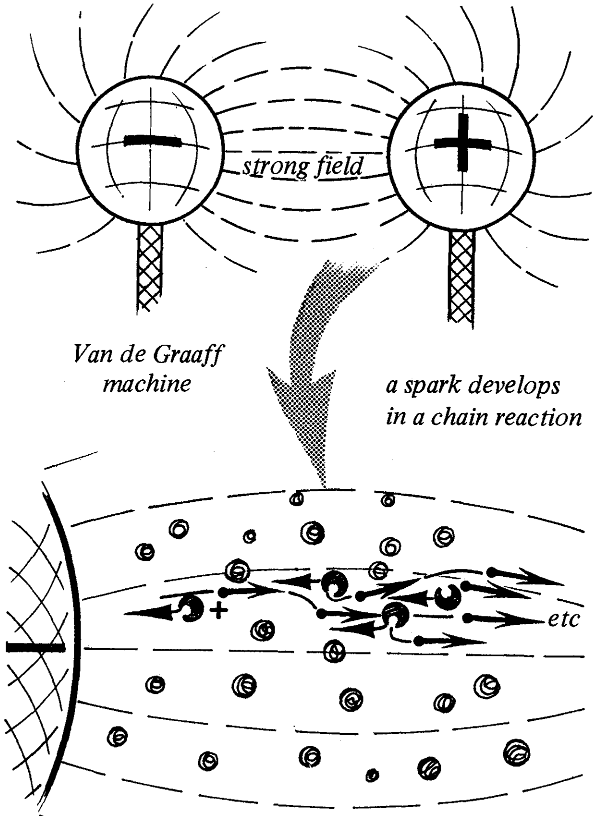
Electron volts We sometimes measure the energy of a small thing like an electron or a molecule in electron·volts. **One electron·volt (eV) is the energy gained when one electron charge falls through one volt.**

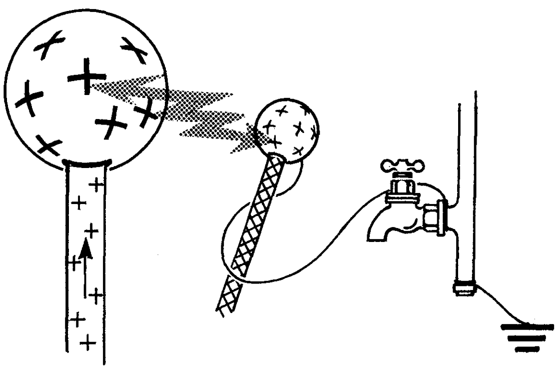
To detach an electron and make a pair of ions a colliding particle must bring in a lot of energy. The amount needed ranges from a few eV for some metals to 20 or 30 eV taken from a fast particle as it rushes through air.





Model of chain reaction in a spark. The rows of balls represent gas molecules regimented one free path apart. At a large tilt of the board one 'ion' will make many more in a chain reaction.





The average kinetic energy of air molecules at room temperature is about 0.03 eV—no wonder their collisions are elastic.

ELECTRONS FROM GUNS

Muzzle speed *(OPTIONAL NOW)* Although an electron has a small charge, its mass is so tiny that we can give it enormous accelerations by using the ordinary voltages and electric fields at our command.

Next Year you will calculate the speed of electrons from, say, a 100-volt gun. They emerge with K.E. $\frac{1}{2}mv^2$ at the expense of energy from the gun battery given by

$$\begin{bmatrix}\text{electron charge } e \\ \text{(in coulombs)}\end{bmatrix} \times \begin{bmatrix}\text{battery voltage} \\ \text{(in joules/coulomb)}\end{bmatrix}$$

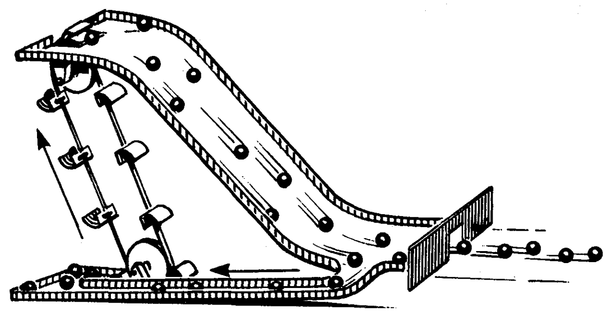
From $\frac{1}{2}mv^2 = eV$ you could calculate speed v if you knew e and m, or just e/m. You will measure that next year.

Electrons in wires? Have you any evidence for electrons being free to move inside wires?

Electrons at work: oscilloscope If you have time to spare try some experiments with a small oscilloscope in your own hands. Otherwise, wait and try them next year.

A rough model of an electron gun The sketch shows a fanciful model with marbles representing electrons. The marbles 'fall through' the height of the sloping plank, gaining K.E., then emerge through a hole in the wall at the bottom, the gun muzzle.

Many collect in a pool and are carried back up—gaining potential energy for another trip—by an escalator which represents a battery.



Progress Questions

CURRENTS

2. We know when a current of water is flowing somewhere because we can see it, feel it and hear it. We know when an electric current is flowing in something because of what it does. Where have you seen an electric current:

a. making something hot?

b. making something into a magnet?

c. causing a spark?

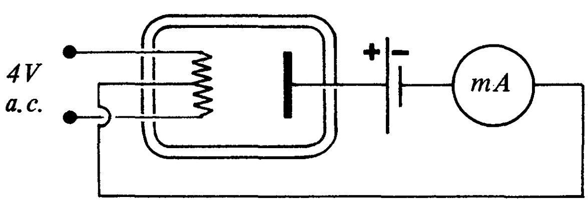
d. causing a crackling noise?

e. giving someone a 'shock'?

f. producing hydrogen gas and oxygen gas out of water?

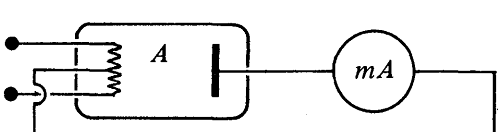
g. causing any other chemical effect?

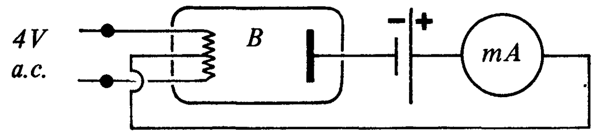
DIODE

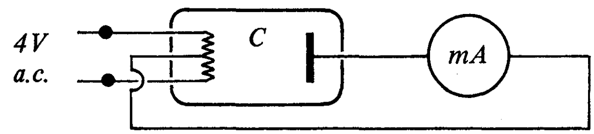


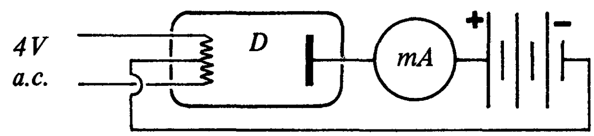
3. This shows the circuit that will make a diode conduct current.

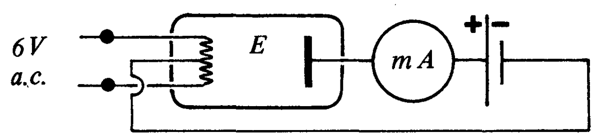
Now look at the arrangements A, B, C, D, E. For each one, say what has been changed and what difference it will make.



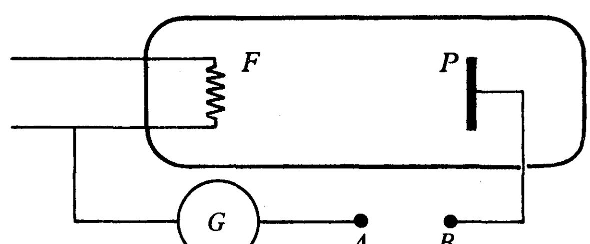








3X. The sketch shows a demonstration *diode* with a wire filament that can be heated electrically and a metal plate. The inside of the glass envelope is as



nearly as possible a vacuum. G is a galvanometer to see whether any current flows. A high voltage set can be connected between A and B.

a. Copy the diagram, and label the parts in words.

b. The filament is cold, and a high voltage is connected in the gap AB. Does G show any current?

c. Draw the demonstration diode in a circuit with a supply to heat the filament and with B connected to the positive side of a high voltage supply; and A connected to the negative side.

Does G show any current?

d. When A is connected to the positive side of the supply and the filament is glowing, does G show any current?

e. Copy and complete:

Current flows through a diode when the filament is (/*hot*/*cold*/) and the plate is (/*negative*/*positive*/) relative to the filament.

f. In the case when there is current, how does it get across the gap between F and P?

g. If something is carrying charge between F and P, why do we think it is something coming from the filament and not from the plate?

h. If it is coming from the filament, is it negative or positive electricity?

4. You are given a diode and a 12-volt battery. You also have a 2-volt cell, and a milliammeter.

a. Draw a circuit showing how you would apply 12 volts across the diode.

b. Now add the 2-volt cell to heat the cathode.

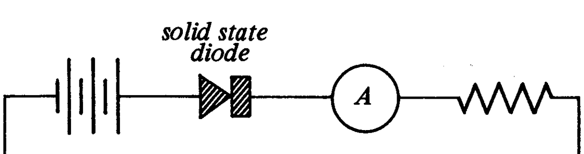
c. Show where you could put the milliammeter to measure how much current the diode is conducting.

5a. Small hot-filament diodes that were used in radio sets are now replaced by solid-state diodes. What is the advantage of that change?

b. Why is a hot filament still used in a TV picture tube?

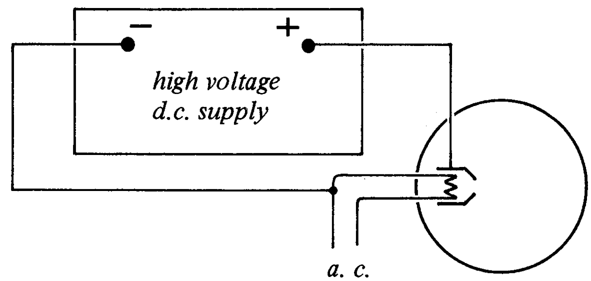
6. A rectifier is something which lets current pass through it only when connected in a particular way. It is drawn like an arrow. Positive electricity can only go in that arrow's direction; negative electricity can only go the opposite way.

a. Will the rectifier in the circuit sketched let current pass through (if connected like this)?



b. Draw a similar circuit showing a diode with a heated filament conducting current.

ELECTRON GUN



7a. This sketch shows a special diode called an electron gun. Copy the sketch.

b. It has a cylindrical anode instead of a flat plate (muzzle). Label this.

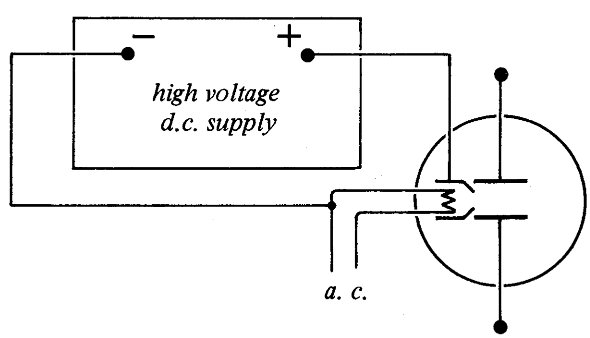
c. It has a heated cathode (filament). Label this.

d. Electrons move away from the cathode due to the high voltage supply. Where will most of them go?

e. Where will the rest go?

f. You could get the electrons moving using a low voltage. Why do you think a high voltage is used?

g. If there were some gas molecules in the tube, what effect would that have upon how far the electrons could travel?



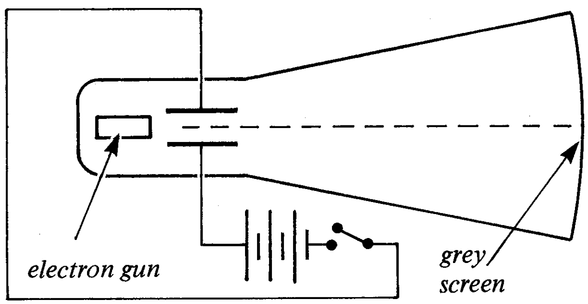
8. This tube has an electron gun which fires a stream of electrons between two metal plates, with a field between them. The high voltage supply and the low voltage heating supply are switched on.

a. What makes it possible for you to see the path followed by the electrons? Sketch the tube and show where the electron stream goes.

b. The top metal plate is joined to the +, and the bottom plate to the – of another high voltage supply. Sketch the electron stream path between the plates now.

c. On the same sketch, draw a dotted line to show the path you guess the electrons take after they have passed between the plates.

OSCILLOSCOPE



9. An oscilloscope (C.R.O.) is very like a fine beam tube except that its glass front is covered with a grey screen. When the C.R.O. is switched on a stream of electrons strikes the screen, making a spot in the centre. Suppose the time base is off.

a. Draw what you see on the screen.

b. Draw what you see on the screen when switch S is closed.

c. Battery B is replaced by an a.c. supply and switch S is closed again. What do you see now?

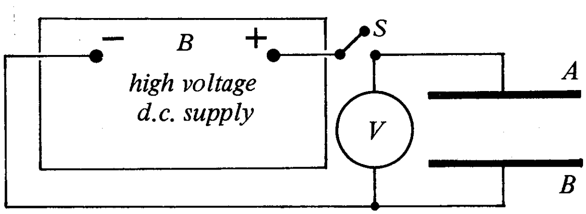
10. The C.R.O. now has its time base on. This makes the spot travel across the screen at a steady speed, then back again extremely fast. It makes the spot repeat this action many times a second.

a. Draw what you would see on the screen when the time base is on and:
(i) switch S is closed.
(ii) switch S is closed but the battery is reversed.
(iii) battery B is replaced by an a.c. supply and S closed again.

b. If the time base was speeded up what would be the effect in (a) *(iii)*?

Questions

MILLIKAN EXPERIMENT



11A. Here are two metal plates connected to a high voltage supply. We have between the plates an oil drop which is negatively charged, that is, it has some extra electrons on it. It is now falling under the pull of gravity.
a. If switch S is closed where will negative electrons from the electricity supply travel, to the top plate or the bottom one?

b. What effect will closing switch S have upon the movement of the oil drop?

c. What can you do to the electricity supply to make the drop stay still?

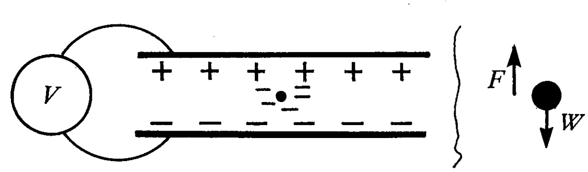
d. When the drop is still, what can you say about the size of the electric force upwards and the pull of gravity downwards?

e. What adjustment could you make to compel the drop to move *upwards*?

11B. A negatively charged oil drop, is just held still when the voltage across the plates is 2000 volts.

a. If somehow the charge on the oil drop is *increased*, that is, it suddenly carried *more* extra electrons, what would you see happening to the drop? (*Hint:* it wouldn't stay still).

b. Would you make the voltage between the plates bigger or smaller to keep the droplet still again?



11C. The sketch shows a droplet between two parallel plates. The droplet carries a negative charge. A battery maintains a potential difference (voltage) between the plates. It keeps + and – charges on the plates as shown. These charges pull and push the droplet's charge so that the droplet is pulled upwards. Its own net weight, W, is a force pulling it down.

The voltage V is adjusted so that the drop remains still. Then the 'electric force' F pulls it up, and its weight W pulls it down.

a. If the drop stays still, what can you say about F and W?

b. Suppose the charge on the drop (we call it q) changes, but we also change the voltage V to correspond, so that the drop remains stationary. Then, although q changes, qV remains the same—how do we know that?

c. We do not know q, but V can be read on a voltmeter. If the charge q varies in steps—that is, whole numbers of electrons—what happens to $1/V$?

d. Why is it $1/V$ that matters, and not V?

e. If, however, the charge q varies not in steps but continuously so that it can take any value whatever, what happens to $1/V$ now?

f. What do we find (about $1/V$) in the actual experiment?

g. What do we decide about electric charge?

12. Give some details about the apparatus used for the Millikan experiment, and say how the apparatus was used.

13. Look back at the 'Mr X' egg question (1), and also at the 'Millikan' oil-drop questions.

a. What is it in the oil-drop question that corresponds to an egg in the egg question? (Don't say 'oil-drops'—the oil-drops are more like the paper bags. Choose your answer from one of the following: *molecule, atom, electron.*)

b. What is it in the oil-drop question that corresponds to the weight of an egg? (Choose your answer from one of: *charge on drop, weight of drop, weight of electron, charge on electron.*)

c. What is it in the oil-drop question that corresponds to the reading of the spring-balance in the egg question? (Choose your answer from: [*voltmeter reading*], 1/[*voltmeter reading*].)

14. A number of marbles lie touching each other, inside a tube. You cannot count them, but you can measure the length of the row of marbles, which is 15.6 cm. Someone takes *one or more* of the marbles out. Now, when you measure the length of the row, it is 13.0 cm.

a. If you assume all the marbles have the same diameter, what is the *largest* diameter this could be?

b. Some marbles are added and the length of the row is 20.8 cm. Does this alter your estimate of the largest possible diameter for a marble? Explain the reason for your answer.

c. Some marbles are taken away, and the length of the row is now 16.9 cm. Does this cause you to change your estimate of the largest possible diameter? Explain.

d. You are now beginning to think that the 'largest possible diameter' is in fact the actual diameter. To test this idea further, the experiment is done four more times. The eight readings for the length of the row, including the first four, are:

15.6 cm	11.7 cm
13.0 cm	13.0 cm
20.8 cm	19.5 cm
16.9 cm	18.2 cm

What is your final estimate of the diameter of a marble? How many marbles were there at the start, when the length was 15.6 cm?

15a. What resemblance is there between Question 14 and Questions 11A,B,C? (Or, to put it another way, why is Question 14 here at all?)

b. What, in Question 14 corresponds to an electron in the oil-drop question?

c. What, in Question 14 corresponds to the charge on an electron?

d. What, in Question 14 corresponds to

$$\frac{1}{\text{voltmeter reading}}\ ?$$

CURRENTS

16. Where have you seen the effects of electricity travelling through:

(i) several metres of solid which is a metal?
(ii) a few centimetres of any other solid?
(iii) a few centimetres of liquid?
(iv) about a millimetre of ordinary air?
(v) many, many metres of air in a storm?
(vi) a metre-long tube of gas at low pressure?
(vii) a vacuum?

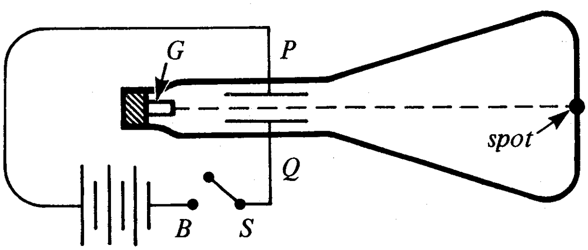
b. For which of these must the voltage be the highest to make electricity flow at all? Have a guess.

OSCILLOSCOPE ETC. (OPTIONAL NOW)

17a. Do electrons coming from an 'electron gun' themselves glow so that you can see them? (Yes or No.)

b. If 'No', what enables you to see where an

electron stream goes:
(i) in a 'cathode-ray oscilloscope tube'?
(ii) in a 'fine-beam tube'? (If you have not seen one, do not answer this.)



18. In the sketch, G shows an electron gun in an oscilloscope tube. A narrow stream of electrons from the gun travels through the tube. The stream passes between two plates P and Q, and makes a spot at the centre of the screen.

a. Draw a sketch, similar to the diagram, but showing what happens when the battery B is connected to plates P and Q with P positive and Q negative.

b. Draw another sketch showing what happens when the battery is reversed, and the switch is closed.

19. Battery B in the sketch above consists of three cells. When B is joined to a 6-volt bulb the bulb lights normally. Battery B is removed and, in its place, the secondary terminals of an a.c. transformer are connected to P and Q. This transformer also makes a 6-volt bulb light normally.

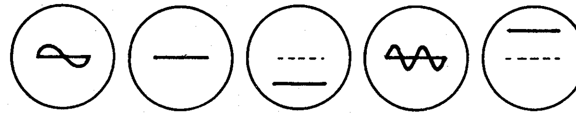
a. What happens to the electron beam now?

b. What is the appearance on the screen at the end of the tube? (Draw a diagram showing the end of the tube.)

c. (Harder question for thinking and guessing). You would expect the spot to behave differently with alternating voltage. If you try the experiment, you will find this is true; *but* the spot moves much farther than you might expect, 40% farther. Can you think out why?

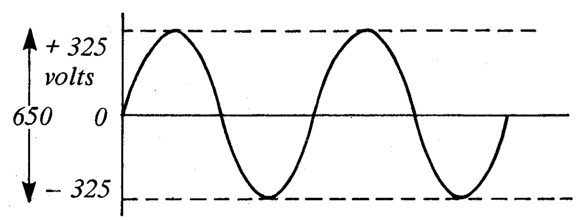
20. We now apply to the same oscilloscope tube a 'time base'. This makes the spot move across the screen from left to right. The spot then flies back again in almost no time at all. It repeats this 50 times a second.

Various things (A–E below) are joined to the plates P and Q. Each time we draw a sketch (five in all) showing what the screen looks like. Unfortunately we forget to label the sketches. Copy the sketches, with the right label, A, B, C, D, E, under each.



A = Plates P and Q joined together, no battery or a.c. supply to PQ.
B = Battery, P joined to + ve, Q joined to − ve.
C = Battery, P joined to − ve, Q joined to + ve.
D = a.c. supply, (50 cycles a second, or 50 Hertz).
E = a.c. supply, (100 cycles a second, or 100 Hertz).

21. The supply of electricity to houses in a certain city is stated by the Electricity Board to be '230 volts a.c.'. When this supply is applied to a cathode-ray oscilloscope, the voltage is found to swing from +325 volts to −325 volts (see sketch).



a. Is the Electricity Board wrong in calling this 230 volts a.c.?

b. If the Board is not wrong, what do they mean by calling this '230 volts'?

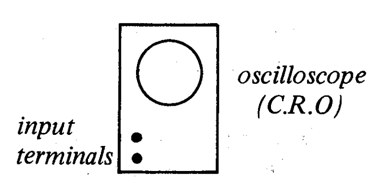
c. What is the peak voltage of the supply shown in the graph?*

d. What is the average voltage?*

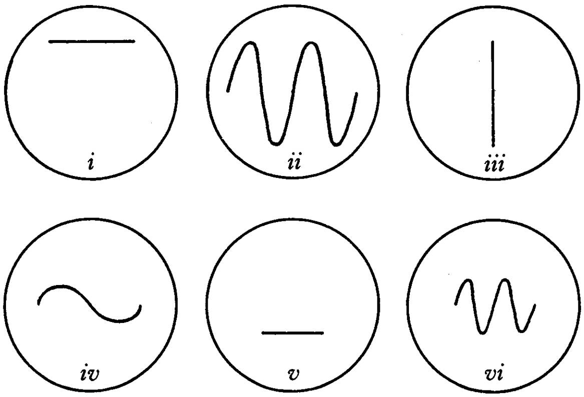
e. What is the r.m.s. (root mean square) voltage?*

* Choose your answers from the three values, 0 volt, 230 volts, 325 volts.

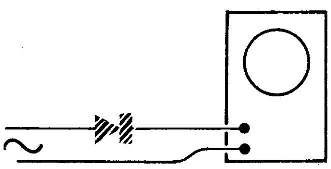
22a. Copy the diagrams of a C.R.O. screen. Say what was applied to the input terminals to give the trace shown in each case. Choose your answers



from: '2 volts a.c., peak-to-peak'; '1 volt a.c., peak-to-peak'; '2 volts d.c.'; '1 volt d.c.' Say also whether the time base was on or off in each case.



b. For diagrams *(ii)*, *(iv)* and *(vi)*, say which has the electron beam going across the screen the greatest number of times per second.



c. Suppose you have connected an a.c. supply and a rectifier into the input as shown, draw what the trace would look like, with the time base on.

APPENDIX

THINKING AND GUESSING

Precise measurements and rough guesses. Scientists make very careful measurements. They measure the precise amount of energy needed to melt 1 kilogram of ice. They can measure the size of the Moon accurately, without going there. But scientists also make very rough estimates which are useful in engineering, in industry, and in building up science.

Even when they do not know enough for a careful guess, scientists make a guess that is much better than nothing. They know their guess may be three times too big, or three times too small; but still their guess is 'in the right county'—or, as scientists would say, 'of the right order of magnitude' meaning something like 'to the nearest power of 10'.

Here is an example:

A SPECIMEN ESTIMATE

Suppose you are the Mayor of a city in U.S.A., and one night there is a great fall of snow. The snow is unexpected. The streets are clogged with snow and people must walk to work. But even the pavements are covered too deep. You must send out men with shovels to clear the pavements.

It has stopped snowing now, at 2.0 a.m., and you want to get the pavements clear by 7.0 a.m. *HURRY AND START THE MEN OUT. HOW MANY MEN? QUICK: MAKE UP YOUR MIND.*

In this emergency, it will be better to make a quick rough guess than to take a lot of time planning accurately. Your short discussion with the City Engineer might go like this:

YOU (THE MAYOR) 2.0 a.m. now. We've got till 7.0 a.m.—five working hours.

E (THE ENGINEER) No we haven't. It will take about an hour to call men by phone and radio.

YOU Yes. And half an hour more before they are out at work.

E I suppose we should aim at finishing by 6.30 a.m.—a margin of half an hour.

YOU Then we have only three working hours. How many long avenues are there in the city?

E Eight important ones and four unimportant ones.

YOU Let's call that ten altogether. How long are they?

E They are all different. The longest is 6 kilometres, the shortest 2 kilometres. Most are 3 or 4 kilometres.

YOU Take a rough average: 4 kilometres for each of the ten.

E Then we have to clear two pavements on ten avenues each 4 km long. That means $2 \times 10 \times 4$ km of clearing. 80 km.

YOU Now about cross-streets.

E It's difficult to say how many there are.

YOU Well, if the city is 4 km long with a cross street every 100 metres, that would be about 40 cross streets. Let's say 40.

E The city isn't a square shape, but it's somewhere between $\frac{1}{4}$ as wide as it's long and $\frac{3}{4}$ as wide as long. Let's say half: then 2 kilometres wide.

YOU Then we have 40 cross streets, each with two pavements, each 2 kilometres long. $40 \times 2 \times 2$ kilometres.

E That makes 160 kilometres of snow clearing. With 80, that makes 240.

YOU As I walk across the room here, I am imagining I am shovelling snow. It takes me 5 seconds to shovel one metre along.

E You'll soon get tired at that rate. Watch me.

YOU You are taking 15 seconds for shovelling one metre. Let's take 10 seconds a metre for a rough guess. That's 10 000 seconds for a kilometre.

E One hour is 60 minutes or 3600 seconds; that is about $\frac{1}{3}$ of 10 000 seconds. So one man can shovel a kilometre in about 3 hours.

YOU Good. Then we need 240 men.

E And add 10% for supervisors, say 260 men.

YOU Start telephoning for 300 men.

That estimate may be seriously wrong. Yet it won't be ten times too big or ten times too small. It is a rough estimate, but a useful one.

We often have to make rough estimates like that in science. Try your hand at some of the ones asked for below.

MAKE SOME ROUGH ESTIMATES

(These are things to try in class or to think about at home.)

CHOOSE ANY TWO OF THE FOLLOWING THINGS; AND IN EACH CASE MAKE THE BEST ROUGH GUESS YOU CAN. THAT IS SOMETHING A GOOD SCIENTIST OFTEN HAS TO DO.*

How many grams of stuff in a pair of nylon socks?

What is the average lifetime of a wild rabbit?

What is the volume of air in your school lab (in cubic metres)?

How many teachers are there in all the schools in your town?

What is the volume of water in a swimming pool (in cubic metres)?

What is the average lifetime of a pair of jeans?

How many stitches are there in a pair of socks?

How much does a pair of nylon socks weigh (in newtons)?

What is the *weight* of a man's felt hat (in newtons)?

What is the *weight* of a small car (in newtons)?

How long would it take you to walk from school to London (or to Edinburgh)?

How many watts of electric power is your house taking on a winter evening?

How many watts do all the street lamps take in the street where you live?

MORE ESTIMATES

IF YOU DID NOT TRY MAKING ROUGH ESTIMATES LAST YEAR OR THE YEAR BEFORE, CHOOSE ANY TWO OF THE FOLLOWING (FROM EARLIER PUPILS' TEXTS). DO THE SAME FOR THEM.

What is the distance in *metres* between your home and your school?

What is the speed of a sparrow in flight?

What is the heaviest basket (airline bag, etc.) of books you can comfortably carry to school every day?

What is the average lifetime of a bird?

How many teaspoonfuls are there in a cup of tea?

How many *square millimetres* are there on the surface of your finger nail?

How long would it take you to read aloud one page of a novel?

How long would 100 heartbeats take (when you are not frightened)?

How many hairs are there on your head?

How many eggs do you eat in one year?

How many pencils are there in a kilogram of pencils?

How many $\frac{1}{2}$-litre containers of milk does a family of two parents and two children take in one year?

---

* If you know about standard form, use that and carry the figures as far as you think wise.

Examples: 1320 in standard form is $1.32(0) \times 10^3$
2 million is 2×10^6 0.022 is 2.2×10^{-2}

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This volume contains the material for pupils for the fourth year of Revised Nuffield Physics. The main topics are: Mechanics continued: Newton's Laws, momentum and momentum conservation, kinetic energy; Gases; Kinetic theory and predictions; Conservation of energy; Human energy and power; Electricity continued: voltage, Ohm's law and others, power in electric circuits; Electrons.

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