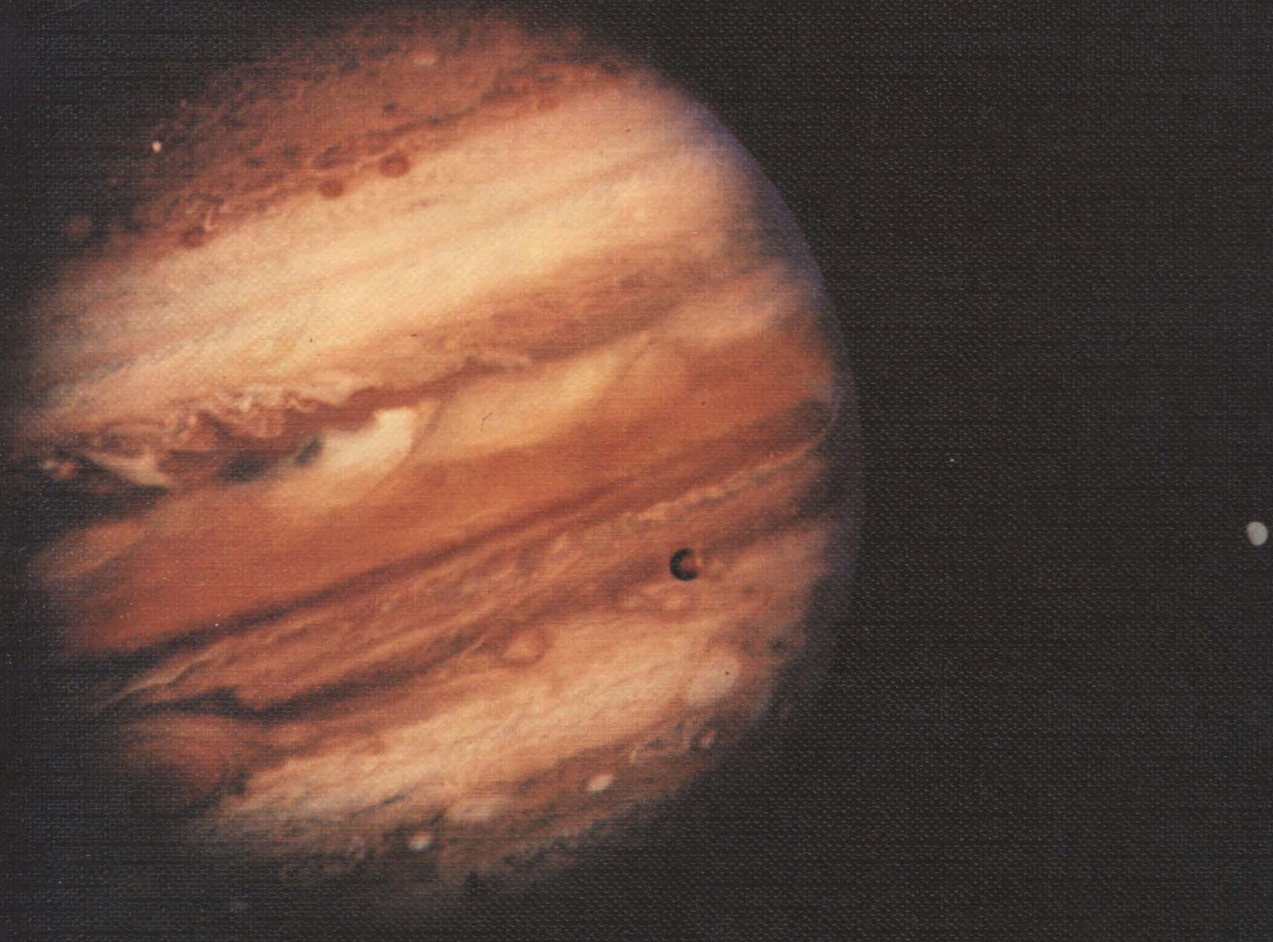
REVISED

NUFFIELD PHYSICS

Pupils' Text Year 5



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Nuffield Physics PUPILS' TEXT YEAR 5

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Cover photograph

The planet Jupiter with two of its moons, Io and Europa, seen from *Voyager I*

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REVISED NUFFIELD PHYSICS PUPILS' TEXT YEAR 5

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CONTENTS

'Scientific knowledge is *knowledge*, not fact – a gallery of pictures painted by men to portray in some simplified, comprehensible way the seemingly infinite complexity of nature. The pictures are put up and taken down, cleaned, replaced, and destroyed. Any account of scientific knowledge is therefore . . . an account of unfinished business.

'Indeed, in the eyes of those who have made them, all these pictures are only fragments of a single picture. It is a picture of nature that is always incomplete, but must always hang together with the consistency contributed by the single palette used in painting it: the mind of man.'

Alan Holden in the Foreword to *Conductors and Semiconductors*, Bell Telephone Laboratories, Inc., 1964.

Note: the foreword, preface, and acknowledgements for the work in Year 5 appear in the companion *Teachers' Guide* to this volume.

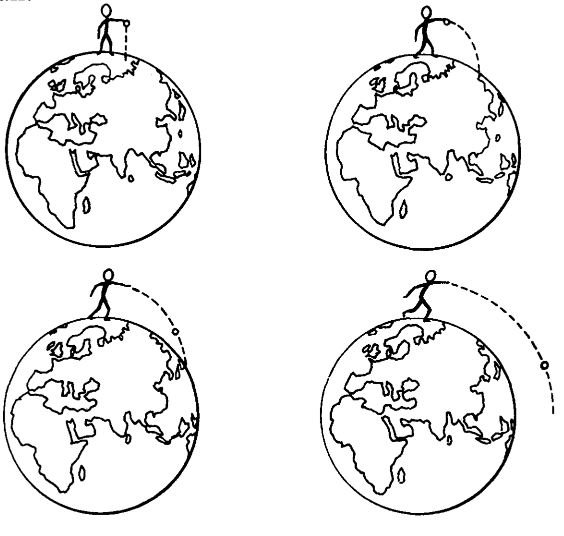
CHAPTER 1

Motion in an orbit

Central acceleration; inward force; Earth satellites

Introduction Some of your physics this year will be concerned with things that move round an orbit: electrons, atomic nuclei in a mass spectrometer, planets – including the Earth itself – Earth satellites, . . .

Try an experiment: take a small piece of wood (or any small object that is dense but not heavy). Let it fall and watch its motion. Pick it up, throw it out horizontally at shoulder height, and watch it fall.



A thought experiment in extrapolation.

Throw it out again, faster than before. Then FASTER. Then FASTER still. It always falls, but it goes further and further before it reaches the ground. Now remember that the Earth is round, so the ground itself falls away from your present level. If you could throw your projectile fast enough its fall might just match the falling-away of the round Earth. Then where would your projectile stop?

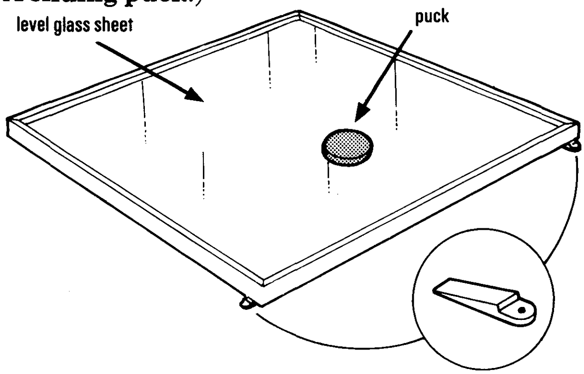
ORBITS

Equilibrium In mechanics, equilibrium means equal balancing of forces. When we say an object, or a machine, is in equilibrium we mean all the forces on it add up to zero: the resultant force is zero.

A pole supporting a large tent is in equilibrium, even though the many ropes attached to it will pull it in different directions. The resultant force, when *all* the forces on the pole are added as vectors, is zero.

Equilibrium does not always mean 'staying at rest'. A skater at rest on smooth ice has two equal and opposite forces acting on him, his WEIGHT and the UPWARD PUSH of the ice. When he is gliding steadily along in a straight line on the ice, the forces on him are still his WEIGHT and the UPWARD PUSH of the ice. No cord is pulling him and he is not kicking backwards to make the ground give him an extra push. He is in equilibrium.

A puck sliding on a smooth glass table is in equilibrium if you leave it alone, whether it is at rest or moving. (You may see **Demonstration 1 A sliding puck.**)

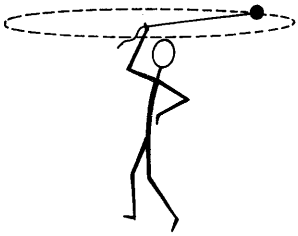


In all these cases the resultant force is zero, and the acceleration of the object is zero. Something which is moving with constant speed in a straight line does not need a force to keep it going. Or, as you saw in Year 4 when studying Newton's First Law, an object which has no resultant force on it will just go on moving in a straight line.

Think about the Moon, orbiting once round the Earth in a month. Is the Moon in equilibrium? What forces do you think act on it out there?

Experiment 2
Try an orbit; whirling a small satellite

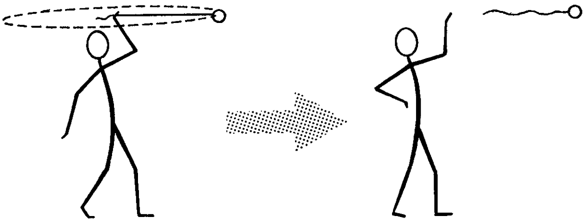
Tie a block of wood or rubber to a string and whirl it in a circle round your head. Is the block in



equilibrium? What kind of force does the string exert on the block, an outward force, an inward force, or no force? (Remember: *'strings pull; they never push'.*) Gravity pulls the block, as always, and you will notice that the string you are using slants down slightly. The pull of the string has an upward component, which just balances the block's weight. Is there any other force on the block? If you say there is centrifugal force, be careful. Do you see any real agent, such as a string, or a rod, or an attracting Earth, or a magnet, exerting an outward force on the block? We shall discuss that very soon.

Demonstration 3
Stop the revolution

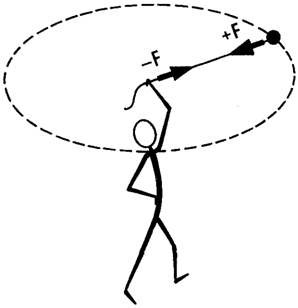
See what happens when, while the block is being whirled round, the hand holding the string suddenly lets it go. Does the block fly outwards, carried by that centrifugal force which someone suggested?



You have heard people say 'fly off at a tangent'. When let go, does the block move along a tangent to its previous orbit? Does it suddenly hurl itself along a tangent with unexpected energy? Or does it just *continue* along a tangent? Once you have let go of the string, the block is on its own; and it shows you an example of Newton's First Law of Motion. It moves in a straight line at constant speed, in equilibrium.

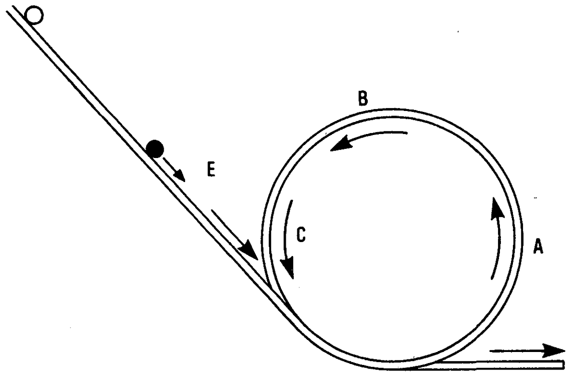
Experiment 2 (repeated)
Try an orbit: whirling a small satellite

Now whirl the block on the string again and think about the forces involved. The string pulls your fingers *outward*, but that is a force *on your hand*. The other end of the string pulls the block *inward*, and that is a force *on the block*. We can give it a descriptive name, a *centripetal* force, meaning *centre-seeking*.



Demonstration 4
Loop the loop

Let a ball rolling on a rail loop the loop. As it goes round the orbit of the loop, what compels the ball to go round a circle? What pushes or pulls it with a real force to make it do that? *What direction has that force, and what provides it?* It must be some real *inward* force, towards the centre of the loop.



What provides that force at A, half-way up the loop? It must be the rails that push inward. Does gravity also act on the ball when it is there? Yes, of course. But gravity pulls vertically, and its only effect is to give the ball a downward acceleration so that the ball slows a bit.

What provides the inward force at B, the top of the loop? The rails may push downwards, but what other force helps? Yes, gravity helps fully now whether it is wanted or not!

Look what happens when we have the ball moving much slower, needing less force for its orbit. Gravity provides too much force and makes the ball fall away from the rails.

What are the forces on the ball at C? Discuss these forces with your teacher.

See what happens if the ball is given too poor a start by being released at E.

Find by trial the lowest starting point, X, from which the ball can just make the loop. Think about the forces at the top, B, when the ball starts from X. Could the motion do without the rail there?

Centrifugal and centripetal Discuss some other examples of orbital motion with your teacher. The ideas of centrifugal force and centripetal force are not easy to settle, so you should discuss them carefully. In this part of physics we call centripetal force, inward to the centre of any orbit, the real force that needs a real agent pulling or pushing the object inward – otherwise the object cannot move round the orbit. The agent may be a string, rails, banked road, extra air pressure, gravity pull, but in each case it must be a real agent and not something we have just imagined. 'No inward force, no orbit' shall be our motto.

Centrifugal force We shall say centrifugal force is a mistaken idea suggested by the outward pull on your hand when you whirl a block.

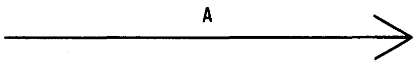
....

Progress Questions

1. Some things always travel in *circles*. Some other things sometimes travel in circles. Make a list of such things. Give several examples of each kind.

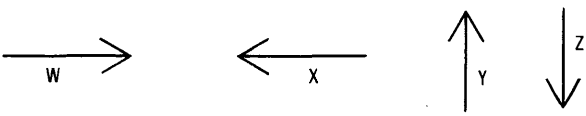
2. How did people find out that the Moon travels in a circle round the Earth?

3. Suppose a trolley is running along a very smooth, flat, level runway at a certain speed. It will



go on and on, at the same speed. The line A shows its motion.

a. Suppose you use a large, sudden push to slow



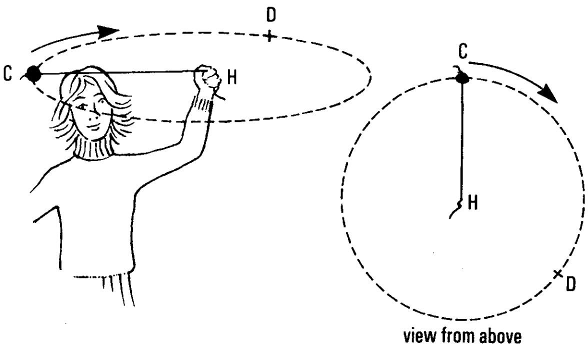
down the trolley. In which direction would you push, W, or X, or Y, or Z?

b. Suppose you want to:
(i) speed up the trolley, which direction of force would be needed? W, X, Y, or Z?
(ii) turn the trolley to the left like this, which direction of force would be needed? W, X, Y or Z?

(iii) turn the trolley to the right like this, which direction of force would be needed? W, X, Y, or Z?

c. Suppose the trolley has turned a bit to the right as in *(iii)* and then no further force is given. What will the trolley do now?

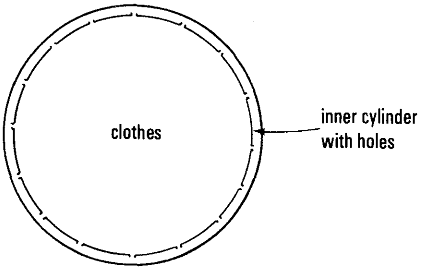
4a. Joan is whirling a conker, C, on a string in a horizontal circle above her head. The string is pulling on the conker all the time. In which direction is the pull? Is the pull along the edge of the circle, or towards her hand in the middle?



b. Suppose she lets go of the string when the conker is at D. Copy the righthand sketch and draw in the path of the conker when it flies off.
c. Newton's First Law says that an object goes on travelling at a steady speed in a straight line if there is no force pushing or pulling it. Explain to someone why it is reasonable that the conker flies off in the direction you have shown.

5a. You are sitting in the back seat of a car which comes to a sudden stop. Which way do *you* slide, backwards or forwards?
b. The force of friction between brake and wheels brings the car and anything fixed to it to a halt. You come to a halt inside the car too. What sort of force changes the forward motion of your body and brings you to a halt? In which direction does this force act on you?
c. You are sitting in the back seat of a car which turns to the *right*. The car makes the turn very

quickly. You slide along the seat and are stopped by one side of the car.
(i) Which side of the car do you hit, the *left* side or the *right*?
(ii) The side of the car exerts a force on you when it stops you. What is the direction of that force, *left* or *right*?

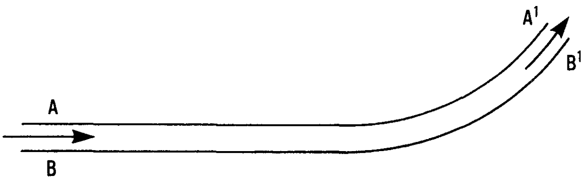


6. You put wet clothes in a spin drier and set it going.
a. When the inner cylinder is turning, the *water* goes out through the holes. How would you explain this to a friend? Try to use Newton's First Law to explain it.
b. What happens to the *clothes*?

7. Try this experiment:
Whirl a conker (or something similar) in a horizontal circle as in question 4 above. Keep the length of string the same and make the conker whirl faster. Do you need to pull inwards with a greater or smaller force when it's going faster?

Questions

8. AA′ and BB′ are the two rails of a single flat railway track. A train runs from the straight portion at AB towards the curve at A′B′.

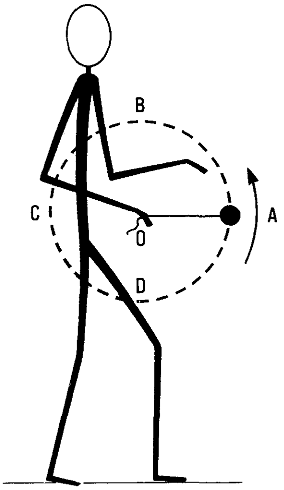


a. First suppose that there were no flanges on the wheels. What would happen when the train reached the curve?
b. But of course there *are* flanges on the wheels, and these flanges fit inside the rails. When the train rounds the curve, which rail presses against the wheel flanges? Is it the inner rail, AA′, or the outer, BB′? Give a common-sense reason for your answer, using the word 'momentum'.

9. (*Advanced*) In Question 8 you thought about the horizontal forces between rails and train. Now think about the *vertical* ones.

When the train is on the straight portion AB, its weight is equally supported by each rail.
a. When the train is moving round the curve, are the rails still exerting equal upward forces? If not, which rail exerts the greater force?
b. What happens if the train goes round 'too fast'? (Think of a toy train if you like; the answers are the same for a toy train and a real train. Saying 'it comes off the rails' is not enough.)
c. Give reasons for your answers to **a** and **b**.
d. Both on toy tracks and on real tracks, curves are usually 'banked'. Which way are they banked, with AA′ lower or BB′ lower? Give a reason for the kind of banking you suggest.

10. The sketch shows a stone attached to a string held at O, and being swung round in a *vertical* circle (that is, in a vertical plane).



a. What force is keeping the stone moving in a circle when it is at A, or at C?
b. What *two* forces are keeping the stone moving in a circle when it is at B?
c. If the string is weak it is most likely to break when the stone is near D. Why is this?
d. Draw a sketch showing the path of the stone if the string breaks at D. You may suppose that ground level is below D at a distance equal to BD.
e. Draw a sketch showing the path of the stone if, in the portion AB, it is 'not moving fast enough'.

11. Half fill a pail with water and turn it upside down, *keeping the water in the pail all the time.* (If you have not sufficient confidence in the principles of physics you had better wear a macintosh – or a swimsuit – and do it in the garden in any case.)

a. How did you do it?

b. Why did the water stay in the pail? (This is quite difficult to answer – if you answer it properly you really do understand motion in a circle.)

12. By now you may be convinced that a 'centripetal' force (force towards the centre) is needed whenever a body moves in a circle. What agent provides the centripetal force in the following cases of circular motion?

a. A marble when it loops the loop.

b. A car going round a bend.

c. The Moon going round the Earth.

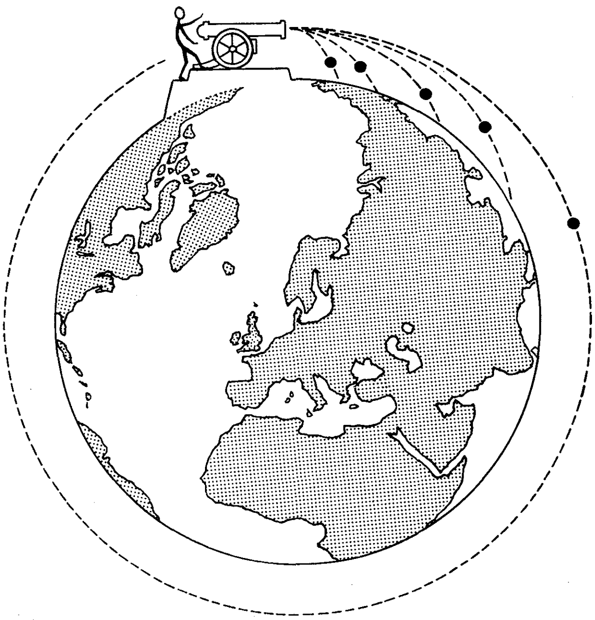
d. The Earth going round the Sun.

e. A stream of water going round inside a bent pipe.

f. An aeroplane flying round a horizontal circle.

The Moon again At each point in its orbit the Moon would continue steadily along a tangent if it were left alone. Instead of that it seems to fall inward from the tangent to its circular orbit, again and again. In this case the inward pulling agent is invisible but we are sure we know what it is: gravity. The Moon is an Earth satellite.

We can now put up Earth satellites that circle round in much shorter time than the Moon's month.



The gun on the hill As suggested before, you can imagine starting an Earth satellite yourself. This is a 'thought experiment' – an imaginative trick such as we often use in thinking out some Science. Imagine that you put a gun on a hilltop, aim it horizontally and fire a slow bullet. The bullet comes out of the gun muzzle and follows a parabola to the ground.

Now fire a faster bullet horizontally: it travels further before it reaches the ground. Now fire a still faster bullet, and another faster still, until you fire a bullet that *'falls over the edge of the Earth'*. Then, the Earth's surface falls away from the bullet's original direction just as much as the bullet's path does – the bullet's path matches the curve of the Earth. But to the bullet, all parts of the Earth are the same. It just goes on and on round the world, keeping just above the ground, until it arrives back at the starting point and hits you from behind.

In practice, of course, air resistance would soon take away much of the bullet's energy; but you can imagine doing the experiment without any atmosphere or, as real satellites are fired, high up above the atmosphere. Now, in imagination you have your own Earth satellite. (Newton imagined a gun firing satellites like that three centuries ago but thought air resistance would make them impractical.)

The story above started with a projectile from a gun. What motion does that have? It is a steady velocity horizontally and an acceleration g vertically down. Therefore, at every point in its orbit, your Earth satellite must have an acceleration g inward towards the centre of the Earth, because every part of its motion is just like a piece of projectile motion.

Satellites have acceleration Then the Moon, or any other Earth satellite, is *not* in equilibrium, but has an inward acceleration. That is not very surprising because we already found an inward force necessary for an orbit: the pull of a string, for example. If we trust $F = ma$ to apply to this motion, anything moving round an orbit must have an inward acceleration.

THE SATELLITE ORBIT EXPERIMENT

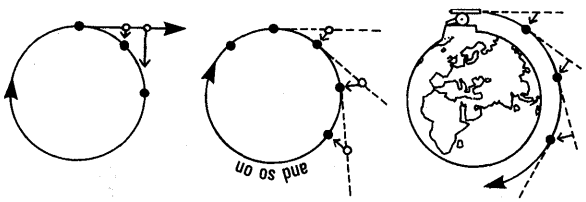
Before you start work on the mechanics of orbits, you may find it interesting to predict the time a satellite close to the Earth takes to go right round, by treating it as an ordinary projectile with gravity fall.

For that, you should make a scale drawing of part of an Earth satellite's circular orbit, to illustrate the following story:

Experiment 5
Finding the orbit-time for an Earth satellite

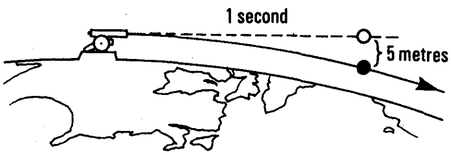
Suppose we launch a satellite 200 kilometres or so above the Earth's surface. Compared with the radius of the Earth, some 6400 kilometres, the satellite is not really much further away from the Earth's centre than a ball thrown in the air. You know that for a falling ball the pull of the Earth produces an acceleration about 10 m/s per second. So a stone dropped from rest falls 5 m in the first second ($s = \frac{1}{2}at^2$). Any projectile does the same: instead of continuing along a straight line in the direction in which it is fired, it drops 5 m from that straight line in the first second. (You may remember the 'monkey and hunter' experiment from Year 3.)

Now think of that Earth satellite travelling round the Earth in a circle, about 200 kilometres up. Instead of travelling along a straight tangent to

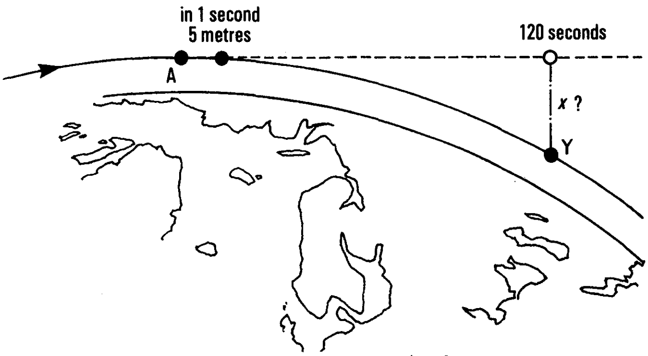


The satellite idea.

that circle the projectile falls in from the tangent again and again – really falling continually – to keep in a circular orbit. In one second it must fall 5 m from its straight-line tangent to its circular orbit. You could make a large-scale drawing of the satellite's orbit and mark the 5-m fall on that.



However, 5 m would hardly show on any drawing small enough to fit in your lab. You had better think of the satellite falling from its tangent path for a much longer time: say 2 minutes or 120 seconds instead of one second.



You may use the formula $s = \frac{1}{2}at^2$ again to find how far the satellite will fall in 120 seconds. It must be $\frac{1}{2} \times 10 \times 120^2$ m. Or you could argue that in 120 seconds the falling object gains 120 times as much speed as in 1 second; and it has 120 times as long to use its speed; so altogether it falls 120×120 times as far.

Work out that fall in kilometres. Then put that on your big scale drawing to find out how far the satellite travels along its orbit in 2 minutes. From that you can predict how long an Earth satellite will take to go all the way round the Earth.

Instructions for making your drawing Since we are waiting for the result of your calculation of the fall in 2 minutes, we shall call it x kilometres in these notes. But you should use your own result of course. Use a scale of $\frac{1}{2}$ millimetre to represent 1 kilometre.

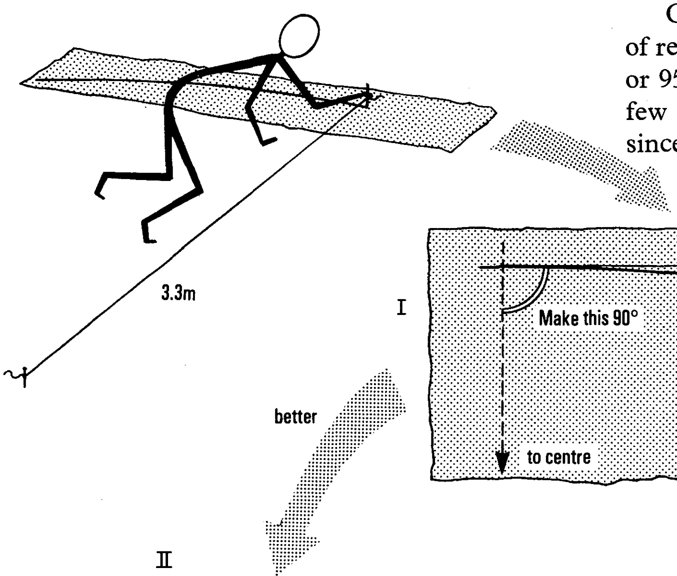
For the orbit, whose real radius is [6400 kilometres + 200 kilometres], use a circle of radius $6600 \times \frac{1}{2}$ mm. That is 3300 millimetres or 3.3 metres. Take a tough thin wire, 3.3 m long; anchor one end on the floor, stretch the wire taut across the floor and attach a pencil to the other end.

Keeping the wire taut, draw an arc on a long sheet of paper. You will need a piece of brown paper (or lining paper or newspaper) about $1\frac{1}{2}$ m long to take the length of arc; but it need not be more than 15 or 20 cm wide.

The sketches show how to treat your drawing: sketch I shows how you could draw a tangent to the arc and find the distance along the tangent to the place Y where the vertical drop-down to the arc is the fall x that you calculated.

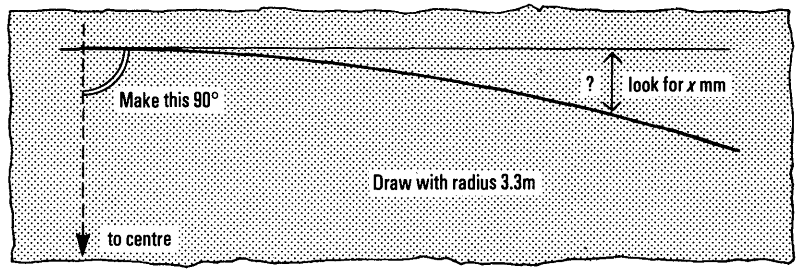
But it is much better to draw a double length of arc, XAY, as in sketch II. Then you can drop down AM, a distance x from the mid-point of that arc. Draw a chord XY across through M, perpendicular to AM, like the string of a bow; and find the point where it cuts the arc. The distance

Compare your result with the measured times of real satellites in orbits near the Earth, about 90 or 95 minutes. The table gives some details for a few of the many hundreds of satellites launched since the first one in 1957.



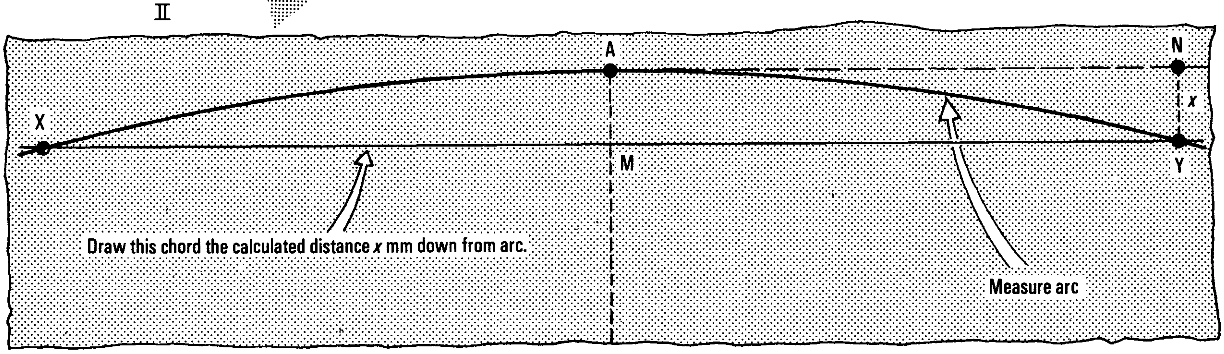
Sketch the orbit to scale

I



Investigating the motion of a satellite near the Earth.

II



NY is the satellite's fall. Then you can measure how far the satellite must have travelled, from the mid-point, in 120 seconds.

On your drawing, mark the distance x (your calculated value), then measure the distance AY, which is travelled in 120 seconds – MY will do for that. Convert that to kilometres for the real orbit. You know the distance round the whole orbit: it is the circumference $2\pi \times 6600$ kilometres. Calculate the time for the whole orbit.

Notes:
Sputnik 1, mass 84 kg, was the first artificial Earth satellite. It transmitted for 21 days.

Vostok 1, with Yuri Gagarin on board, made the first manned spaceflight. It performed a single orbit which lasted 108 minutes.

Apollo-Soyuz made an international joint manned flight.

Intelsat is a geosynchronous communication satellite. The period of just less than 24 hours

Data for some Earth satellites*

	Sputnik 1	Vostok 1	Apollo-Soyuz	Intelstat 4A(F-3)	Tiros-K
Launch date	4 Oct 1957	12 Ap 1961	15 Jul 1975	7 Jan 1978	13 Oct 1978
Decay or recovery date	4 Jan 1958 (?)	12 Ap 1961	21 Jul 1975 (Soyuz) 24 Jul 1975 (Apollo)	—	—
Estimated lifetime in years	—	—	—	10^6	500
Inclination to equator in degrees	65.1	65.0	51.8	0.3	98.9
Period in minutes	96.2	89.3	88.9	1436.1	102.1
Lowest point in km	215	169	217	35 768	860
Highest point in km	939	315	231	35 806	878

allows for the motion of the Earth round the Sun.

Tiros is a new generation of American weather satellites, transmitting Automatic Picture Transmission (APT) on 137.625 MHz.

* Acknowledgment is made to the Royal Aircraft Establishment for the data and to Mr G. E. Perry of Kettering Boys' School for making the representative selection and for the notes.

ACCELERATION OF AN OBJECT IN ORBIT

An object moving round an orbit does not fly straight along a tangent but continues to fall in from tangent after tangent to the round orbit.

What makes it fall? There must be some real inward force to make it do that. If we trust $F = ma$ to apply to this motion, anything moving round an orbit must have an *inward* acceleration. We can work out what that acceleration is by some geometry concerning an orbit. The result is important in:

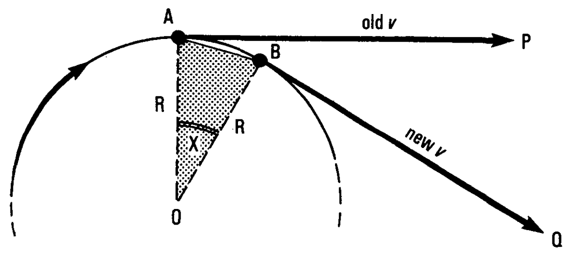
measurements on electrons,
design of mass spectrometers for modern chemistry,
control of Earth satellites,
atomic theory, and
the theory of the solar system.

You should see how we obtain the formula to calculate the inward acceleration of an orbiting object. You should go right through the story given here, although you would not be expected to produce it in a Nuffield Physics examination. You may be asked questions to test whether you understand how the formula is worked out.

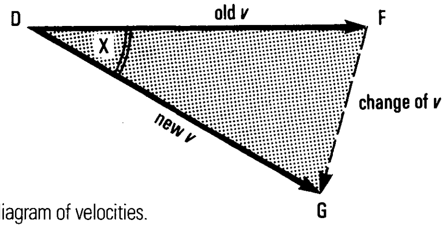
CALCULATING THE INWARD ACCELERATION

An object (or a point) moving round a circle with constant speed v has an acceleration v^2/R towards the centre. Since this is an important expression for many motions in physics, you should see how it is arrived at, and not just accept it as a mysterious 'formula'.

Draw a circular orbit, with an object moving from A to B in time t. The object's speed, along the curved path, is v. At any instant, its velocity is v *along the tangent*. Draw a vector AP to represent the object's velocity at A. That is along the tangent at A. Draw another vector, BQ, of the same length,



Picture of orbit.



Vector diagram of velocities.

to represent the object's velocity at B along the tangent there.

Draw those vectors again in another place nearby; this time *start both from the same point D.* There you have two vectors, each of length v, which we label:

OLD VELOCITY (velocity at A)
NEW VELOCITY (velocity at B)

Since you want to find an acceleration, you need to know the *change* of velocity. Ask yourself:

What must be added, as a vector, to the OLD VELOCITY to get the NEW VELOCITY?

It is the vector FG in the sketch.

Join A and B, and draw radii OA, OB. Then you have two similar triangles, AOB and FDG. That is because each velocity-vector is along a tangent, so it is perpendicular to the corresponding radius – so the angles at O and D are equal. Then, from the property of similar triangles:

$$\frac{\text{CHANGE OF VELOCITY}}{\text{VELOCITY, } v} = \frac{\text{chord AB}}{\text{radius } R}$$

$$\therefore \text{CHANGE OF VELOCITY} = \frac{(\text{AB}) \times v}{R}$$

Suppose this kind of change of velocity, which is perpendicular to the actual motion, is related to an acceleration just like any other acceleration – a surprising supposition, which must be tested. If the supposition is safe you can calculate that acceleration as usual:

$$\text{ACCELERATION} = \frac{\text{CHANGE OF VELOCITY}}{\text{TIME taken A to B, } t}$$

$$= \frac{(\text{AB}) \times v/R}{t}$$

$$= \frac{v}{R} \times \frac{(\text{AB})}{t}$$

$$= \frac{v}{R} \times v, \text{ as } \frac{(\text{AB})}{t} \text{ is SPEED } v$$

$\therefore$ ACCELERATION $= \dfrac{v^2}{R}$ and is directed towards the centre.

(*Note:* In dealing with the similar triangles, we took AB to be the *chord* straight across from A to B. But when we said $(\text{AB})/t = v$, we took (AB) to be the distance *along the curved arc* from A to B. Strictly speaking, we should allow for this switch by inserting a correcting factor (AB chord)/(AB arc), but in the limit as B is moved nearer and nearer to A, that factor tends to the limit 1. And to find the acceleration 'at an instant of time' we must move B right up to A and look at the limit.)

A PRACTICAL TEST

The force If an object moving round a circular orbit has an inward acceleration v^2/R there must be a real inward force acting on it. The force is given by

$$F = ma = mv^2/R$$

A real agent must provide that force – otherwise *NO FORCE, NO ORBIT.*

The real agent may be a string for a block whirled in a circle, rails for a toy car looping the loop, extra pressure on the wings of an aeroplane, gravity pulling on a satellite, or forces made by electric or magnetic fields on an orbiting electron.

As you have seen, the theoretical prediction that the inward force is mv^2/R is based on the geometry of the motion and on Newton's Second Law. Can this be right for this strange case where the acceleration is not *along* the motion but *across* it?

The actual force to keep a body in orbit can be found by experiment.

You need now to make an experimental test to see whether the THEORETICAL FORCE, $F = mv^2/R$, agrees in fact with the ACTUAL FORCE.

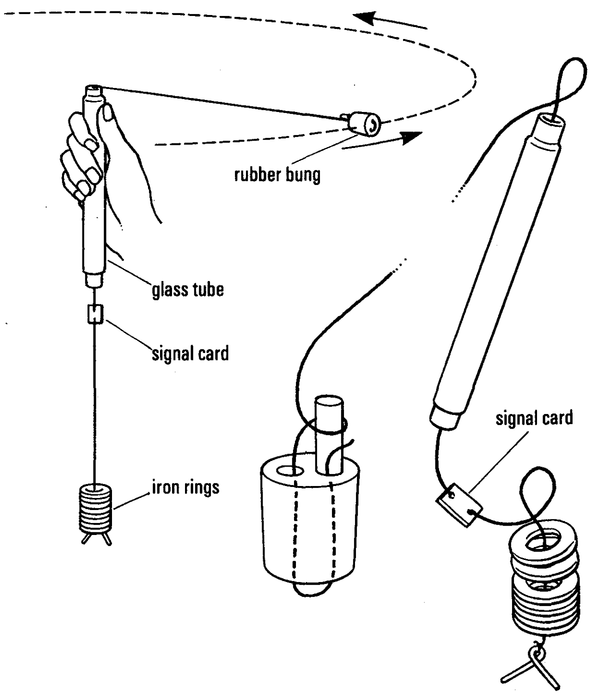
Experiment 6
Experimental test of $F = mv^2/R$

The scheme Make a test with the apparatus sketched. Whirl a block of rubber in a horizontal circle – as a model of an orbiting satellite.

Hold the block in orbit by a pulling cord, which is itself pulled by a load W hung on the other end.

The pull of the Earth on W will tell you the actual inward pull on the block.

Preparation of apparatus Tie a piece of cord about $1\frac{1}{2}$ metres long to the wire hook. Pass the other end through the two holes of the signal card; then through the glass tube; and then through one hole of the rubber bung. Then pass the other end back through the other hole of the bung and anchor it by plugging the hole with the wooden rod. Finally hitch the string round the wooden rod, or just tie it there.



The experiment Slip several iron rings over the wire hook as loads to provide the inward pulling force.

Adjust the signal card so that it will be just below the glass tube when the bung is out at the radius you choose for the orbit.

Whirl the bung round above your head, holding the glass tube in your hand. Keep the signal card just below the glass tube. The card will probably spin when it is not touching the tube and this will tell you whether it is clear of the tube or not.

Practise keeping the orbital motion going evenly. Then continue while your partner times 50 revolutions with a stopclock. At the start give him a count down: 5-4-3-2-1-; then start at 0-1-2-3- . . . and go on till 48-49- and stop at 50.

Then change with your partner and let him whirl the 'satellite' while you time 50 revolutions. Take the average time for a revolution.

Calculate the forces Measure the radius R of the orbit in metres. The indicator card will help you to do that.

You will need the mass of the bung, m, in kilograms. Find that using a balance.

Calculate the speed of the bung round the orbit, v.

Then calculate the THEORETICAL (predicted) inward FORCE mv^2/R.

Work out the ACTUAL FORCE due to the load W. (Remember that the Earth pulls 10 newtons on each kilogram.)

The test You wish to test whether $F = mv^2/R$ does successfully predict the force needed to hold the bung in its orbit. This THEORETICAL FORCE came from thinking about the motion with the help of Newton's Second Law.

The ACTUAL FORCE that keeps the bung in orbit is the inward pull of the cord.

Are these equal? That is the test question.

Although you may hope for close agreement you will know, when you have done the experiment, that this is rather a rough check. So it is also a test of your own experimental skills.

Questions If your test suggests you can trust $a = v^2/R$ and $F = mv^2/R$ you could use them to calculate the answers to some questions.

. . . .

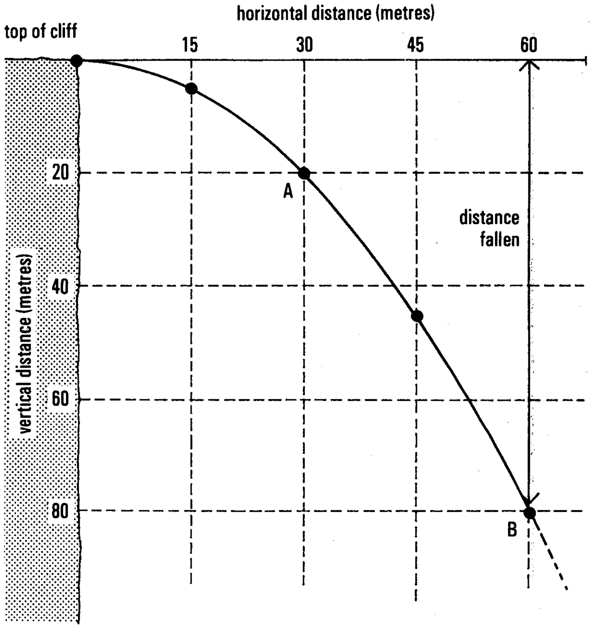
Progress Questions

Preparing for orbits

13. A stone falls with an acceleration of 10 m/s per second.

a. What is its speed after 3 seconds?
b. What is its average speed during the 3 s?
c. How far does it fall in 3 s?

14. You throw a ball straight forward from the top of a cliff with a speed of 15 m/s. It goes on going forward. At the same time it falls under gravity. The graph shows its actual path.



Use the graph to answer:
a. How long does it take to reach A? To reach B?
b. How far has it fallen when it gets to A? When it gets to B?
c. What is its average downward speed as far as A? As far as B?
d. Copy the graph and draw the curve for the ball when it is thrown forward at half the speed of the one shown.

Satellites

15. You can use the method of Question 14 to find out how far a satellite would fall if it is, say, 100 km up above the Earth and is moving at high speed parallel to the Earth's surface.

Taking the acceleration of free fall to be 10 m/s per second,
a. what is the downwards speed after 2 minutes (120 s)?
b. what is the average downwards speed if at the beginning of this time it was zero?
c. so how far does it fall in those 2 minutes? (Check: your answer should be 72 000 m. Put the fall into km.)

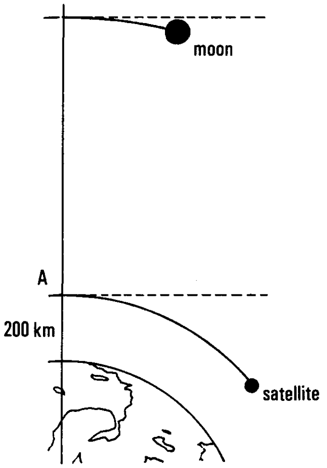
16. We believe that the Moon travels in a circle round the Earth. This is probably because the Earth's gravity pulls the Moon inwards, just like a satellite.

a. Guess how far the Moon is from the Earth (you can look for the data in the astronomy section). About a million km? one third of a million km? One quarter of a million km? One tenth of a million km? If you know it more accurately, write it down.

b. How long does the Moon take to go once round the Earth? About a day? About a month? About a year? If you know it more accurately, write it down.

c. About how long does a satellite close to the Earth take to go once round the Earth? About 90 s? About 90 minutes? About 90 hours?

d. The figure is not drawn to scale. It shows only roughly the paths covered by the Moon and by a



satellite in the same length of time. Look at the distances they both fall in that time. Copy and complete:

The Moon falls towards the Earth [more slowly/more quickly] than a satellite. So the Earth's gravity pull on each kilogram of the far away Moon is [bigger/smaller] than its pull on the nearby satellite.

17. A satellite is launched from a point A, 200 km above the Earth's surface as shown in the figure on p. 6.

a. Trace the sketch, and label on your copy the path which the satellite would follow after launching, *if* there were no gravity acting on it.

b. But there is gravity acting on it. Sketch the path (A, B, or C) which the satellite would follow if its launching speed was

(i) just right to keep it in circular orbit,
(ii) a little too fast,
(iii) a little too slow.

A formula needed

18. When a space vehicle is sent off, whether it is a satellite circling the Earth or a mission to the Moon, careful calculations of forces and velocities are needed. One thing we need is a theory to do the job.

When something travels in a circle instead of in a straight line its velocity is changing *direction* all the time.

Say why it changes.

The force needed to keep the direction changing is given by $F = mv^2/R$, where

F is the size of the force in newtons,
m is the mass of the object in kg,
v is the steady circular speed of the object in m/s,
R is the radius of the circle it travels round in metres.

Use this formula in the next few questions.

19a. What force is needed to keep a $\frac{1}{2}$-kg object moving at 3 m/s round a circle of radius 2 m?

b. What force is needed to keep a 2-kg object moving at 3 m/s round a circle of radius 2 m?

c. Copy and complete:

Something with a big mass needs a [big/small] force to keep it moving in a circle.

d. *Think about this:* you whirl a small, light lump of metal round on a piece of string. Then you whirl a heavy lump at about the same speed on the same string.

(i) What difference would you expect to feel?
(ii) How does this fit in with (c)?

20a. What force is needed to keep a $\frac{1}{4}$-kg object moving at 4 m/s round a circle of radius 2 m?

b. What force is needed to keep a $\frac{1}{4}$-kg object moving at 4 m/s round a circle of radius 1 m?

c. What force is needed to keep a $\frac{1}{4}$-kg object moving at 4 m/s round a circle of radius 4 m?

The testing experiment

21. This question asks about the experiment with the whirling rubber bung, to test the theoretical prediction $F = mv^2/R$. Two pupils made the following measurements:

Experiment A: Radius of circle: about 30 cm.
Force used: Earth's pull on 6 iron rings.
Time for 50 revolutions: 40 s.

Experiment B: Radius of circle: about 30 cm.
Force used: Earth's pull on 24 iron rings.
Time for 50 revolutions: 21 s.

Look at the two speeds and then at the two forces. Now copy and complete: The speed in Experiment B is about [half/double/four] times the speed in Experiment A. The force in Experiment B is about [half/double/four] times the force in Experiment A. The theory shows that for double the speed you need [half/double/four] times the force. So this experiment [does/does not] fit with the theory.

....

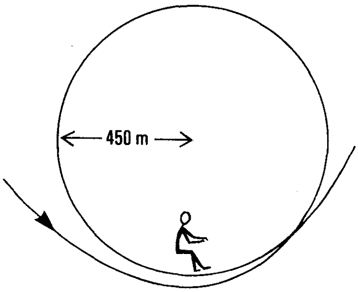
Questions

Local orbits

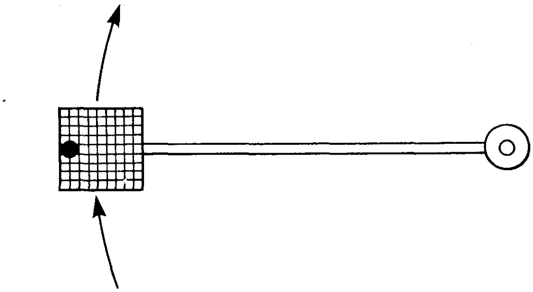
22. A motor cyclist is travelling at 20 m/s (72 km/hour). He comes to a sharp corner where the road has a radius of 30 m. He leans over as he tries to round the corner. Does he succeed?

Assume (man + bike) total 100 kg. Assume that the *maximum* force that road friction can exert on his tyres – in any direction – is just equal to the *weight* of (man + bike).

a. Calculate the weight of (man + bike) in proper units.
b. In rounding the corner he is following part of an orbit. What provides the needed force?
c. Find out whether he can succeed.
d. Explain how you arrived at your answer to (c).
e. Can he succeed if the radius of the road is 50 m and he keeps the same speed?
f. (*More advanced*) Suppose the radius of the road is 40 m. At what speed could he *just* succeed, if he leans over at the same angle as before?



23. A pilot in a light aircraft loops the loop in a vertical circle. At the bottom of the loop, where he is moving fastest, he is sitting upright, his feet towards the ground. His speed is then 150 m/s and he is flying in a circle of radius 450 m. Unless he takes proper precautions, he will 'black out'. Explain why.



24. You are inside a cage which is being swung round rapidly as in the sketch – the sort of thing you might pay to have done to you at a fair. Afterwards you say to a friend that '*centrifugal* force flung me against the outer wall and kept me pressed there'. 'Rubbish', she says, 'there is no centrifugal force; you just tried to go straight on, as Newton said.' Explain what happened to you from your friend's point of view, that is, in terms of *centripetal* force.

25. (*Advanced*) Explain using centripetal force (not centrifugal) how it is that a spin-drier can extract water from wet clothes.
b. A spin-drier has a tub which is 0.25 m in radius. It makes 5 revolutions per second. What is the value of the centripetal acceleration (v^2/R) at the rim of the tub?
c. Your answer to **b** should be in m/s per second. The acceleration of gravity, g, is 10 m/s per second. How many times gravitational acceleration might the owner be using to dry clothes?

Earth satellites

26. If a satellite is in orbit quite near to the Earth's surface, gravity gives it an inward acceleration g just as for any other projectile.

$$\therefore \frac{v^2}{R} = g \qquad \text{(Equation A)}$$

Since v is the satellite's speed along the orbit

$$v = \frac{2\pi R}{T} \qquad \text{(Equation B)}$$

where T is the time the satellite takes to go round once.

a. Put these two equations together to make an equation that reads

$$g = \ldots ? \ldots$$

(with only R and T in it and NOT v).

Then change that to an equation that begins with $T^2 = \ldots$

b. Calculate T. Take R, the radius of the Earth, to be 6.4×10^6 m, and give g its usual value. You may take the value of π^2 as approximately 10. Calculate the value of T in seconds, then in minutes.

27. A communication satellite stays above one place, for example a point in the middle of the Atlantic Ocean. Then telephone talk or a television programme can be sent from Europe to the satellite and relayed from the satellite to America.
a. Is such a satellite moving? If not, how does it stay up? If it is moving, why do we think of it as staying still?
b. What must be the period (orbit time) of a successful communication satellite?
c. Some satellites have orbits which are ellipses, but a communication satellite's orbit *must* be a circle. Explain briefly why.

The formula

28a. If an object moving in a circle has a centripetal acceleration, then there must exist a centripetal force producing that acceleration. Mention *three* examples of an object moving in a circular path or orbit, and say in each case what agent provides the centripetal force.
b. The acceleration is v^2/R, so the force must be mv^2/R. Why?
c. In the expression v^2/R, where did the v^2 come from? Or why v^2 rather than v or $1/v$ or v^3, etc.?
d. In the expression v^2/R, where did the $1/R$ come from? Or why $1/R$ rather than R or R^2 or $1/R^2$ etc.?

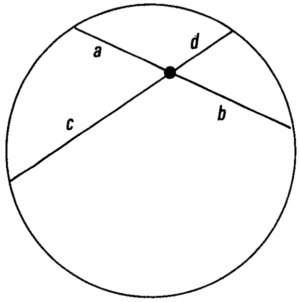
Finding the formula

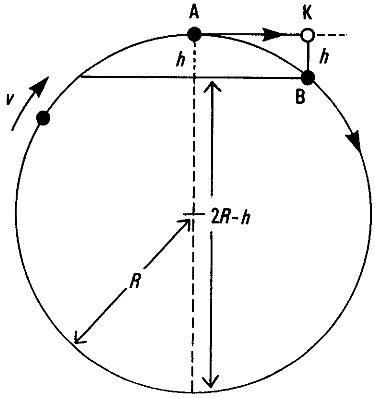
29. Look at the proof of $a = v^2/R$ (pp. 8–9) and at the diagram on page 8 and explain, as if to another pupil:
a. why FG is labelled CHANGE OF VELOCITY,
b. what similar triangles are,
c. why FDG and AOB are similar triangles,
d. what CHANGE OF VELOCITY/TIME is,
e. why $\dfrac{\text{CHANGE OF VELOCITY}}{\text{TIME}} = \dfrac{(\text{AB}) \times v/R}{t}$

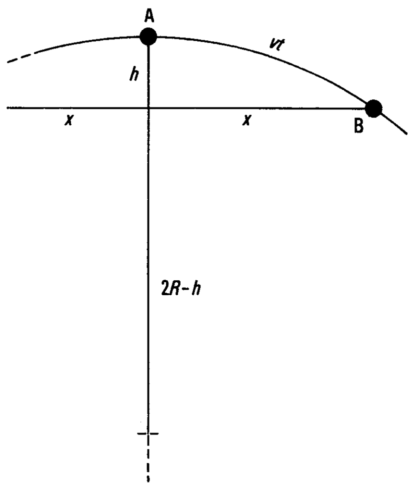
30. *The derivation of the formula for centripetal acceleration using the 'crossed chords' theorem.*

The theorem tells us that, if two chords of a circle cross each other, so dividing one chord into lengths a and b and the other into lengths c and d

$$a \times b = c \times d$$







Suppose an object moves in orbit from A to B with speed v in time t. If it had been left alone it would have continued along the tangent to K (Newton's First Law). But it reaches B along the orbit instead, so we say it falls a distance h from K to B. We may now write

$$x \cdot x = h(2R - h)$$

a. Explain, as if to another pupil, why this is correct.

Then we may say $x^2 \approx h2R$

and $h \approx x^2/2R$

b. Explain why we are able to leave the h out of $(2R-h)$.

In the limit, when B approaches A,

$$h = x^2/2R$$

and arc (AB) = length x

But x is the distance travelled in time t. So $x = vt$,

$$\therefore h = \frac{(vt)^2}{2R} = \frac{1}{2}\frac{v^2}{R}t^2 \qquad (1)$$

Now h is the distance fallen from K towards the centre of the orbit. So we also have

$$h = \tfrac{1}{2}at^2 \qquad (2)$$

And we see that $$a = \frac{v^2}{R} \qquad (3)$$

c. Explain how equations (1) and (2) lead to equation (3).

31. (*Advanced, optional*) Whether you have used the method given in the chapter of proving v^2/R for centripetal acceleration or the method given in Question 30, you have had to make approximations, or use phrases such as 'for practical purposes'. Yet the final relation, $a = v^2/R$, is not an approximation; mathematically it is correct. Explain (as if to another pupil) why this is so.

Experimental tests

In answering Questions 32 and 33

(i) draw a sketch of the apparatus you use. Of course one sketch will do for both questions, if you use the same apparatus;

(ii) say what measurements you take and how you take them;

(iii) say how you would use the measurements to arrive at the result you are asked to obtain.

32. Explain how you would show experimentally that the centripetal force, required to keep an object moving in a circular path, varies as the *square* of the speed of the object ($F \propto v^2$).

33. Explain how you would show experimentally that centripetal force varies inversely as the radius of the circular path ($F \propto 1/R$).

Note: this is not quite straightforward. The question means that centripetal force varies inversely as R if the velocity is the same for different radii.

Physics (Nuffield) O Level Examination questions*

* These questions are reproduced here by kind permission of the Oxford and Cambridge Schools Examination Board.

N.1 (1971)

(*a*) At its surface the Earth exerts a gravitational pull of about 10 newtons per kilogram. What is the force on a mass of 50 kilograms?

(*b*) What effect will this force have on this mass if it is allowed to fall freely?

(*c*) Suppose that the mass was projected horizontally. What can you now say about its motion?

(*d*) If it were travelling horizontally at 15 metres per second as it left a platform 1.8 metres high, how long would it take to fall to the ground?

(*e*) Where would the mass hit the ground?

(*f*) Suppose the mass were to be projected horizontally from a platform at a height of 200 kilometres, which is equal to the height of the satellite orbit shown (Fig. 1). How far will it fall below this level in 100 seconds? You can assume that the strength of the Earth's gravitational field at this height is the same as it is at the Earth's surface.

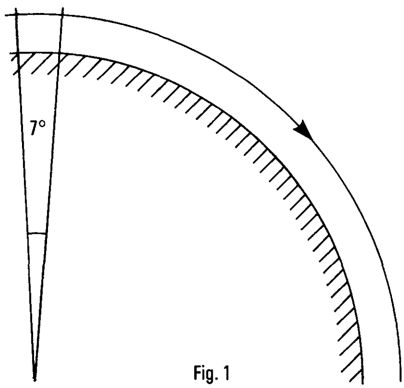


Fig. 1

(*g*) A scale drawing based on this calculation shows that, in this time, a satellite will have turned through an angle of 7° in its orbit around the Earth. How long will it take to complete an orbit?

(*h*) The same treatment might be applied to the Moon and, if so, it will be found that the Moon will cover 0.9° of its orbit in 100 seconds. This leads to a time of orbit of about 11 hours. But the Moon is known to complete an orbit in 27 days, which is sixty times longer. Can you suggest a reason for this difference?

N.2 (1969)

This question is about a space-station, to be in orbit several thousand miles above the surface of the Earth. It will be provided with 'artificial gravity', obtained by building the station in the form of a ring-shaped doughnut, and then making it spin about an axis through O, perpendicular to the plane of the paper in Fig. 2. Fig. 3 shows a semi-circular half of the space-station, and also a square-shaped room ABCD in which people can live. E is the centre point of the room.

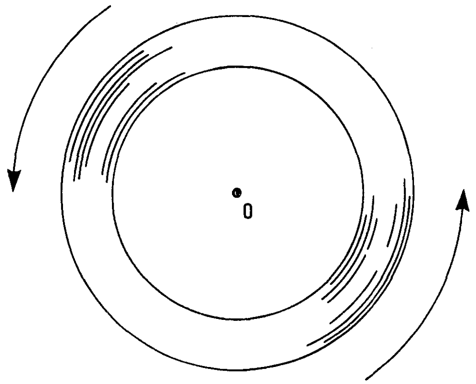


Fig.2

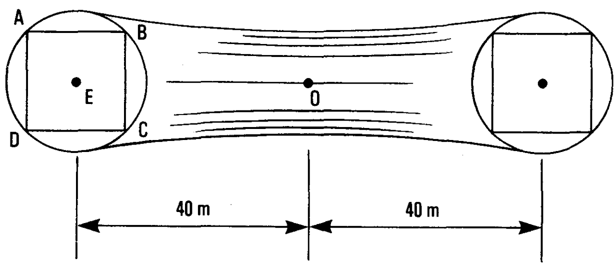


Fig. 3

(*a*) Which is the floor (i.e. place to stand on) in room ABCD? What happens to an object released at E (as seen by a man in the room) when the station is steadily rotating? What happens to an object released at E when the rotation is still being speeded up to its final value?

(*b*) The length of the radius OE is 40 metres. The rate of rotation is just sufficient to provide, at E, an 'artificial gravity' having the same effect as that of the actual gravitational acceleration g at the Earth's surface. What is the tangential speed of E in its motion round O (metres per second)?

(*c*) A man in a space-suit is sent out, through an air lock, to tighten nuts on the outer rim of the station. The man is safely held by a rope, but he lets go of the spanner. Use Newton's First Law to explain what happens to the spanner.

(*d*) How could the station be set rotating by the use of two jets? Where would you mount the jets? Could it be set rotating by one jet only, and if so, what advantage is there in using two?

(*e*) Discuss whether an electric motor could be used, instead of the jets, to set the station rotating.

CHAPTER 2
Measuring electrons

Estimate of e/m; comparison with e/M of protons; positive ions and the mass spectrometer; an atom model

Scientists – physicists, for example – are concerned with two aspects of science. They enjoy increasing their understanding by asking questions of Nature – that is, by doing experiments – and then painting a fuller picture to describe Nature for themselves and for you. They also offer practical uses of the knowledge they gather.

In this chapter we shall concentrate on how some of our knowledge of the electron is gained. You have already seen a film to see how the electron's charge was measured. Now we ask you to join in an experiment that will tell you the electron's tiny mass. This is one of the few examples of the careful physical measurements made in the business of building powerful knowledge which we can offer in a school physics programme. We hope they will be enough to give you a sense of understanding both about atoms and the insides of atoms and about scientists.

Preparation for the experiment: the electron gun You are going to join in a measurement of the mass of the electron. To prepare for that, you should make sure you know about the electron guns that make narrow beams of electrons. As you saw in Year 4, an electron gun is a diode with a heated cathode from which electrons boil off and a

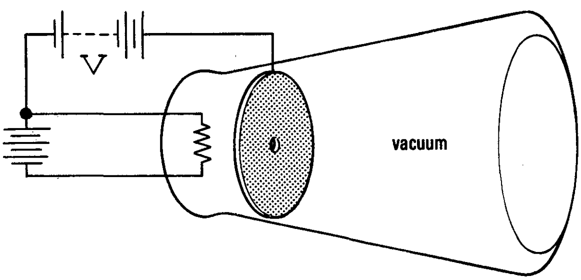
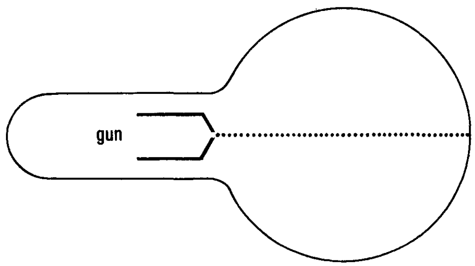


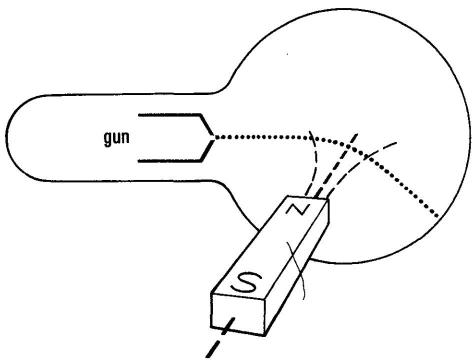
plate with a hole in it. A large potential difference is applied between the cathode and the positive plate to accelerate the electrons across the vacuum between them. Those electrons that pass through the hole go straight on out and keep constant speed thereafter. So the plate is the 'muzzle' of the electron gun.

Glowing gas In some tubes with an electron gun, a tiny amount of gas is left in the tube to make the path of the electrons visible. The atoms of the gas give out a glow of light after they have been hit by electrons.

Demonstration 7
Electron stream in a fine-beam tube; effect of a magnetic field

Look at a stream of electrons shot from an electron gun in a glass globe containing a thin gas to make their path visible. Once out of the gun muzzle, the electrons do not accelerate. Do they move in a straight line? Is each in equilibrium?



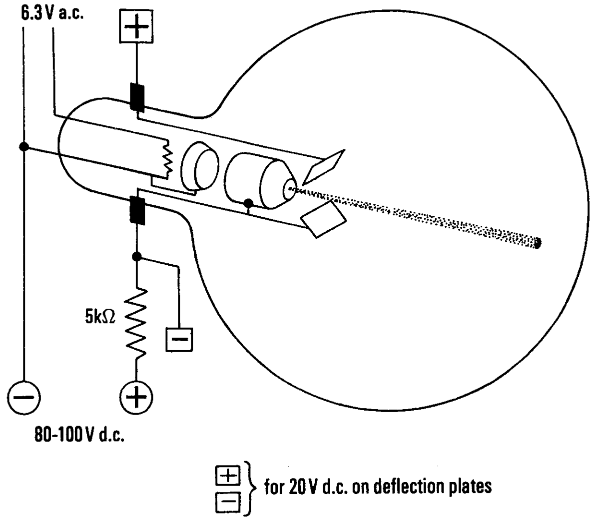


Watch the effect of a magnetic field when a magnet or a coil carrying current is brought near.

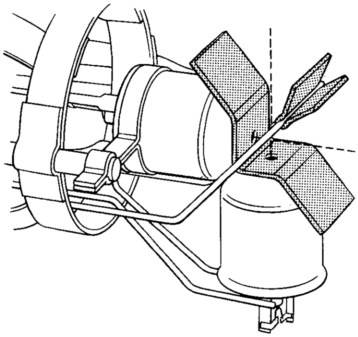
What kind of force is the magnetic field exerting on the current of electrons? Can you give the force a name which you met in Year 3?

Demonstration 8
Electric field deflects an electron stream

Watch the effect of an electric field on the beam.



Just beyond the gun muzzle are small metal plates which can be connected to a battery, so as to apply an electric field across the beam. See this with the tube's horizontal gun in action.

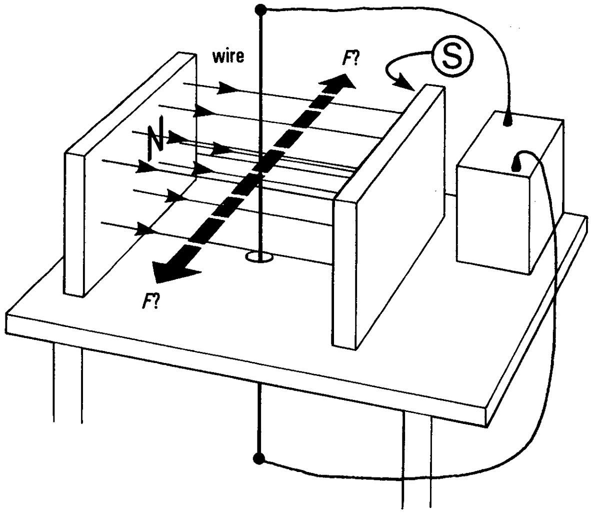


If you can see the connections, so that you know which plate is connected to the positive terminal of the battery, you can find out whether the moving things in the beam carry positive electric charges or negative ones.

Note that an electric field pushes or pulls the charged particles *along* its own field lines. A magnetic field has a quite different effect: a catapult force *perpendicular* to both the field and the stream.

CATCHING UP ON CATAPULT FORCES

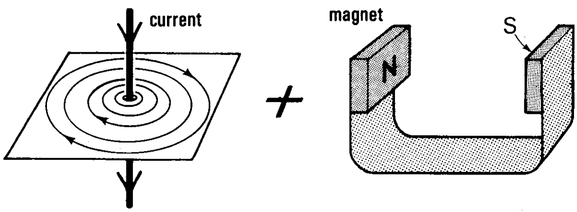
You probably saw 'catapult forces' used in Year 3. In case you are not quite sure of that work, here are some reminders.

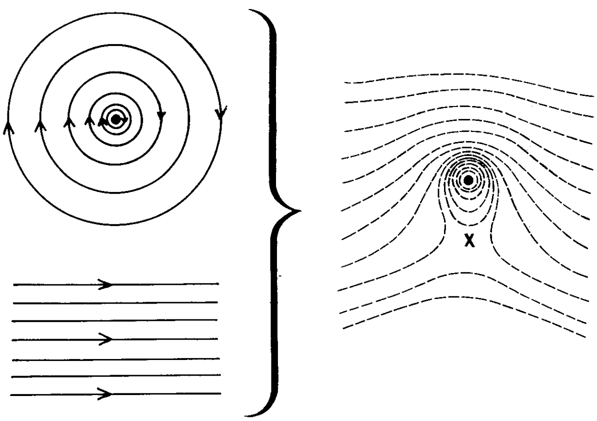


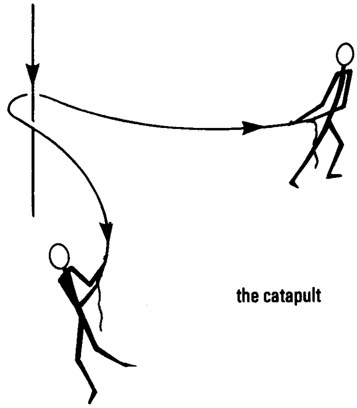
Force *F* on the wire is in or out, perpendicular to the paper.

The force is exerted by a magnetic field on a wire carrying an electric current. The magnetic field must run *across* the wire (perpendicular to it); then the force is perpendicular to both the wire and the field, as in the sketch.

The name catapult comes from the pattern of the combined magnetic field (of magnet and current). Imagine the field lines to be stretched elastic strands which would catapult the wire; that would tell you the direction of the actual force.





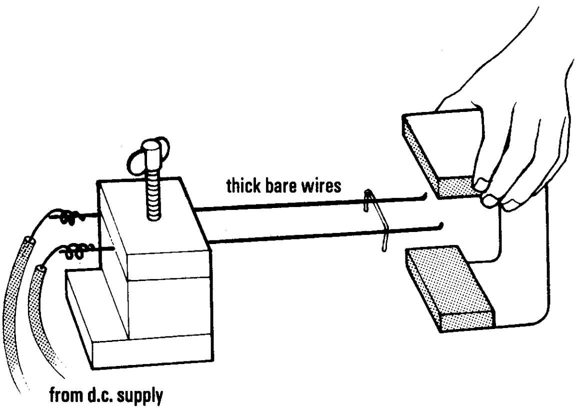


Hence its name. (See the sketches.) Of course, the field lines – like contour lines on a map – don't actually exist, but they make a useful picture.

As a reminder of the catapult forces, try an experiment.

Experiment 9
Movable bridge and catapult force

Clamp two 15-cm lengths of thick, *clean*, bare copper wire in a support block as shown. Use a third piece of wire to make a movable bridge resting on these two rails.



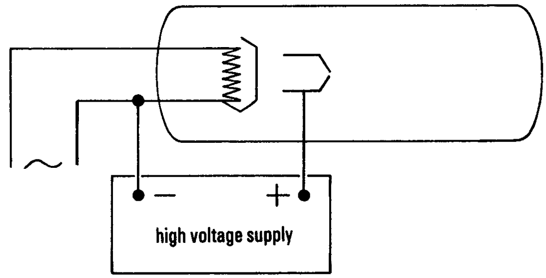
You may know from an earlier experiment how to place the U-magnet. Place it so that you expect it to make the bridge move when you switch the current on or off. If you are not successful try other positions for it. What happens when you reverse the current?

If you did not see the real catapult field pattern marked by iron filings, you should have a chance to see it either as a special demonstration now, or as a demonstration that you yourself set up to show to others, sometime during this year.

Catapult forces are useful; they drive electric motors – large and small – and they also play a part in some loudspeakers and in some types of microphone.

Progress Questions

1. This is a sketch of an electron gun.



a. Copy the sketch and label the gun muzzle (anode) and the heated cathode.

Electrons move away from the cathode because of the high voltage supply.

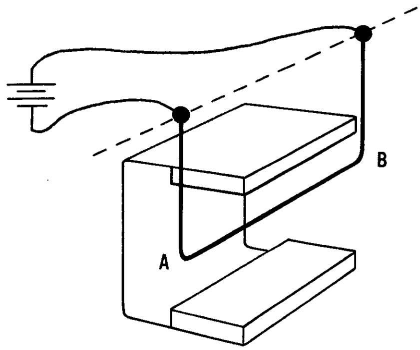
b. Where do most of them go?

c. You could get the electrons moving using a low voltage. Why is a high voltage used?

d. The tube has most of the gas molecules pumped out. If a lot had been left in, what effect would that have had on how far the electrons could travel?

Catapult forces

2. The sketch shows a wire swing AB hanging in the magnetic field of a U-shaped magnet. When there is a current in the wire, electrons are moving along AB.



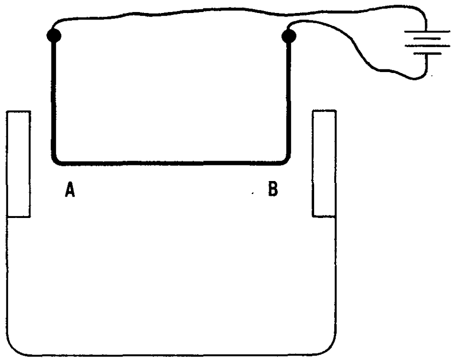
a. What will the wire swing do when the current is switched on?

b. Does this show that there is a force on moving electrons in a magnetic field?

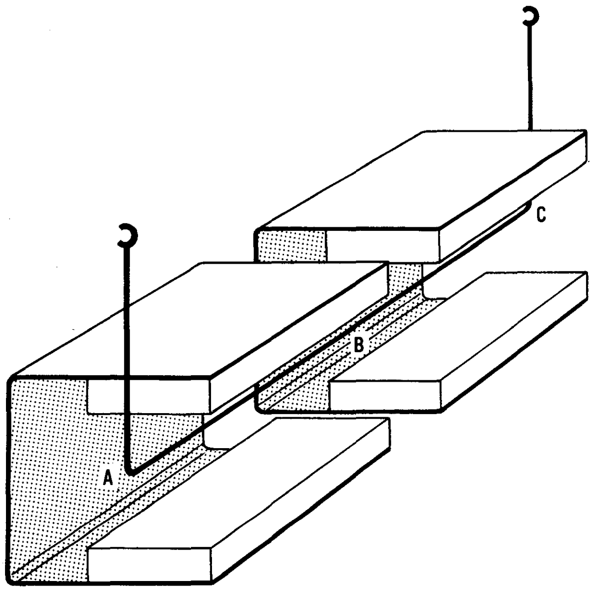
c. If the battery is turned round so that the electrons move the opposite way, what will the wire swing do?

d. The U-shaped magnet is then turned upside down. That reverses the magnetic field. What will the wire swing do? Is it the same as before?

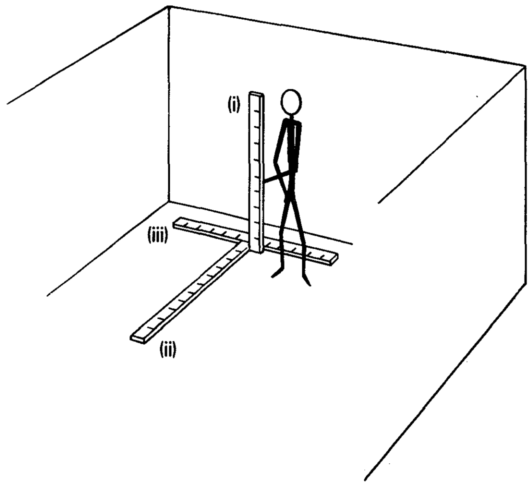
3. In the experiment in Question 2, the electrons in AB are moving across the magnetic field and at right angles to it. We could arrange the magnets as in this sketch so that the electrons move *along* the magnetic field. Would the swing then move, when the current is switched on?



4. You have found that there is a force acting on a wire carrying current across a magnetic field. An electric motor and an ammeter both use this force.
a. Suppose the magnetic field is made stronger. Would the force be the same? Larger? Smaller?
b. The current is increased. Would you expect the force to be the same? Larger? Smaller?
c. Suppose the length AB of the wire in the field is increased to AC. That could be done by putting two magnets side by side as in the sketch. Would the force be the same? Larger? Smaller?



5. Take three rulers or pencils, and place them so that
(i) one is in an up-and-down line (vertical),
(ii) the second is in a line from the front to the back of the room,
(iii) and the third is in a line from one side of the room to the other.



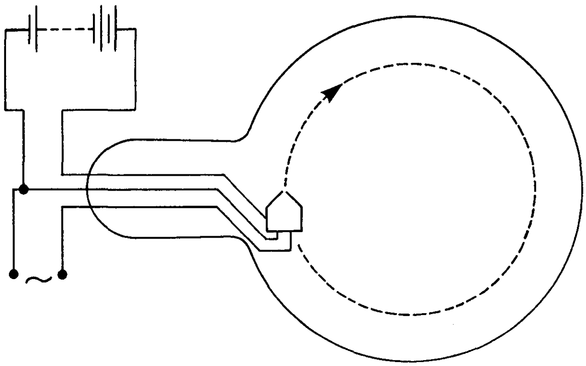
a. Which of these rulers is showing the way the current can go in Question 2?
b. Which is showing the way the magnetic field can be?
c. Which is showing the direction of movement?

6. Do you see that the three rulers in Question 5 are all at right angles to each other? When the field is up-or-down and the current is to-front-or-back, the movement will be to-left-or-right. Now suppose the field is left-or-right and the current is up-or-down, which way do you think the movement will be?

Fine-beam tube

7a. In a fine-beam tube there is a little gas at low pressure. What do the gas molecules do when they are hit by electrons, that enables you to see where the electrons have been?
b. Suppose you gradually increase the gun voltage from about 40 volts. What happens to the distance travelled by the electrons through the gas?
c. What effect does increasing the gun voltage have on the speed at which the electrons come out of the gun?
d. Why do the electrons keep that speed, even when their path is bent into a circle?

8. The sketch shows a fine-beam tube. A stream of electrons is fired from an electron gun. This



stream starts upwards, then it goes round in a circle. There is a magnetic field at right angles to the sheet of paper.

a. What makes the electrons travel in a circle?

b. Suppose the electrons are made to go slower by decreasing the gun voltage. Does the circle then get bigger or smaller?

c. What else can we change, instead of the gun voltage, to make the circle smaller?

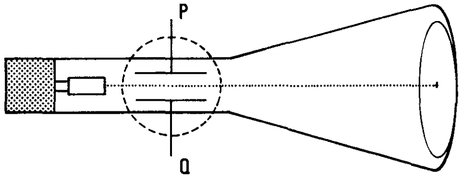
....

Questions

Electron streams

9. The electron beam is visible *inside* the fine-beam tube. An ordinary cathode-ray tube does not have a visible beam. How is the beam in the fine-beam tube made visible?

10a. The diagram is a sketch of an oscilloscope tube with a beam going straight through the tube



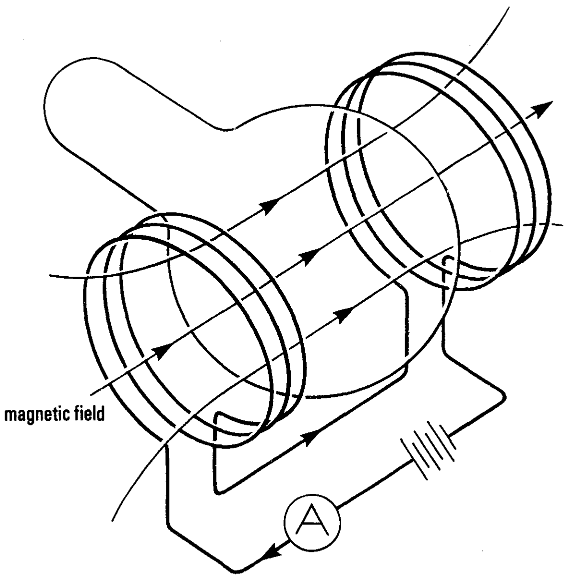
and forming a bright spot on the screen. Draw a similar but larger sketch showing the path of the beam when a potential difference is applied between P and Q with P positive and Q negative. Omit the dotted circle.

b. Draw a second sketch, omitting P and Q, but showing what happens when the beam passes through a magnetic field which covers the space shown by the dotted circle. The direction of the magnetic field is such that a wire carrying a *positive* electric current going from left to right would be deflected towards the top of the paper.

Demonstration 10
Fine-beam tube: effect of a uniform magnetic field

Remember what happened when you brought a bar magnet near to the side of the tube. Think about the direction of the magnet's field – lines sprouting straight out from the magnet's N pole. The field ran *across* the stream of electrons, perpendicular to the stream, when it had most effect. And which way was the stream then made to move? (Try that again if you like.)

The magnetic field exerts a catapult force on the stream of electrons, just as it would on any other electric current.

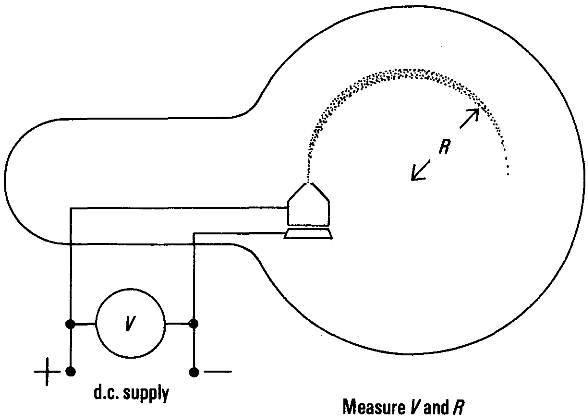


Now make a *uniform* magnetic field – with the same strength and direction across the whole tube. That can be done by sending a steady current through a pair of coils suitably placed. Then the catapult field has the same steady value at all places along the stream, as long as the electrons keep the same speed.

Since the catapult force is always perpendicular to the stream (as it is when it acts on any electric current), it does not change the speed of the electrons. It only pulls their path into an orbit. It acts as a tether, like the string that holds a whirling block in orbit. With that constant catapult force, the orbit is a circle.

Further preparation for the experiment
Two measurements for electrons

With the fine-beam tube we make two measurements and extract two pieces of information about



the electrons in the stream: their speed v (given them by the gun) and the value of

$$\frac{\text{ELECTRIC CHARGE}}{\text{MASS}}$$

e/m, for a single electron. For those two, v and e/m, we measure the gun voltage V and the radius R of the orbit of the stream in a measured, uniform magnetic field.

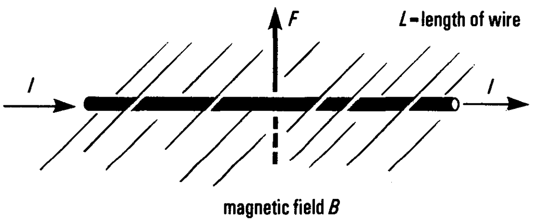
Gun voltage measurement: energy of the electrons If the voltage between the cathode (where the electrons boil off) and the gun muzzle (anode) is V and an electron's charge is e (measured in coulombs), each electron gains the following energy between the cathode and the gun muzzle:

$V \times e$ (measured in volts × coulombs, which are [joules/coulomb] × [coulombs], that is, joules)

Since the electron is being accelerated in a vacuum, all the energy it gains is kinetic energy.

Therefore $\frac{1}{2}mv^2 = Ve$ Equation (I)

We measure the gun voltage with a voltmeter, but we need another measurement before we can separate out the values of v and e/m. We use the effect of a magnetic field for the necessary second measurement. So we must be able to measure a catapult force.



A formula for the catapult force When a horizontal wire carrying a current I is placed across a horizontal magnetic field, the catapult force on the wire is vertically up or down. If we double the current in the wire, the catapult force is doubled. If we have twice the length of wire carrying current, all perpendicular to the magnetic field, the catapult force is doubled. So, for a length L carrying current I, the force is given by F in

$$F = (B) \times (\text{current}, I) \times (\text{length of wire}, L)$$

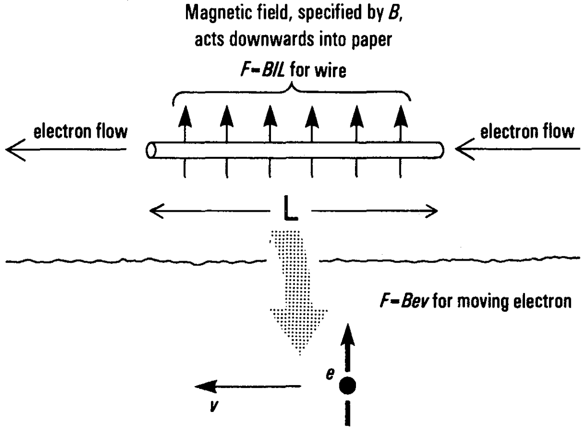
or

$$F = BIL,$$

where B is a measure of the magnetic field.

Fortunately, in your measurements on electron streams, you need not know how to calculate B from the coils and currents that are used to produce the magnetic field. Instead, you will be able to measure B directly for the actual magnetic field you use in your experiment.

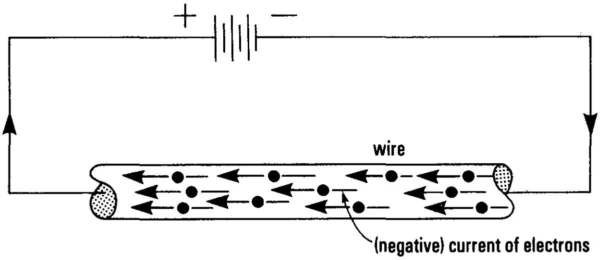
A major shift in knowledge is needed The catapult force is BIL on a wire carrying current I. But what is the force on a *single particle* carrying a charge e (for the electron) moving with a speed v? We will show that ev takes the place of IL.



That shift of knowledge from the case of a current in a wire to the case of a moving charged particle will seem a strange step. It was a very big and difficult step for all scientists when they first had to extend the well-developed theory of electric circuits and forces to moving electrons and other charged particles, late in the last century.

Is the new use safe? There is evidence from the Hall effect that there are loose negative electrons in a wire that is carrying current. As these drift along in the electric field they make up the current.

Catapult force on one electron Since we believe that there are moving electrons in a wire, drifting along when a current flows, we picture them there and try to calculate the catapult force on a single electron – inside the wire or outside. We



Without the applied magnetic field electrons just drift along, driven by the electric field. (They also have a very rapid, random motion, with or without any applied electric field.)

take the catapult force on the whole wire, then say that is the force on all the *moving* electrons in it; then boil that down to the force on each electron.

To show that IL in BIL can be replaced by ev The sketch shows a wire carrying a current. Think about the section XY in which there are N electrons all drifting with speed v towards Y. Post an imaginary observer at the outgoing end Y and ask him to count the passing electrons, like a child counting cars as they go by. He starts counting when the first electron emerges at Y. He finishes counting when the last electron (the one that was at X when he started counting) arrives at Y a time t later. That electron has travelled a distance of L with speed v. In that time t, all the N mobile electrons (that were originally in XY) pass Y.

In time t the observer counts a total charge which is:

N (the number of moving electrons originally in XY)

$\times\, e$ (the electron charge)

If he divides that total charge by the time, he is behaving like an ammeter, which counts coulombs passing per second. Therefore the observer says:

the current is $\dfrac{Ne}{t}$

But the length L from X to Y is vt, because the electron that started at X just gets to Y after time t.

$$\therefore \quad I = \frac{Ne}{t} \text{ and } L = vt$$

$$\therefore IL = \frac{Ne}{t} \times (vt)$$

or $IL = Nev$

Then the catapult force BIL is the same as $BNev$.

But that is the force on N moving electrons in the section XY.

$\therefore$ the force on a *single* moving electron is Bev.

Holding the electron stream in orbit Now you can deal with single electrons moving across a magnetic field. You should re-read the story leading to $F = Bev$ above because you need to trust it in the experiment itself.

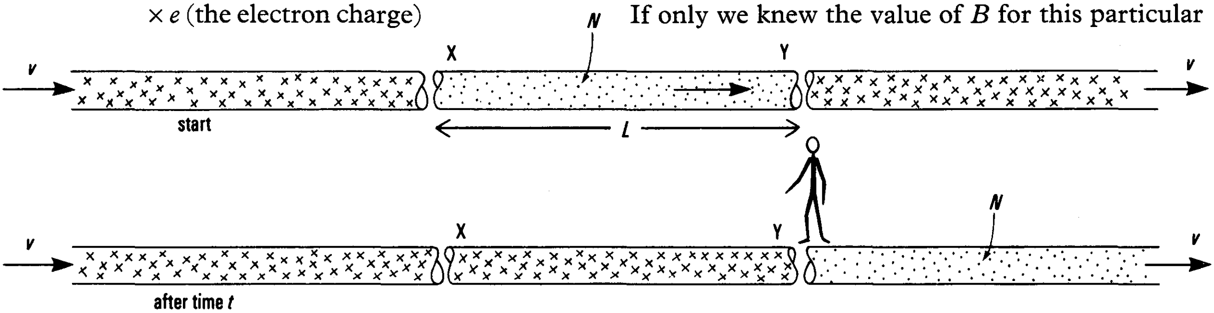
We make a uniform magnetic field by sending a current through two round coils suitably placed, one each side of the fine-beam tube. The catapult force exerted by that magnetic field on a moving electron holds it in a circular orbit. The whole stream of electrons is pulled into a circular path.

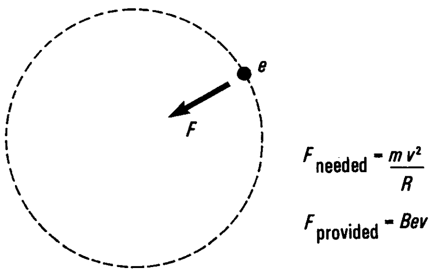
The inward force, on one electron, that is *needed* if the electron is to follow the orbit, is mv^2/R, and you now know that the force *provided* by the magnetic field to hold it there is the catapult force Bev.

Then, for a successful orbit, mv^2/R must be equal to Bev.

$$Bev = mv^2/R \qquad \text{Equation (II)}$$

If only we knew the value of B for this particular

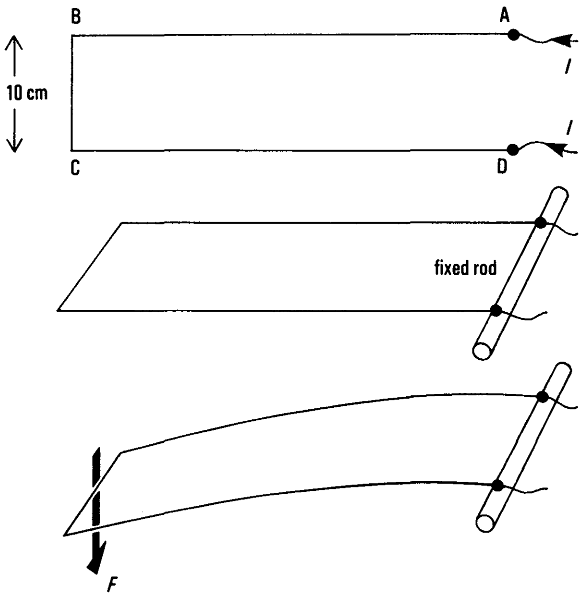




electron in orbit

magnetic field, we could find out a lot about electrons in the stream. And we *can* find the value of B. We *measure* B by taking the fine-beam tube out of the magnetic field and putting a special *current balance* in the field instead. The balance will measure the actual force on a short section of wire carrying a known current.

Current balance The balance is a long loop of bare copper wire ABCD. One end BC is adjusted to a known length of 10 cm. The wire is firmly

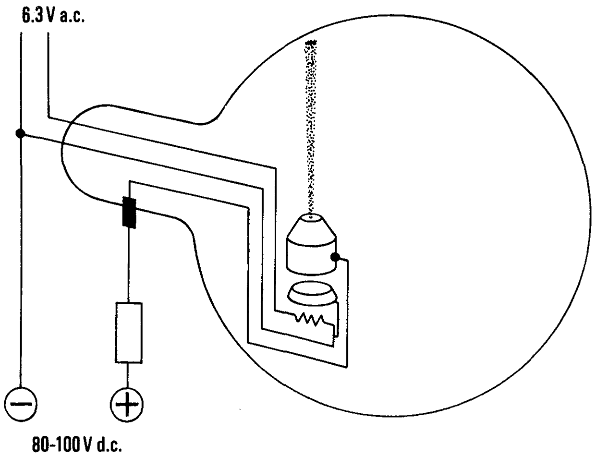


clamped at the other end. The wire's elastic forces control its sagging when we hang a small load on BC or apply a catapult force to BC.

Now we are ready for the main experiment.

Experiment 11
Measuring speed and e/m for electrons in a stream

(i) Start the heater for the gun, and give it time to heat up and provide a good supply of electrons.



Apply a gun voltage. Turn on the magnetic field current in the two coils, adjust that current, or adjust the gun voltage to make the stream form a large clear orbit.

Read the gun voltage and record it. You will use that in:

$$\tfrac{1}{2}mv^2 = Ve$$

(ii) Note the reading of the ammeter for the current through the coils, because you will need to keep that current the same when you use the current balance to measure B.

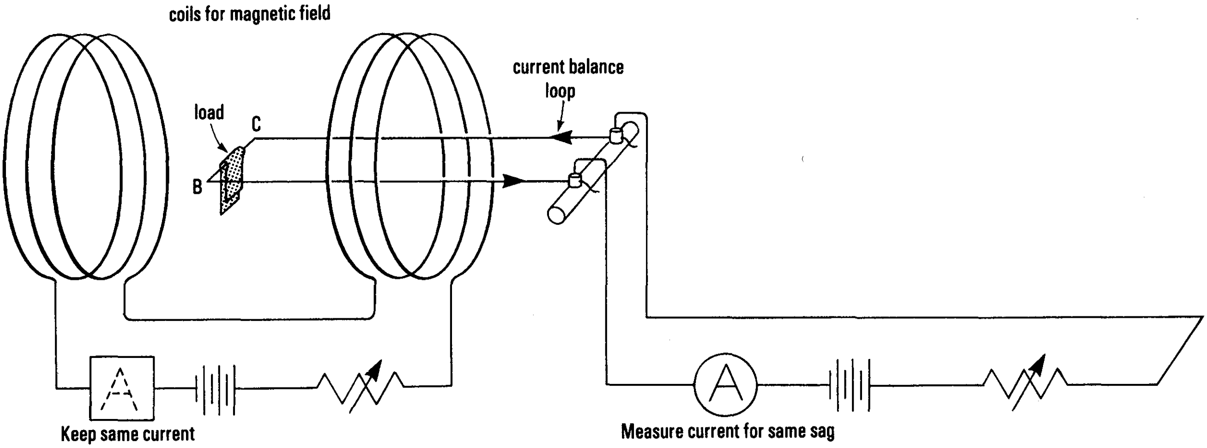
(iii) Measure the diameter of the orbit by holding a ruler up beside the tube. Or you might arrange a virtual image of an illuminated scale *inside* the tube, where the orbit is, and so measure the diameter. Even if you make a rough guess by holding a ruler nearby it will still give you an estimate of important things in atomic physics.

Halve the diameter to get the radius, R, and express that in metres.

(iv) Measure B for the magnetic field. *Keep the same current running through the coils*, but remove the tube and install the current balance itself, with its cross-bar BC where the orbit was.

Hang a small piece of ticker tape as a load on the cross-bar BC, so that the loop sags, lowering the cross-bar a few millimetres. Then turn on the current in the loop and adjust that current, I, to match the effect of the tape load. You may either remove the load and find the current that makes the loop sag the same amount, or keep the load on and find the (reverse) current that brings the loop up to its original position with no load. Record the current I. It will be between 5 and 10 A.

Weigh a long sample of tape, say 1 m; and calculate from that the weight (in newtons) of the short load you use. Use that in $F = BIL$:



weight of tape load =
$B \times I \times$ (length of cross-bar)

From that calculate the value of B which belongs to the pair of coils and the current through them that you used with the electron stream.

(v) Results for electrons Now you know the value of B for the magnetic field you used to hold the electrons in orbit. You know B in

force needed for orbit = the catapult force
mv^2/R $\qquad$ Bev

$\therefore mv/R = Be$

And, from the gun voltage reading,

$\frac{1}{2}mv^2 = Ve$

Divide one equation by the other and keep v on one side by itself. You should do that algebra yourself.

ALGEBRA NEEDED HERE

Then, $v = 2V/BR$.

Calculate v from your measurements. That is the speed of the electrons as they come out of the gun, the speed they keep all the way round the orbit. That speed depends on the gun voltage but, as you have seen, it is not directly proportional to it. For a gun voltage of a hundred volts or so, the electrons have an enormous speed of several million metres per second.

This huge speed for electrons tells us something about them: in comparison with the charges we can put on large visible masses, the electron has an enormous charge for its size, so quite small electric fields can accelerate it to great velocities. No wonder electrons obey the signals very quickly in an oscilloscope or a television tube!

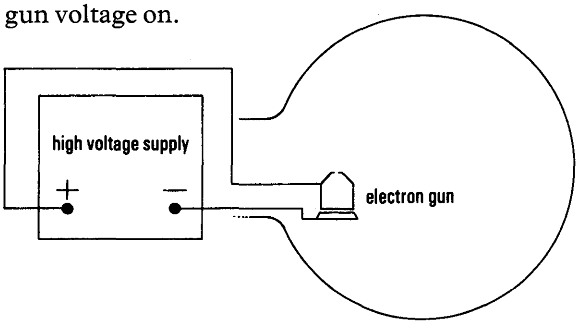
(vi) Now find your value of e/m. Charge/mass is the characteristic 'luggage label' that we attach to any charged atomic particle. It has many values for positive ions, but only one universal value for electrons. Wherever they come from all electrons have the same value of e/m.

Estimate the value of e/m from your experiment, by putting the value for the speed v which you calculated in either of your two equations ($\frac{1}{2}mv^2 = Ve$ looks easier). Work out your value of e/m in coulombs/kilogram.

Very careful measurements give $e/m = 1.76 \times 10^{11}$ coulombs per kilogram. Even if your estimate differs a lot from that, you should still be proud of it. It is a measurement in atomic physics concerning something far smaller than any atom.

Progress Questions

11. Here is a side view of a fine-beam tube with the gun voltage on.



a. Copy the sketch and show the kind of path the electrons would follow if you brought up one end of a magnet in a direction at right angles to the paper.

b. Repeat **a** but using the other end of the magnet. You are 'reversing the direction of the magnetic field.'

c. You could use coils carrying electric current instead of a magnet in parts **a** and **b**. What would you do to reverse the direction of the magnetic field made by the coils?
d. Suppose you increase the current in the coils. What effect will this have on

(i) the strength of the magnetic field?
(ii) the shape of the electrons' path?
(iii) the size of the electrons' path?

e. Suppose you increase the voltage applied to the electron gun. What effect would this have on the speed of the electrons? What effect would it have on the electrons' path?
f. Sketch the electrons' path. Draw on your sketch several arrows showing which way the force due to the magnetic field must act on the electrons.

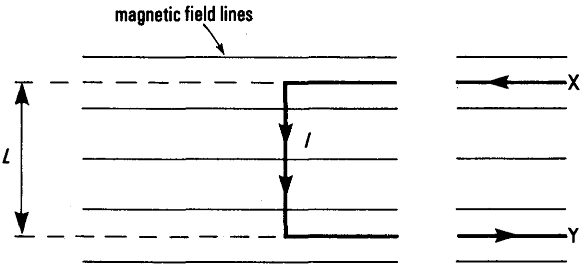
12. The experiment with the fine-beam tube can be carried out, using some theory, to find the speed of the electrons in the tube. What result did your class get for this speed? If you are not sure, try a guess. Which of the following speeds, all in metres per second, is the nearest?

10 100 1000 10 000 100 000
1 000 000 10 000 000 100 000 000 m/s

Do you know anything else that travels as fast as or even faster than this?

Questions

Catapult force formula
13. The sketch shows a piece of wire of length L, carrying a current I and placed in a magnetic field. The current enters and leaves the wire by two leads X and Y coming from a battery well outside the magnetic field.

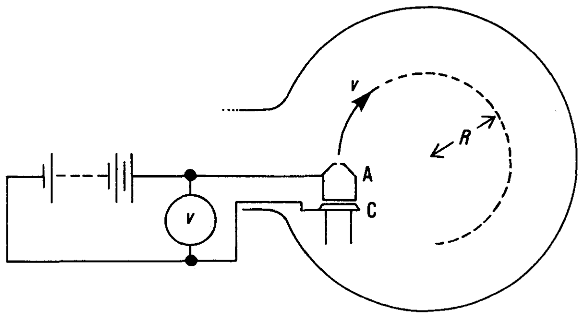


a. In what direction is the force on the piece of wire?
b. Why does no force act on the leads X and Y?
c. The force on the piece of wire varies directly as its length L and the current I. On what else besides I and L would you expect the force to depend?
d. If B = the force on a wire of unit length carrying unit current (or, more correctly, B = force per unit length per unit current), what is the force F on a wire of length L carrying current I? (Write $F = \ldots$ something in terms of B, I, and L.)

Measuring electrons
14. a. With no magnetic field, the electron beam in a fine-beam tube follows a straight path. How would you describe the path when a magnetic field is switched on?
b. If the path is circular, it is because a centripetal force is exerted on the electrons, given by $F = Bev$.

But we can also write an expression for the centripetal force needed by a particle of mass m if it is to move with a speed v in a circular path of radius R. What is this other expression?
c. Write an equation putting Bev equal to the second expression you wrote in (b).

15. The equation of **14c** contains an unknown quantity v, the speed of the electrons, as well as e/m. To find v and e/m separately we must use another equation as well. We get this by measuring the potential difference, V, between the cathode and the anode of the 'electron gun' from which the electrons come.
a. What does *potential difference* mean? And what does *1 volt* mean (in terms of coulombs and joules)? Look it up if you have forgotten.
b. The sketch is a simplified diagram of the connections to the cathode, C, and anode, A, of an



electron gun. If the charge on an electron is e and the potential difference between cathode and anode is V, how much energy does each electron acquire by the time it reaches A?
c. This energy is in the form of K.E. of motion of an electron. Write down the usual expression for the kinetic energy of a particle of mass m having velocity v.
d. Write an equation putting the two expressions for energy from (b) and (c) equal to each other.

16. Write down again the answer you obtained (after checking its correctness) to Question **14c,** and the answer to **15d.**

a. Find from these two equations an expression for the velocity v of the electrons.
b. Now find an expression for e/m, the ratio of charge to mass, for the electrons.
c. If you know the value of the electron charge, e (from Millikan's experiments for example), how do you find the mass m of an electron?

Some answers

Question 16 is important. You cannot answer it without working through the questions preceding it. Here are the answers to parts of those questions, so that you may check your own work.

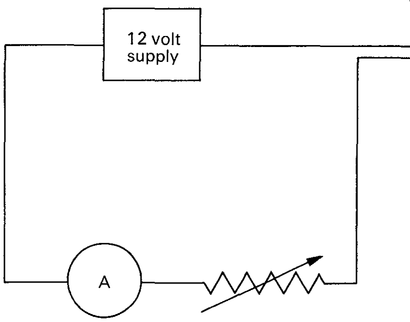
14a. Circular.
b. mv^2/R
c. $Bev = mv^2/R$

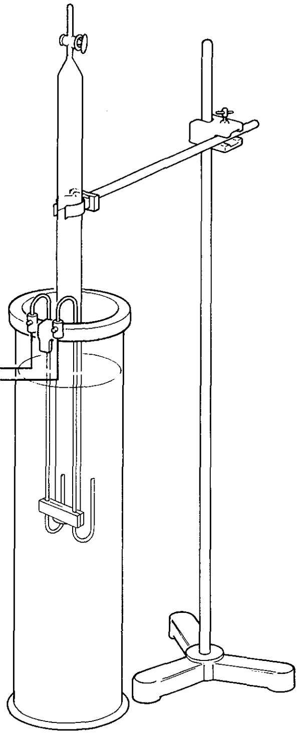
15b. Ve
c. $\frac{1}{2}mv^2$
d. $Ve = \frac{1}{2}mv^2$

COMPARISON OF ELECTRONS WITH HYDROGEN ATOMS

An atom of hydrogen easily loses its one electron and becomes a positive ion, a positive hydrogen nucleus, which we call a *proton*. You can measure e/M for a hydrogen ion by driving an electric current through water and measuring the hydrogen gas that is liberated. If you have not seen that experiment *and measurement* in an earlier year (or in Chemistry) you should try it yourself now, or watch a demonstration.

Demonstration 12
Electrolysis of water





Hydrogen and oxygen gases emerge from water when a current is passed through it. A little acid has to be added to provide plenty of ions, but ultimately it is only the water that is used up to yield those gases.

You now need to know the mass of hydrogen liberated by a known current in a known time, that is, by a known electric charge.

Run a measured current through the apparatus for a measured time such as 20 minutes. Then the total charge passing across is given by

CHARGE (*in coulombs*) =
CURRENT (*in amperes*) × TIME (*in seconds*)

The hydrogen gas that is released collects in one of the tall tubes. (How do you know which one? Just as a trick for remembering, think of the chemical formula H_2O.)

The tube is marked in cm^3 of volume. Read the volume of hydrogen and calculate its mass. To do that you need to know the density of hydrogen – that is, the mass of unit volume. You have not measured that density, and you may not have seen it measured, but the measurement is just like the weighing of a sample of air, which you met in an earlier year. So you are not accepting something mysterious if you use other people's measurement for hydrogen. For hydrogen at room temperature and ordinary atmospheric pressure:

the mass of 1 cm^3 is 8.4×10^{-5} gram
or the mass of 1 cubic metre is 8.4×10^{-2} kg (0.084 kg)

From your measurements, calculate the proportion ELECTRIC CHARGE/MASS (in *coulombs/kilogram*).

The measured value for hydrogen ions in solution or in gas Precise measurements yield the result shown in the box, which you should use in calculations:

> 1 kilogram of hydrogen is released when 95.7 million coulombs pass through the electrolysis apparatus. For that large quantity
>
> $$\frac{\text{CHARGE}}{\text{MASS}} \text{ is } \frac{95\,700\,000 \text{ coulombs}}{1 \text{ kilogram}}$$
>
> and *the same proportion should hold for every ion* in that large quantity.

Therefore e/M for a single hydrogen ion, H^+, is 95 700 000 coulombs/kilogram (9.57×10^7 C/kg).

Compare that with a precise measurement for a single electron, 176 000 000 000 coulombs/kilogram (1.76×10^{11} C/kg), which is enormously larger.

In round numbers:

about 100 000 000 coulombs/kilogram for hydrogen ions	about 200 000 000 000 coulombs/kilogram for electrons

proportions: 1 to 2000

Either the electron has a much larger charge or it has a much smaller mass than the hydrogen ion. Some other experiments tell us that they both have exactly the same size of charge, though one is + and the other −. Therefore the electron must be much lighter. How much lighter? Try dividing. Since the electron is so much lighter we may take the mass of a whole hydrogen atom (ion + electron) as almost the same as the mass of the hydrogen ion. Then:

$$\frac{\text{electron CHARGE } e}{\text{MASS of hydrogen atom } M}$$

divided by

$$\frac{\text{electron CHARGE } e}{\text{MASS of electron } m}$$

is $\frac{e}{M}\Big/\frac{e}{m}$ and that is $\frac{e}{M} \times \frac{m}{e}$ or $\frac{m}{M}$

So, $\frac{95\,700\,000}{176\,000\,000\,000}$ gives us $\frac{m}{M}$

This tells us that the electron's mass is only about $\frac{1}{2000}$ of the hydrogen atom's mass (more precisely, $\frac{1}{1840}$).

An electron is only a chip off an atom.

MASSES OF ATOMIC PARTICLES

Using the result of Millikan's experiment for the electron charge, e, we can calculate masses. For an electron, $e = -1.6 \times 10^{-19}$ coulomb and $e/m = 1.76 \times 10^{11}$ coulombs/kilogram. Use those to calculate the mass of a single electron in kilograms.

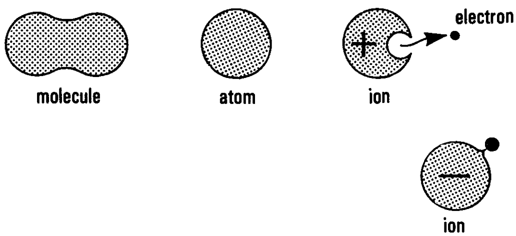
If you *could* have 1 kilogram of electrons in a bottle, how many would there be? And what would be the total electric charge? As you might guess from that huge charge, it seems impossible to bottle up so many electrons, all repelling each other.

For a hydrogen ion or proton, $e = +1.6 \times 10^{-19}$ coulombs and $e/M = 9.6 \times 10^7$ coulombs/kilogram. Calculate the mass of a single hydrogen atom, that is, a proton + an electron. In comparison, the electron's mass is trivial.

WHAT ARE ATOMS MADE OF?

When we tear atoms to pieces with very strong electric fields we find many electrons, all with the same negative charge and the same e/m, as well as various positively charged particles. The positive particles (positive ions) are atoms that have had one or more electrons chipped off. They have different values of e/M, according to the chemical elements in the experiment.

Analysing a mixture of atoms Those positive ions are the massive remainders of atoms (sometimes, even of molecules) each carrying a positive



electric charge. They can be accelerated by an electric field and swung into orbits by a magnetic field like the electrons in your fine-beam tube measurement. The streams of positively charged atoms with different e/M values are brought round orbits to focus on a photographic film and make a mark for each e/M. Thus we record the various atomic masses, values of M, in a sample.

The apparatus for this is called a *mass spectrometer*.

MASS SPECTROMETER

We measure e/M for positive ions. Then since we already know e we can calculate M for every kind of ion, for a single atom of every element.

To analyse a sample, we must first make positive ions from its neutral atoms or molecules. We do this by bombarding it with energetic electrons from a small electron gun.

A complete atom – neutral, uncharged – cannot be controlled by electric and magnetic fields. It will stay at rest or continue straight ahead with whatever motion it already has. Converted into a charged particle by chipping an electron off it, an atom is an ion (meaning traveller) with its motion controllable by field forces. Therefore the first thing to be done is to knock an electron off some atoms of the sample which is being investigated.

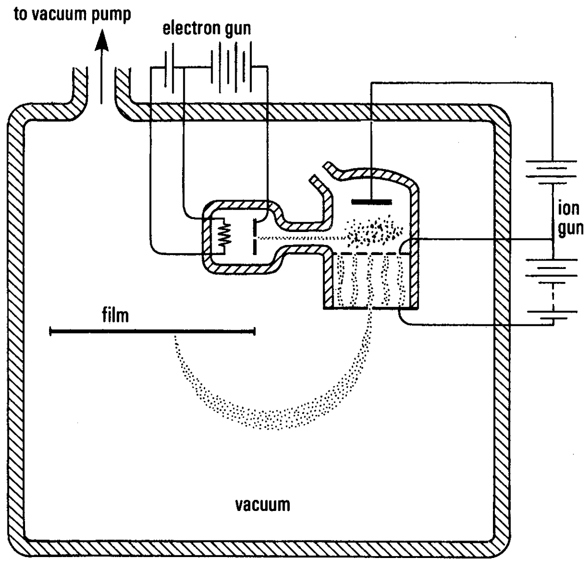
An electron with only a little energy will make an elastic collision. The electrons of the target atom that it hits are too strongly attached, so the missile electron considers it is hitting a great massive atom as a complete structure and it just bounces away, like a tennis ball hitting a wall. But with a larger gun voltage, 10 to 100 volts, the bombarding electrons can knock an electron out of an atom of a gas, leaving a positive ion.

Those ions are then accelerated by an 'ion gun'. This has a positive plate, a grid of wire mesh as a 'first muzzle', then a plate with a hole or slit as the main muzzle.

A small sample of gas to be analysed is fed into the ion gun region, and excess gas is continually pumped away. The sample is bombarded by electrons, so that some ions of its elements are made. A weak electric field is applied to the region where these ions are made, to drive them gently through a grid, so they arrive at the other side of the grid with very little energy. There, however, they are accelerated by a large voltage, so that they all emerge from the muzzle of the ion gun with the same kinetic energy – essentially the energy given them by that main gun voltage.

Then all the ions of any one mass will be held in circular orbits of the same size by the strong magnetic field applied perpendicular to the stream. Ions with a different mass will follow orbits of different size, and they will arrive at a different place.

As the ions emerge from the ion gun, even the paths of one kind can splay out in slightly different directions; but with a suitable shape of magnet all those paths are focused on the receiving film.



All ions which have the same mass are brought to a focus by the magnetic field, which is perpendicular to the paper.

One form of mass spectrometer.

MASSES OF ATOMS: ISOTOPES

Twins in chemistry If you have a chemistry textbook, look at the table of 'atomic masses'. These are the relative masses of atoms of the chemical elements on a simple scale. You will see quite a lot of them which are whole numbers, or nearly so – too many to be the result of mere chance or good luck. These include hydrogen 1.008, helium 4.00, carbon 12.0000 (by definition because it is the chosen standard), nitrogen 14.01, oxygen 16.00, fluorine 19.0, sodium 23.0, aluminium 27.0, phosphorus 31.0, silver 107.9, radium 226.0, and others.

Such measurements made scientists suspect that there may be basic building blocks for all atoms, with a mass of about 1 on that scale – perhaps hydrogen and neutrons, though each has a little more mass: 1.008 for hydrogen and 1.009 for the neutron on that scale.

Yet with careful measurements, some elements failed to fit such a scheme closely. An extreme exception was chlorine, for whose atoms measurement after measurement gave 35.45. For a long time chlorine seemed to spoil the hopes of a single whole-number story.

Then when physicists developed mass spectrometers, early this century, they found the solution to the chlorine 35.45 mystery: there are two sorts of chlorine atom, with different masses, 35.0 and 37.0. They occur in a natural mixture – in sea water and everywhere else – in just the proportions that make an average 35.45.

Isotopes These atoms are inseparable chemically; in any chemical experiments they behave as closely alike as identical twins, but one is more massive than the other – a 5 per cent difference. Such twins are called *isotopes*.

A few chemical elements have only one stable form – all their atoms are exactly alike – but many have two isotopes, and some have three or more. When this was discovered, the fact that a chemical element does not have all its atoms exactly alike came as a great surprise.

A SIMPLE MODEL OF ATOMS

We always find the same value of e/m for electrons whatever source we use – hot filaments of one metal or another; photoelectric effect; bombardment of gases by other electrons; enormous electric fields tearing electrons out of cold metal; and even radioactive nuclei emitting beta rays.

Therefore we think of electrons as universal ingredients of matter, all alike, tiny chips of an atom, all of the same mass and the same negative charge.

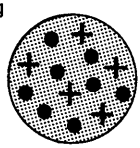
Positive ions seem to be the 'rest of the atom' carrying most of its mass and having, therefore, different masses for atoms of different chemical elements. Mass spectrometer records of positive ions show a great array of different marks, for atoms of different elements, and for isotopes of the same element; but electrons make a *single* mark, they are universally identical.

So we start now with a picture of an atom as a round blob out of which an electron can be chipped. Therefore, since matter is normally electrically neutral the rest of the blob is positive – we cannot tell whether it is a diffuse body of positive electricity like a pudding or made of knobs of positive electricity.

However, we can knock more than one electron off an atom. Analysis of positive ions made by bombarding gases with electrons shows that some ions have twice, three times, or more, the normal e/M. This suggests that they have multiples of the basic electron charge. Very early experiments on streams of positive ions showed that oxygen ions can have several charges, and mercury ions as many as eight positive charges.

Early this century scientists pictured atoms as a sort of pudding of positive electricity with negative electrons as plums in it. This picture was never

electrons (–) in a pudding of positive (+) electricity



intended to be a description of reality but just a way of remembering how atoms behave under electrical attack.

Further models: nuclei? Nothing seen in experiments described so far conflicts with the picture of an atom as a pudding. As good scientists, we shall not build further details into our picture, such as the idea of a small massive nucleus, until new evidence forces us to do so.

New theory by necessity It is a very important thing to remember that the great advances of theory, as in our pictures of atoms, are not just made by imaginative flights of fancy – the scientist's paint brush twirled at random – but are forced upon us by the growth of surrounding knowledge. True, our models always contain an imaginative element; but we try now – as scientists have tried for the last 300 years – to avoid unnecessary imaginative frills. Scientists specialize in economical explanations.

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Progress Questions

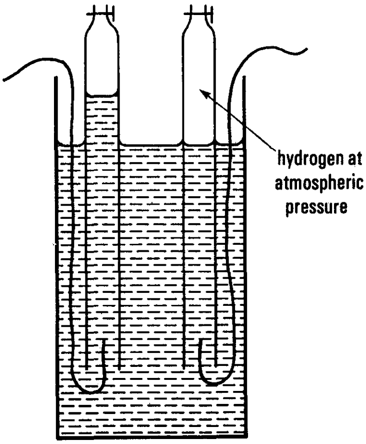
Electrolysis: hydrogen ions

17. There is a sketch of the apparatus used to pass an electric current through water, with a little dilute acid in it, on page 26.

a. Where do you get most gas, above the cathode (–plate), or the anode (+plate)?

b. Hydrogen gas collects in one tube. How can you test for hydrogen?
c. Hydrogen bubbles off at the cathode. Which way do the hydrogen ions (charged hydrogen atoms) carry electric charge through the water? From cathode to anode or the opposite way?
d. So, do hydrogen ions in solution carry positive charges or negative charges?

18. In an experiment using slightly acid water, a current of 2 amperes ran for 7 minutes and 100 cm^3 of hydrogen were collected above the cathode.



a. Remember coulombs = amperes × seconds. How many coulombs of charge were carried by the hydrogen ions?
b. 1 cm^3 of hydrogen at atmospheric pressure weighs 0.000 09 gram (0.000 000 09 kg). How many grams of hydrogen were collected?
c. How many coulombs would have been carried if a whole kilogram of hydrogen had been collected?

Early atom model
19. It is sometimes helpful to think of an atom as a sort of currant bun – a lot of cake with a few tiny currants. Which part is like the electrons in an atom – the cake or the currants? And which part is like the positive part of an atom in that early model?

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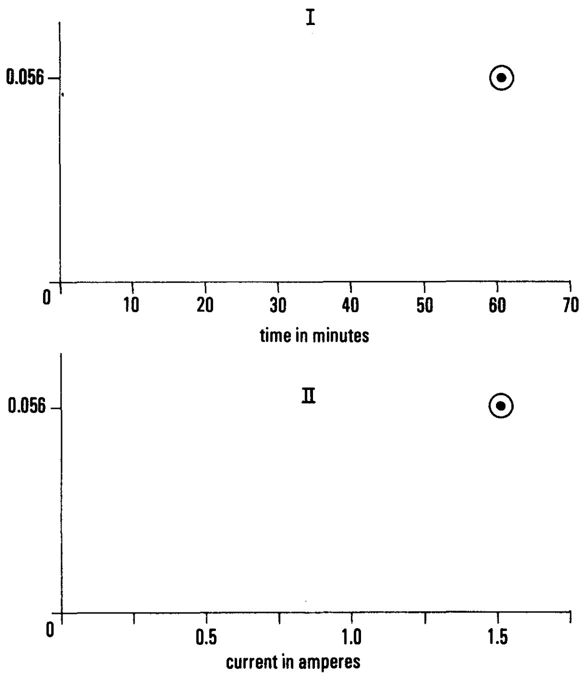
Questions

Electrolysis

20. A current of 1.5 A is passed for 1 hour through weak acid and, at the end of that time, it is found



that 0.056 g of hydrogen had been collected. This result gives one point on each of two graphs I and II.
a. Copy and complete graph I, drawing a line showing how the mass of hydrogen collected by 1.5 A increases with time. How long will it take for 0.10 g to be released by 1.5 A?
b. What assumption about mass released and time elapsed have you made in drawing your graph?
c. Copy and complete graph II drawing a line showing how the mass deposited in 1 hour increases with the current. How much current is needed to release 0.10 g in 1 hour?
d. What assumption about mass deposited and current passed have you made in drawing your graph?

21a. Find from the figures given in the first sentence of Question 20 how many coulombs are required to release 0.056 g of hydrogen.
b. How many coulombs are required to deposit half that much, that is, 0.028 g?
c. How many coulombs are required to release 0.050 g of hydrogen?
d. In working your answers to **b** and **c** what are you assuming about grams of hydrogen released and coulombs of electricity passed? Is this assumption the same as, or different from, the assumption made in **b** and **d** of Question 20? Explain.

e. Suppose you wished to extend your answers to very tiny deposits. What would you do to predict how many coulombs would release one millionth of 0.056 g of hydrogen?
f. Can you see any objection to extending your prediction in (e) to one-millionth of one-millionth of one-millionth of one-millionth of 0.056 g?

Comparing atoms and electrons

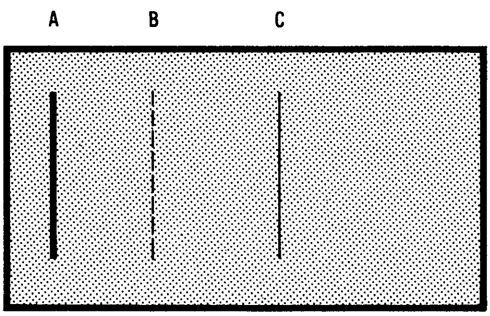
22. The value for e found by Millikan's experiment is

$$e = 1.6 \times 10^{-19} \text{ coulomb}$$

The ratio e/m for electrons is approximately 1.8×10^{11} C/kg.
The ratio e/M for hydrogen ions in electrolysis is approximately 10^8 C/kg.
Find:
a. the mass of an electron;
b. the mass of a proton;
c. the number of hydrogen *atoms* in 1 kg of hydrogen.

Positive ions: mass spectrometers

23a. Neon gas, at low pressure, is fed into a mass spectrometer. When the film is developed it shows *three* traces, a very dark one at A, a very faint trace



at B, and a not so faint trace at C. The gas was pure neon and no other gas was present. How may we explain these three traces?
b. Use this example to explain what is meant by 'isotopes'.

24. A mass spectrometer shows that chlorine gas has two common isotopes. One isotope has an atomic mass of 35, the other of 37. Roughly, the atomic mass of chlorine as found by the chemist is 35.5. What, roughly, is the proportion of '35 atoms' to '37 atoms'?

Physics (Nuffield) O Level Examination question

N.3 (1976)*

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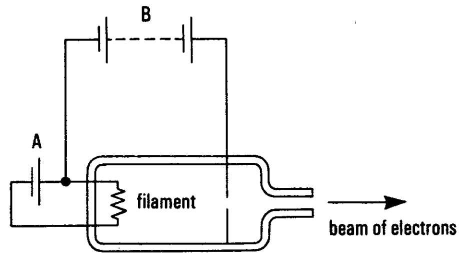


Fig. 1

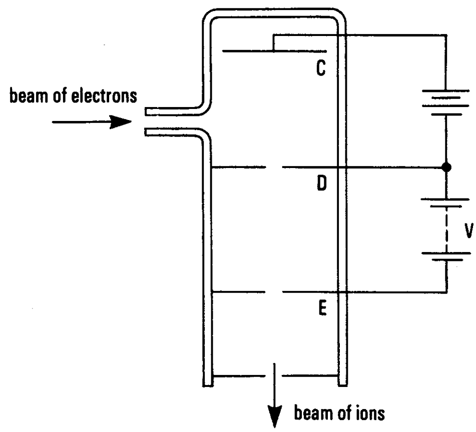


Fig. 2

Fig. 1 shows an electron gun.
(*a*) Does it matter if battery A is connected the other way round? Explain.
(*b*) What is the purpose of battery B?
The beam of electrons from this gun enters the chamber shown in Fig. 2. This chamber, which is called an *ion gun*, contains neon gas at low pressure. Some of the electrons collide with some of the neon atoms and ionize them.
(*c*) What is meant by *ionize*?
(*d*) There is a small potential difference between the electrodes C and D. What will happen to ions in the space between these electrodes?
(*e*) Some of the ions will pass through the hole in D and enter the space DE. There is a large potential difference, V, between D and E. What will happen to these ions as they pass from D to E?
(*f*) Discuss the energy transformations between D and E.

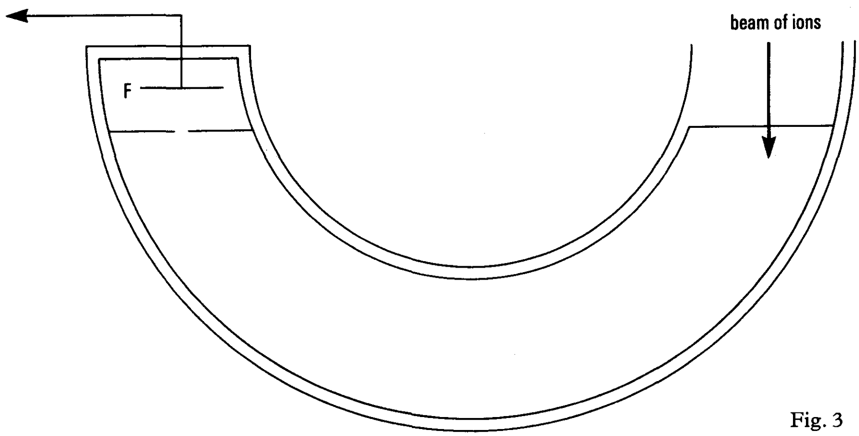


Fig. 3

The ions next enter an evacuated semi-circular tube (Fig. 3). A magnetic field is applied so that the ions travel round the tube to an electrode at F.

(*g*) What can you say about this magnetic field?

(*h*) If the strength of the field is B, an ion (charge q, mass m) emerging from the ion gun will move in a circular path of radius R where

$$Bqv = \frac{mv^2}{R}$$

(i) What does the term Bqv represent?

(ii) What does v^2/R represent?

(*i*) It may be shown that for any ions arriving at F the value of mV/q is constant. A meter is connected to the electrode F to detect the arrival of ions. The graph (Fig. 4) shows how the ion current changes as the potential difference V is changed. What information can you deduce from this graph?

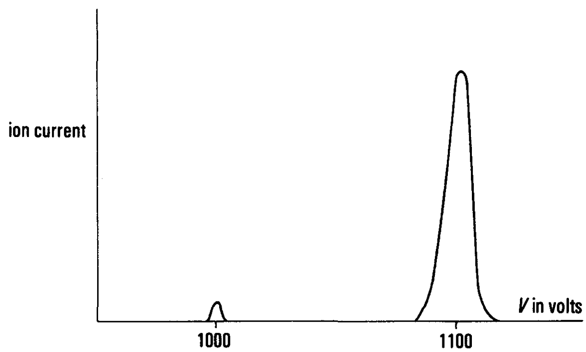


Fig. 4

A NOTE ABOUT PUPILS' DEMONSTRATIONS FOR REVISION

Revising for Nuffield O-Level, or a similar examination in Physics, does not need much learning by heart: instead, making some experiments go as your own demonstrations can refresh your knowledge and will give other pupils some useful revision when they watch your experiment.

If you look back on the experiments you have seen during your physics lessons – and perhaps wonder about others you missed for one reason or another – there may be some that left you uncertain. Perhaps you and a partner would like to set up and run some of these for yourselves.

Your teacher will also suggest other experiments which it would be profitable for you to demonstrate.

We hope that you will enjoy doing such demonstrations on your own. Other pupils will come and learn from seeing and discussing them; and *you* will learn from visiting *their* demonstrations.

Your own experimenting will take more of your time than just watching a demonstration that is already set up and shown by your teacher; but your work will give you valuable experience. Also your demonstrations, and those of other pupils, will provide very good revision for an examination ahead.

CHAPTER 3
Thinking in science: facts and early fancies

The next three chapters deal with astronomy, not to teach you a lot of facts about stars and planets but to enable you to learn for yourself how scientific theories are made and used. You will see how simple ideas developed in the course of centuries into a great theory. And then you will find it easier to understand new theories in physics and the use of theory in many sciences today.

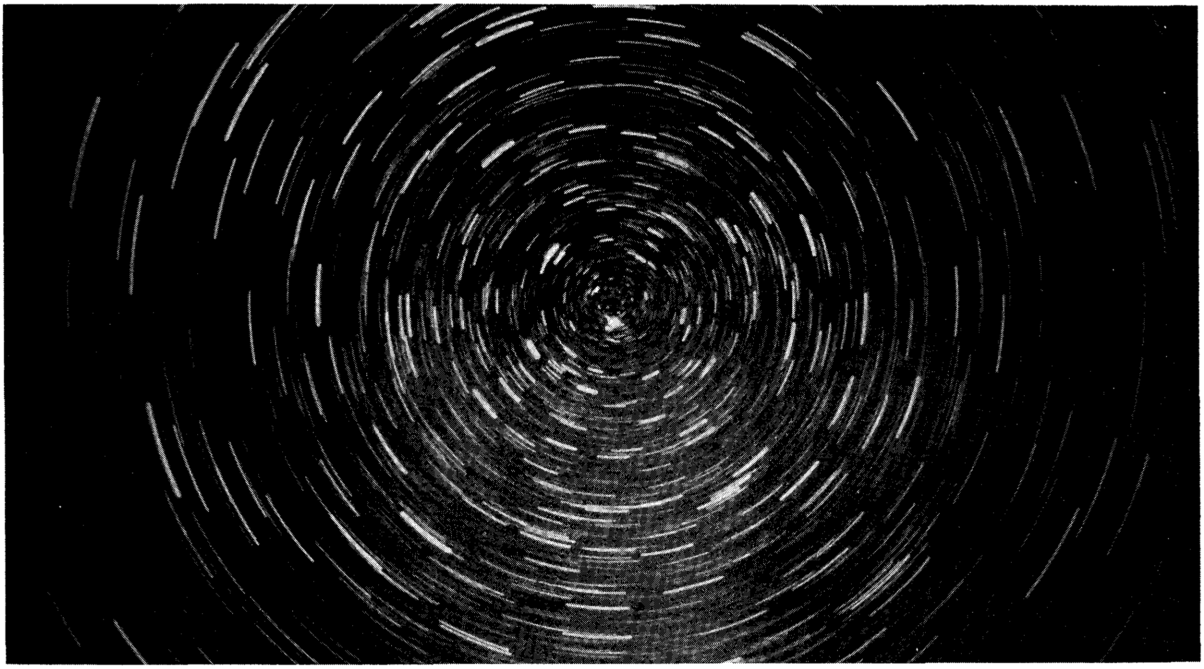
Everyone knows today that the Sun is at the centre of a planetary system which includes our Earth, that the Earth spins on its axis once a day as it journeys round the Sun each year, and that the Moon follows an orbit round the Earth, with the same face always turned towards us. But many generations ago, long before men began to gather into towns and to build cities, they had no such knowledge. They looked out into space and they saw stars in the sky by night and the Sun by day. So we shall start where they started. We shall examine what we can see happening in the sky with the naked eye; from that beginning we shall trace the steps by which men have reached their present understanding, how they made and unmade theories to explain what they saw, and how, as recently as 300 years ago, Sir Isaac Newton brought the knowledge of earlier times into one grand model for the solar system.

WHAT WE SEE

The pattern of the stars If you watch the sky for some time at night you will see that the stars stay in patterns that do not change. A photograph of the stars in the sky tonight will look just like a similar photograph taken a year hence.

That unchanging pattern of stars rolls across the sky during the night, turning round the star we call the Pole Star like a pivot, once in 24 hours.

Photograph of the night sky near the Pole Star, taken with a 45-minute time exposure.
Barnaby's Picture Library.

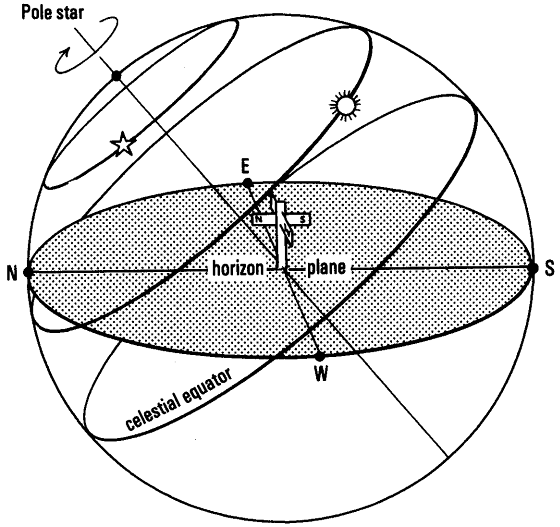


Try watching the stars in a night sky for some hours (**Experiment 13**) and you will see this.

Another thing you can do is to photograph the night sky (**Experiment 14**). Take your camera out of doors on a suitable night and leave it there in its case for about half an hour so that it is at the same temperature as its surroundings. Then, when you open the camera, dew will not form on the lens. Select a large aperture. Fix the camera firmly so that the axis is pointing at the Pole Star. Open the shutter to give a time exposure of at least two hours. At the end of that time, close the shutter.

The stars look very, very remote from the Earth – so far that we may easily imagine that they are part of the inner surface of a gigantic sphere centred on the Earth and spinning about an axis through the Pole Star. This imaginary sphere is known as the **celestial sphere**.

Imagine that the ground you stand on continues out in an immense flat sheet to meet the celestial sphere. This is the **horizon plane**.

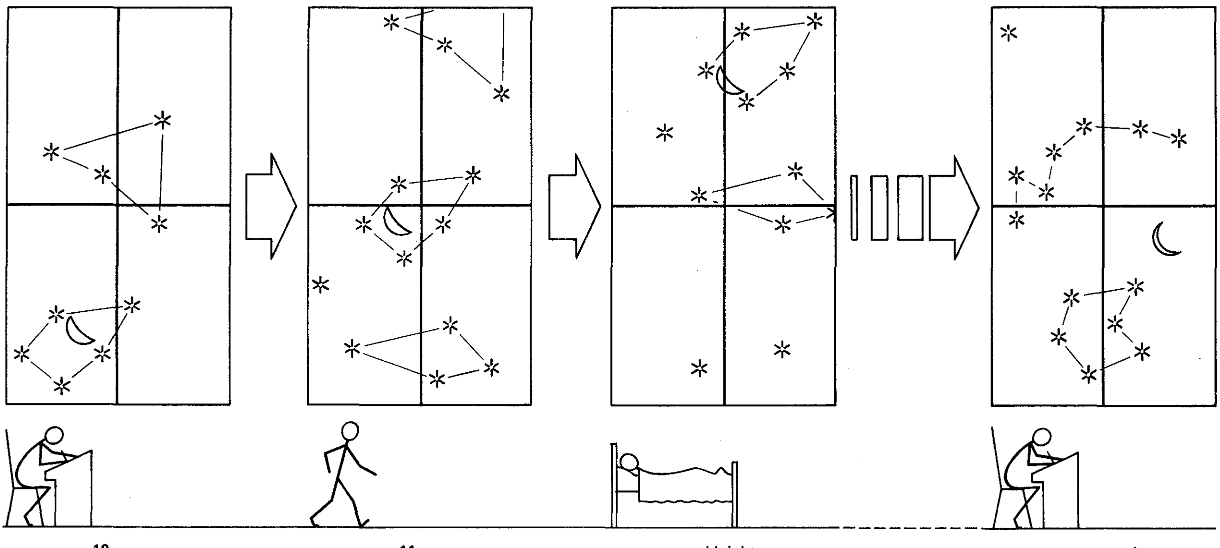


The star pattern revolves.

The **celestial equator** is the ring where the plane of the Earth's equator meets the celestial sphere.

In a single night and day each star makes a complete circle round the Pole Star. Some are always above the horizon; others dip down under the horizon for part of their journey. These stars rise and set.

The Moon On some nights you see the Moon among the stars. On other nights you don't. The Moon travels across the star pattern. To observe this look at the Moon one night and make a note of its position



The Moon, while moving across the sky with the stars, slips eastwards through the star pattern.

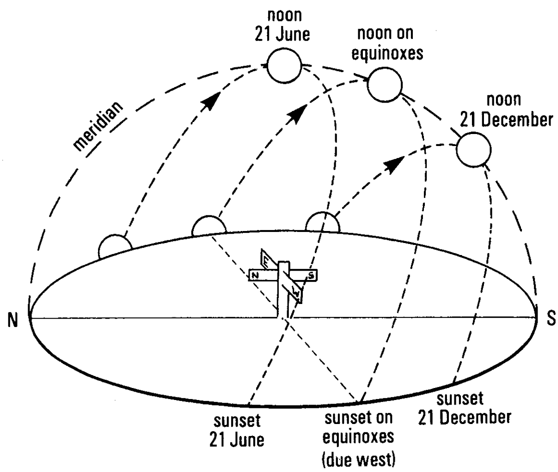
(and shape, too, if you like) among the neighbouring stars. Look again one hour later; two hours later, and then a day or two later (**Experiment 15a**).

In the course of a night, the Moon sweeps across the sky from east to west with all the stars, but not quite so fast. If you watch carefully you will see that it lags further and further behind the stars as the month goes on. That lagging all by itself would carry it from west to east through the star pattern 90° in a week; all the way round in a month (**Experiment 15b**).

You can see a full Moon one night (when the Sun is down below the Earth in just the opposite direction), then a fortnight later no Moon at all; then another full Moon a fortnight later still.

If, from night to night throughout the month, you mark its lagging you will find that its path is a slanting one. It does not just drift eastwards along the same direction as its rapid east-to-west forward motion. It drifts eastwards along a slanting line which is very close to a slanting line we call the 'ecliptic'.

The Sun At noon, in our northern latitudes, the Sun is always due south. In its daily motion it appears to make one complete revolution from noon to noon (except for minor deviations connected with the changing speeds of the Earth's motion round the Sun during the year). But its path changes with the seasons (**Experiment 15c**). High in the sky in mid-summer, low down in mid-winter; and rising precisely in the East to set in the West on those days that we call the spring and the autumn equinox (21 March and 23 September).



The daily path of the Sun at mid-summer, mid-winter, and the equinoxes.

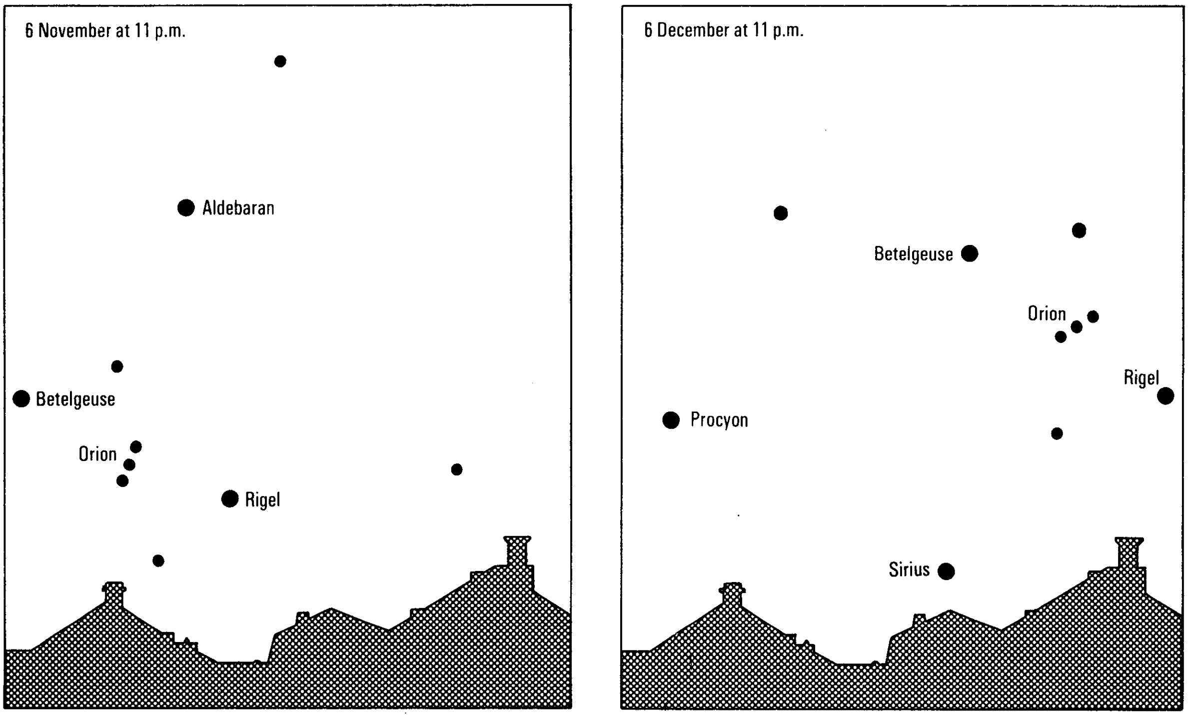
The Sun in the pattern of the stars If you look carefully at the stars at midnight, and at midnight tomorrow, and so on, you will see that although the pattern of stars keeps the same shape, it does change position from night to night. In 24 hours from midnight to midnight the star pattern swings round the Pole Star axis almost 1° more than a full circle. 7° more in a week, 30° more in a month, 360° more or all the way round in a year. So while the Sun seems to go round the Earth 365 times in a year, the stars seem to make 366 revolutions, just one more than the Sun in a year.

We can look at that in a different way; the Sun does not keep a fixed place in the star pattern but slips eastwards by 1° a day. Of course you do not *see* the Sun slipping like that because the stars are too faint to see in daylight. But you *can* see how the star pattern moves westwards by 1° from midnight to midnight; that is equivalent to the Sun drifting eastwards by 1° in the same time.

The eastward drift of the Moon carries it right round in a month; the eastwards drift of the Sun carries it right round in a year.

Freezing the daily motion

Some early astronomers, watching these motions, made a very clever move in their thinking: they imagined each motion to be separated into two parts: the fast, daily westward motion and the slow eastward motion. The daily motion, shared by all, was given a speed of very nearly 361° per day, or 366 revolutions per year. Then the eastward motion, relative to that, was zero for the stars, 1 revolution per month for the Moon and 1 revolution per year for the Sun.

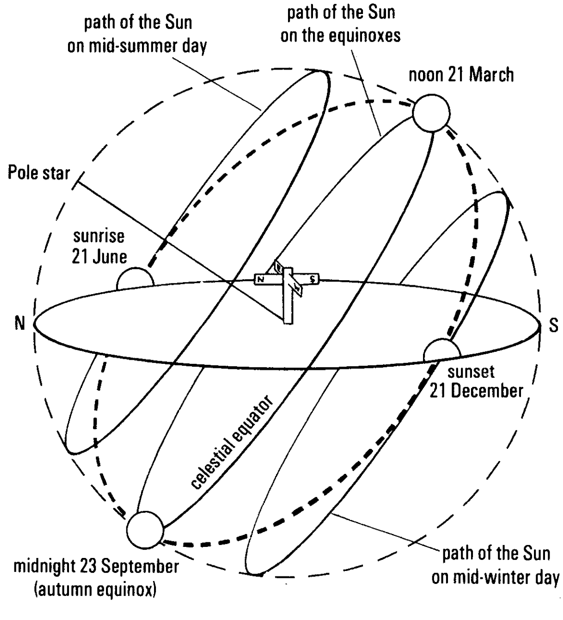


Views of the stars through a window, one month apart. You would see the same change if you waited up on 6 November. How long would you have to wait?

Since the fast motion is the same for all, we can forget about it when we describe the special motions of the Sun and the Moon. By subtracting the daily motion from what they saw, those men were able to catalogue the motions of the Sun and the Moon through a stationary star pattern. This difficult intellectual jump was a great step forward in science, made long, long ago.

The Sun's yearly motion

With the daily motion 'frozen', we should see the Sun moving slowly from west to east along a *slanting* circle through the star pattern, completing the circle in a year. That circle is inclined at $23\frac{1}{2}°$ to the



The ecliptic, the Sun's track through the star pattern in the course of a year. The daily motion is 'frozen'. On 21 June the Sun rose with the constellation of Cancer. One month later it rose with Leo and so on through the belt of constellations called the Zodiac.

celestial equator; we call it the ecliptic. To early astronomers, the ecliptic *was* the path followed by the Sun; today it represents the Earth's yearly orbit round the Sun.

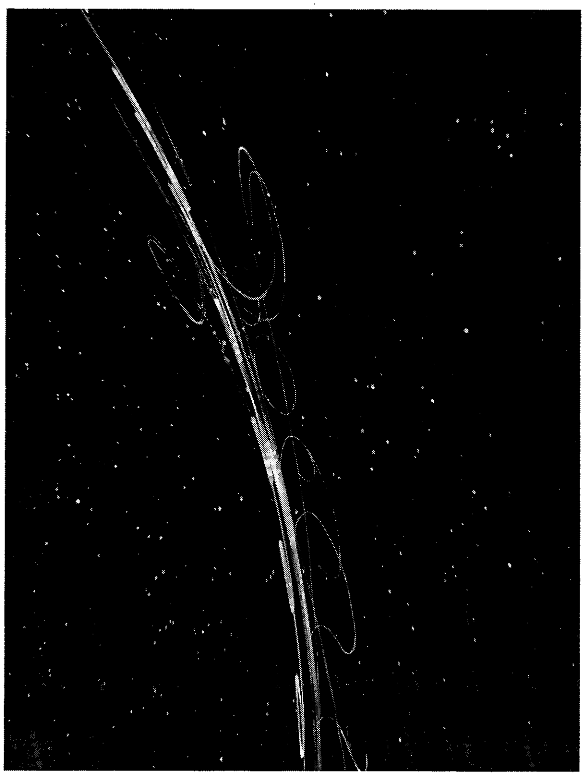
The Sun travels a little faster in the northern winter than in the summer; so the four seasons are not equal in length.

Equinox Mid-way between summer and winter and between winter and summer, there are times when day and night are equal in length. These are the equinoxes. Then the daily path of the Sun makes just a half circle slanting above the horizon plane between sunrise due east and sunset due west. Then the Sun, which is always on the ecliptic, is also on the celestial equator. People living on the Earth's equator will see the Sun directly overhead at noon. These equinoxes occur just 13 weeks (or 91 days) after mid-summer and mid-winter, and in that time the Sun will have moved just 90° eastwards along the ecliptic – a quarter of the full circle which makes up its yearly path.

Planets

Among all the stars, early astronomers noticed a few which did not keep their places in the otherwise unchanging pattern. We call them 'planets', using the Greek name which means 'wanderers'. Like the Sun and Moon, the planets sweep round with the star pattern in a daily motion. Freezing that daily motion, we find in the course of years that each planet slips slowly from west to east through the star pattern along a slanting path quite close to the Sun's ecliptic path and the Moon's path. The paths of the planets, like those of the Sun and the Moon, lie in the **zodiac belt**. This is divided into twelve zones, each named after a 'constellation', a group of stars given an imaginative name by early astronomers. The Sun as it travels round the ecliptic moves from one zodiac zone to the next in a month. These zones are named and used in astrology.

Unlike the almost steady motion of the Sun and Moon, each planet's motion through the star pattern is irregular. The planet slides from west to east for some time, slows to a stop, then moves from east to west for a short time, comes to rest, moves from west to east, and so on. The motion from west to east is longer



A long-exposure photograph showing the movements of Mercury, Venus, Mars, Jupiter, and Saturn, taken at Munich Planetarium.
Erich Lessing/John Hillelson Agency.

than from east to west. For example, the planet Jupiter moves once round the zodiac in a dozen years. During the course of this long, slow motion from west to east, Jupiter makes twelve short east-to-west motions, which look like loops in the planet's path as seen almost sideways on from Earth.

It was this seemingly erratic motion of the planets which presented the greatest problem to early astronomers who wanted to 'explain' the movement of things in the heavens.

Experiment 16
Look at some planets

Two of the planets shine so brightly by reflected sunlight that you can easily pick them out, and you may be able to watch them changing their place among the stars from month to month. They are:

Venus, which never moves very far away from the Sun. It swings out 46° to one side of the Sun and then back, seeming to disappear when we are dazzled by the Sun nearby; then out to 46° on the other side. So you can sometimes see Venus as the 'evening star' in the west, setting soon after sunset; and at other seasons as the 'morning star' in the east, rising before sunrise; but never in the middle of the night.

Jupiter moves very slowly through the star pattern, close to the ecliptic, 12 times slower than the Sun. In crawling eastwards, all the way round in 12 years, Jupiter makes a loop once in a year.

The other planets are more difficult to identify but you can find them with the help of star maps published monthly in some newspapers.

Here is a list of the planets known to the early astronomers, a few thousands of years ago.

Planet	Time for a complete orbit round the Sun (as seen by an observer on the Sun)
Mercury	88 days
Venus	225 days
Mars	687 days
Jupiter	12 years
Saturn	29 years

Sun: orbit round the Earth, 365.25 days

Moon: orbit round the Earth, 27.3 days*

To the early astronomers, the Earth was not a planet. Most of them assumed that the Earth remained fixed at the very centre of the Universe. The Sun and Moon were counted with the five planets to make a total of seven special bodies in the sky.

The apparent path of a planet: epicycloid The path that we see a planet taking through the star pattern seems to be an epicycloid; that is, a compound of motions round a small circle and a big one.

Experiment 17a
Drawing an epicycloid

Sketch one for yourself like this: on a large sheet of paper draw a big circle (diameter at least 25 cm) with a pencil, freehand. Sweep your hand slowly round that circle, but as you do so move the pencil in your hand, faster, around a small circle of diameter, say, 10 cm. You are drawing an epicycloid.

In watching a planet, we see that pattern almost edge on and, of course, only a part of it while watching over a few months. To see what it looks like, tear part of the epicycloid from your sheet of paper and hold it almost at eye level so that you see it from a slanting point of view.

You may see **Demonstration 17b Model of a planetary path**. And you may have an opportunity to visit a planetarium if there is one in your neighbourhood.

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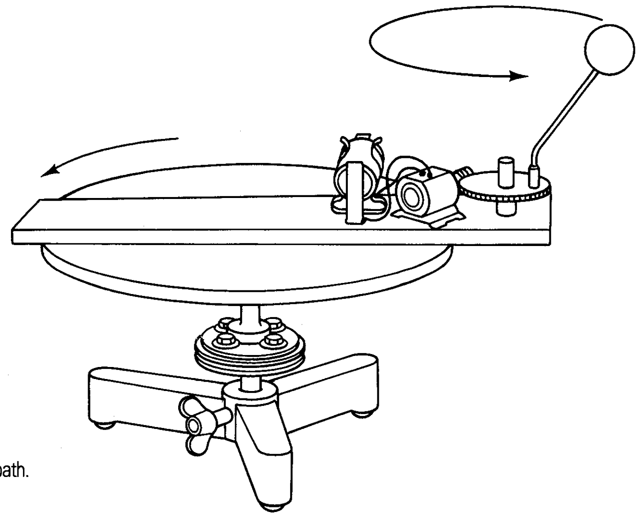
* For the Moon, 27.3 days is the 'true' month, relative to the stars. But, as the Earth moves on while the Moon goes round, the month from one full Moon to the next is longer, $29\frac{1}{2}$ days.



Demonstration 17b. Model of a planetary path.

SCHEMES TO EXPLAIN AND PREDICT

We shall start the story of the development of astronomy a few thousands of years ago; and, until we come to the great change made as recently as 450 years ago by Copernicus, we shall take the heavens as we see them; we shall think of man on a stationary Earth watching the motion of the stars and the Sun as we have just described them.

The earliest people, living by hunting and gathering plants and seeds, may have looked at the stars and wondered. They may have used them as guides at night. They may have welcomed the light of the Moon for hunting. We do not know. They may have used Sun and stars unconsciously as rough clocks; but it is very unlikely that they used them for reckoning days or weeks, or even hours. There was no need to do so.

From food-gathering to food-producing; the first revolution

At different times, in different places, men became more organized; they used better stone and bone tools; they began to supplement their food supplies by cropping plants and herding animals; they made pots and learned to cook. In these new 'food-producing' cultures, village life developed and simple trade was carried on.

The new agriculture called for a calendar to tell the villagers the proper season to sow their grain and other crops. Herdsmen too wanted a calendar for breeding their domesticated animals. To us a calendar seems an easy thing to construct. But to our early ancestors in their villages this was a new idea with no tradition to help in making one. Wise men who learned some rules for simple calendar-making were very important magicians, paid with food and endowed with authority. These calendar-makers were the first astronomers, for they had to use the Sun, Moon, and stars for their work.

From village life to city civilizations; the second revolution

The second great revolution of mankind, with people gathering into cities and developing great civilizations, came at different times in different areas of the world. In the region we call the Middle East this happened about 6000 years ago; in India about 4500 years ago; in China about 3500 years ago, and in Central America about 3000 years ago. Good means of time-keeping, calendar-making, and direction-finding were now essential, just as they are today. Astronomy provided them all.

Things that happened in the sky took on an obvious importance; the calendar-makers became powerful and important and their knowledge seemed grand and mysterious to other men. The Sun, Moon, and planets were treated with awe and came to be objects of worship. And as the great city civilizations developed, this worship produced a strong idea that Sun, Moon, and planets controlled the fates of individual men. The positions of those objects in the sky at the time a child was born were taken to

The Ring of Brogar (Orkney). Using such stone circles, early cultures could anticipate solar and stellar events and so provide a calendar.
Scottish Tourist Board.

determine the child's character and important events in the child's life. Calculating those positions and applying rules to make predictions from them is called 'casting a horoscope'. Horoscopes became important and fashionable in Babylon around 500 BC, and the astrologers who cast them were well paid and much trusted.

Although the early belief in horoscopes has continued down to the present day, we have learned to look upon it as superstitious. Scientists have found it very difficult to believe that the pattern of planets far away in the sky can control the character or fate of a human being. Yet superstition is easily made attractive by fear and hope based on the feelings of insecurity that we all share in one way or another.

In one way this belief benefited astronomy a great deal; the astrologers needed reliable rules for the motions of the Sun, Moon, and planets, and that encouraged observation and the development of astronomical theory.

ASTRONOMY IN EARLY CIVILIZATIONS

By the time the early civilizations – in particular that in Babylon – had grown up, clear rules had been extracted from astronomical observations. The calendar priests knew the motions of Sun and Moon well and could predict the seasons. They could even predict eclipses of the Moon.

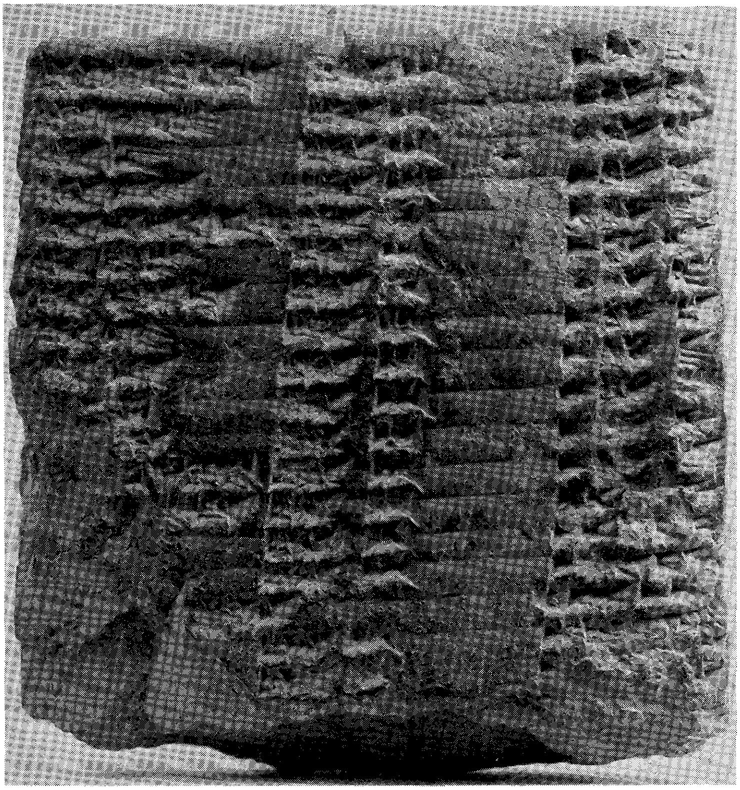
In the later ages of those civilizations, men had a good knowledge of the lengths of the seasons and of the length of the year. They also developed accurate systems of weights and measures, and had some knowledge of geometry (including the theorem of Pythagoras long before his name was put to it).

Their astronomers devised patterns for predicting the slightly irregular motions of the Sun and Moon along their paths through the star pattern. In the hands of the Babylonians, those patterns were used for calendar-making; but the astronomers who used them gave no reasons for the patterns nor did they imagine any mechanism responsible for them.

The first theories: gods and spirits

As a story to tell why stars, Sun, Moon, and planets move as they do, early peoples imagined gods or spirits. The Sun-god drove his chariot across the sky each day; but the planets must have been run by very wayward gods.

Such a picture or explanation was a theory in infancy and we should neither neglect nor despise it. It said 'The things that happen in the sky are not wild and uneven. They are run by sensible gods who behave regularly.' We may still find such attitudes towards natural events in some cultures existing today; and we should remember how strongly such attitudes can influence the learning of science.



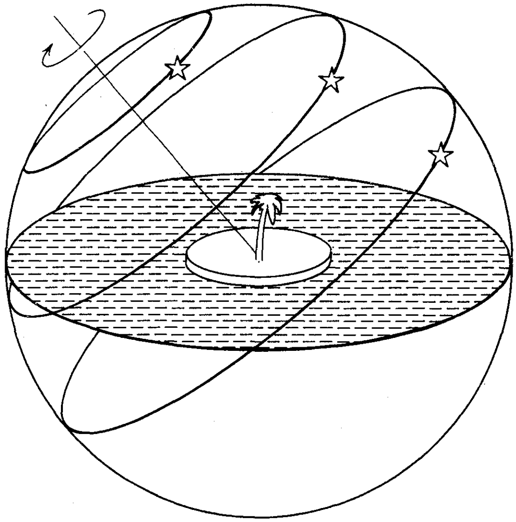
An astronomical tablet from Babylon, 6th century BC, giving details for the planet Venus for each month of the year.
Reproduced by courtesy of the Trustees of the British Museum.

GREEK ASTRONOMY: MACHINERY TO EXPLAIN AND PREDICT

Unlike the astronomers of earlier civilizations, Greek thinkers did not just endow Sun, Moon, and planets with special gods to carry them across the sky. They imagined simple machinery to move the bright objects in the heavens. Then they carried the design of that imaginary machinery far enough to be able to use it to predict future positions of planets, etc. They described things in a way that made Nature seem reasonable. Nowadays we recognize that they made rational scientific theories to fit the facts of observation. We shall look at several of these theories to see how they developed from simple beginnings to very sophisticated systems.

Thales (about 600 BC) was one of the earliest philosopher-astronomers. He thought of the Earth as flat, a great island surrounded by ocean. He described the stars and their motion by imagining a great bowl above us so that we all live on a stationary Earth at the centre of the celestial sphere, which spins round in 24 hours. It carried all the stars, like lamps stuck on it. He did not worry about the slow extra motions of Sun, Moon, and planets.

This was the first and the simplest machine of all: one great spinning bowl to account for the nightly motion.

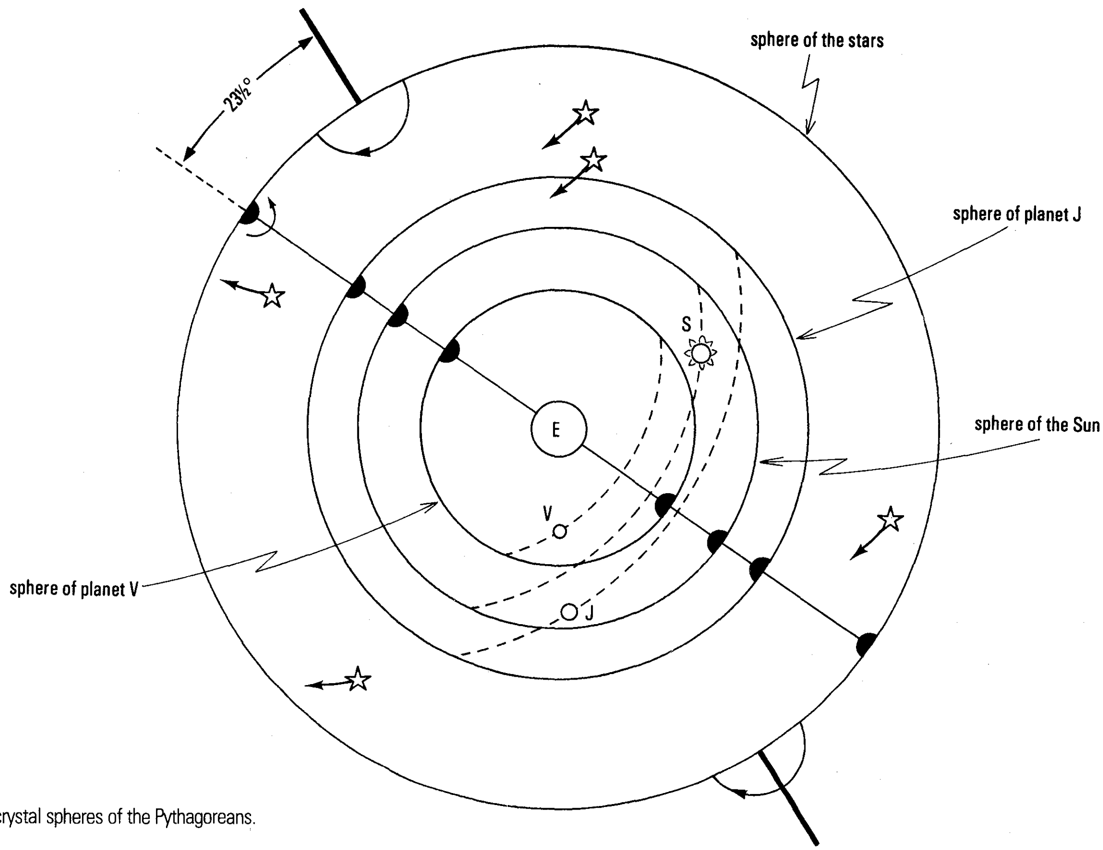


Thales' model.

He knew that the Moon shone by reflected sunlight – and that shows that he applied reasoning to common observations. He was a man of science who assumed that the whole universe could be explained by ordinary knowledge and reasoning.

Pythagoras (about 530 BC) gathered a group of scholars to discuss philosophy, religion, science, politics . . . and a succession of his pupils continued that 'school of philosophy' for some 200 years. They devised better models for the heavens: imaginary machinery that would give Sun, Moon, and planets motions to imitate the observed facts closely.

The stars were placed like bright lamps on a great sphere that rotated once in 24 hours about the Pole star axis, as in Thales' model.



The crystal spheres of the Pythagoreans.

The Sun was embedded in another sphere, inside the sphere of the stars. That sphere rotated slowly the *opposite* way, taking one year to carry the Sun round the ecliptic.

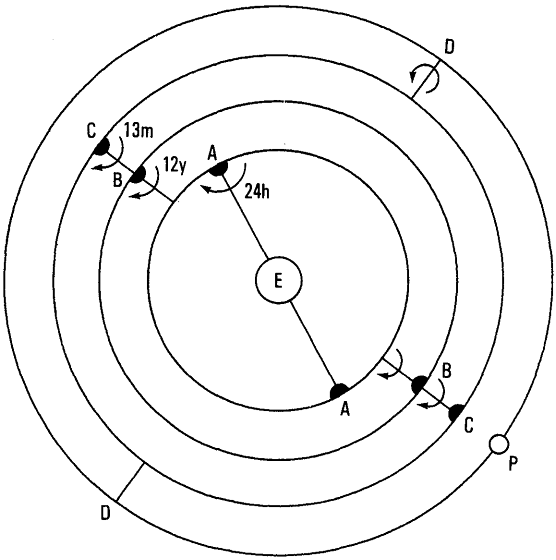
Another sphere carried the Moon round its path through the Zodiac in a month; and other spheres carried the planets in their general eastward motion through the star pattern. All the spheres for Sun, Moon, and planets revolved about an axis making $23\frac{1}{2}°$ with the Pole star axis, that is, an axis perpendicular to the ecliptic. And since the 'axle' of the outermost of those planet spheres had its ends embedded in the outside sphere of stars, that star sphere carried all the inner ones round with the daily motion. These spheres were called 'crystal spheres' – meaning that they were made of transparent, invisible, weightless, glass-like material. In the hands of able astronomers they were imaginary – and therefore completely transparent! But many other natural philosophers thought of them as real, transparent globes, grinding smoothly without friction around appropriate axles at the proper speeds to imitate what was seen in the sky. The power-house for that celestial machinery was supposed to be outside the outermost sphere, which carried the stars, in a heaven where the gods resided.

The sphere for Jupiter, with Jupiter embedded in its equator, revolved slowly backwards, making one revolution in a dozen years.

Although this machinery did not give the planets the 'loops' in their motion it provided a reassuring picture that told people there was no frightening mystery: it is all simple machinery with clear, steady motions. The whole universe was assumed to be made and guided by beings with intelligence.

Pythagoras probably knew that the Earth was round. The sight of ships sailing in over the horizon and travellers' tales of the Pole star being higher in the sky when one was further north, suggested a round Earth.

Eudoxus (about 370 BC) gathered together Greek, Egyptian, and Babylonian knowledge of astronomy and devised a scheme for the heavens which came nearest to a satisfactory solution of the problem. He took the previous scheme of eight spheres slipping round within each other, and inserted



Eudoxus' scheme for a planet P, using four spheres, A, B, C, D.

more spheres, with different axes and motions – 27 in all. The greatest mathematician of his time, he was very clever at the geometry of solid space and he saw how to imitate the planets' looped paths by giving each planet four spheres.

It may seem artificial to imagine this system with the heavens full of invisible smoothly spinning spheres, but the model did fit the facts: it gave a satisfying assurance that the events in the sky are reasonable. Today we realise that Eudoxus' system is a mathematical model: the 27 spheres are mathematical constructions which add up to a model of what we see. It was the first example of a well-used technique which is now applied to such complicated repeating systems as the ocean tides and the notes made by musical instruments. We call it 'Fourier synthesis' after the French mathematician who rediscovered it two thousand years later.

Plato, the greatest philosopher of his time, had asked his pupils for a model to account for the observations of the planetary motions; Eudoxus provided it. To Plato, the spheres were beautiful, intellectual constructions, mathematical ideas rather than material bodies. To fit the facts even more closely later thinkers could easily modify Eudoxus' system as we shall see when we come to the work of Ptolemy.

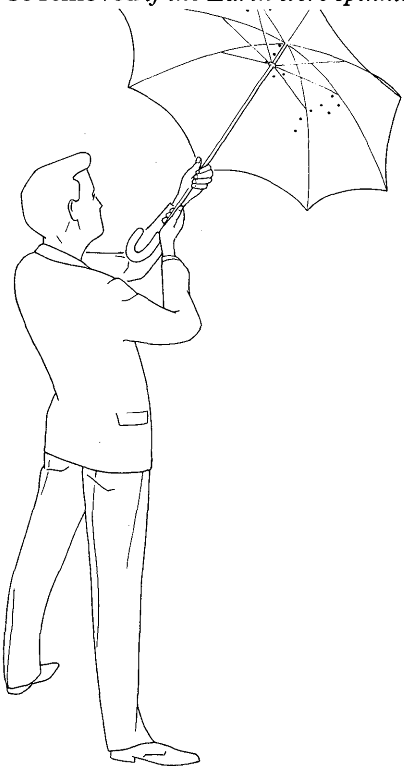
To **Aristotle** (about 340 BC), Eudoxus' model offered a solid basis for a more complete theory which would relate the motions of bodies on Earth to the motions of the stars and planets in the heavens. Aristotle concluded that the heavens were perfect and unchangeable, that circular motions were the 'natural' ones for the heavenly bodies, and that the sphere was the perfect solid shape.

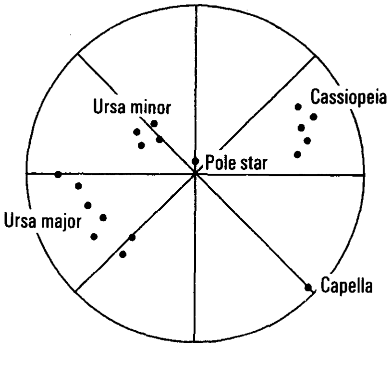
He made a strong case for the Earth being a round ball and not flat. He gave theoretical reasons –
(*i*) Symmetry: a sphere is symmetrical, perfect.
(*ii*) Pressure: the Earth's component pieces, falling 'naturally' towards the centre, would press into a round form.
And he gave experimental reasons –
(*iii*) Shadow: in an eclipse of the Moon, the Earth's shadow is always a part of a circle; a flat disk could cast an oval shadow.
(*iv*) Star heights: even in short travels northward or southward, one sees a change in the height of the Pole star.

Aristotle did much to set science on its feet. He catalogued scientific information and listed good questions. And he emphasized a basic problem of science, distinguishing between 'true physical causes' of things and 'imaginary machines to fit the facts'.

A different Greek view

Aristarchus (about 280 BC) and a few other astronomers at Alexandria suggested quite a different scheme for the heavens. They pointed out that it was unnecessary to have the outer sphere of stars whirling round once in 24 hours, and carrying the other spheres for Sun, Moon, and planets with it. All that *daily* motion could be removed *if the Earth were spinning instead.*





Umbrella model of celestial sphere.

This was an unpopular idea because people did not understand the mechanics of living on a rotating planet with a central gravity pull. They thought that all movable things would fly off a spinning Earth; or at least a falling object would not travel vertically down to the ground.

The other suggestion made by the same astronomers was that the Sun is the fixed centre instead of the Earth; and the Earth is travelling in a circular orbit round the Sun. They pointed out that the Earth's motion would add to the simple motion of a planet and manufacture the pattern of loops that we see. (See **Demonstration 18 Umbrella model.**)

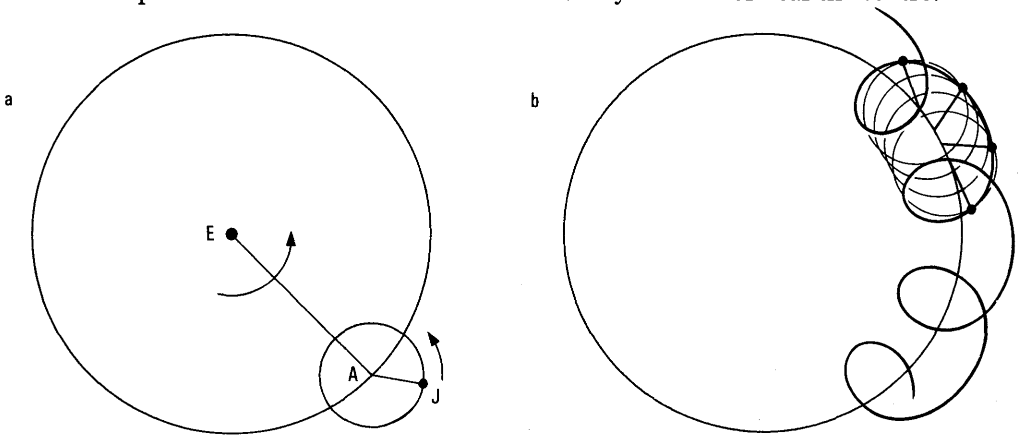
But that suggestion was equally unpopular: a moving Earth hurtling through space on a great orbit round the Sun would leave movable objects behind – men, birds, clouds . . . would trail away in the wake of the Earth.

Furthermore, critics objected that if the Earth moved in a great orbit round the Sun, men would see the star patterns changing in size and shape as we moved nearer and further. Such changes were not observed. (See **Demonstration 19.**)

Many centuries later, these suggestions were revived by others and put into a convincing form by Copernicus.

Simpler Earth-in-centre schemes

An off-centre viewpoint Although Eudoxus' scheme of concentric spheres gave a good imitation, the scheme was difficult to use for the accurate predictions which were wanted for calendar-keeping and astrology. Simpler machinery was devised by astronomers in the great University at Alexandria. This city had been founded at the mouth of the Nile by Alexander the Great. Greek scholars had collected there and had founded a University which grew to be a great centre of learning. Astronomers there made actual measurements of the size of the Earth and of the distances of Sun and Moon from the Earth. They also devised a new model to fit the facts, again using spheres (though we shall use circles in our description). They had an outer sphere for the stars as usual and a stationary Earth at or near the centre.

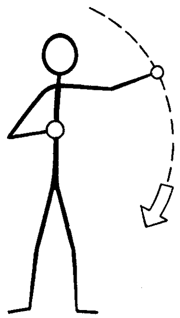


In this epicycle system for Jupiter, arm EA rotates around the Earth once in 12 years, while arm AJ carries the planet J round once in 365 days. The two motions combine to give a pattern b.

The new machinery for a planet is shown in the sketch. The fixed Earth is placed at the centre of a large main circle. A radius of that circle acts as an arm to carry, at its end, a small circle ('epicycle'). A radius of that small circle carries the planet round its circumference at a steady rate, while the arm of the large circle revolves at a smaller steady speed.

Experiment 20
A model of an epicycle scheme

Hold a tennis ball or an orange (for the Earth at rest) in front of your chest, with your right hand. Stretch out your left hand holding a table tennis ball to represent a planet. Make that planet move fairly quickly in

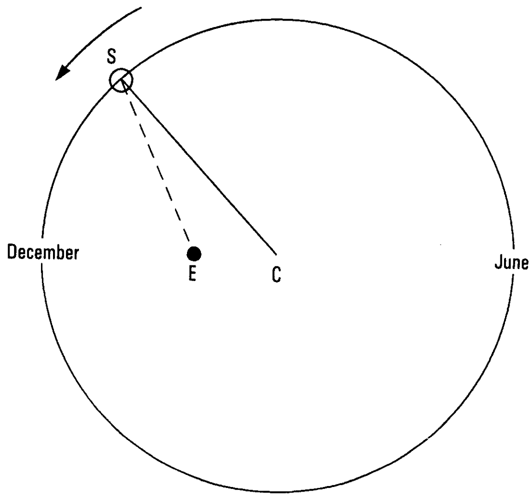


a small circle by twisting your hand round and round your wrist. At the same time sweep your outstretched arm slowly to carry your hand round a large circle. The combined motion will show the 'planet' moving in a circular path with loops.

Then, to see the motion as we see it for a planet, an observer should watch that motion from one side, almost in the plane of the big circle.

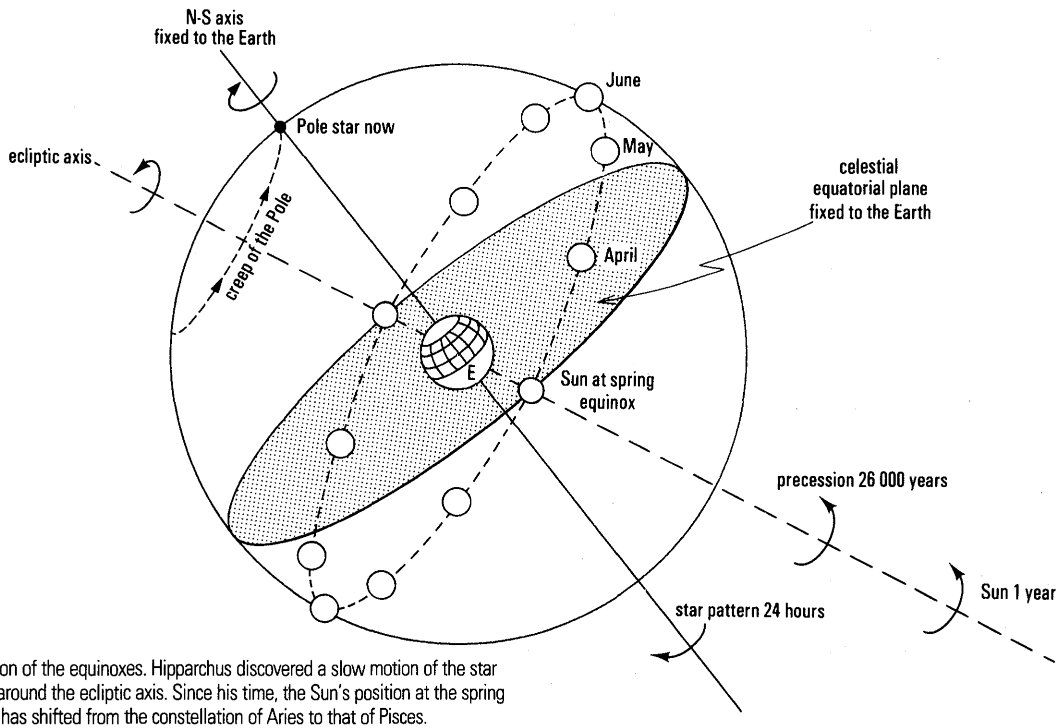
Demonstrations 21a, b also show models of an epicycle scheme. You may see one or both.

The Sun's motion along the ecliptic in one year is not quite at a constant rate. It is a little faster in the northern winter than in the northern summer, so the intervals between mid-winter and spring equinox and between spring equinox and mid-summer are not quite equal. To imitate this uneven motion, the Sun was imagined to move round a circle at a constant rate, but the Earth was placed a little off centre. Then the Sun, viewed along a line of sight from the Earth, would *seem* to move a little faster in December than in June. (See diagram.)



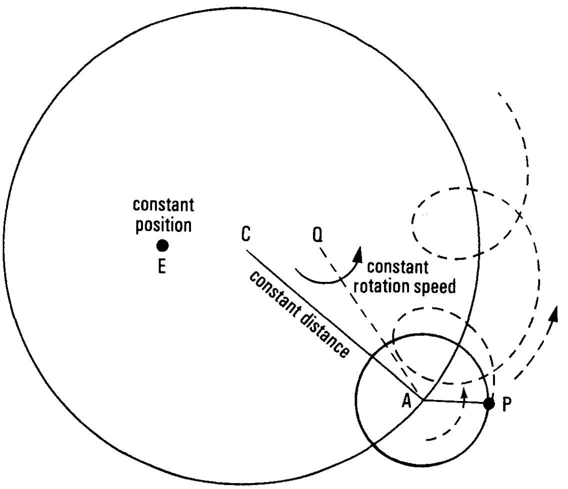
As time went on, this simple epicyclic model did not account for the new observations which were being made. These were growing in both number and accuracy. About 140 BC **Hipparchus** collected careful observations of the positions of as many as a thousand stars by sighting through peep-holes on long, jointed sticks, like a giant pair of dividers. He is believed to have measured angles to one sixth of a degree. By comparing his observations with older records dating back some centuries, he made a remarkable discovery.

Precession of the Equinoxes At the spring equinox, midway between winter and summer, the Sun is at a definite place in the zodiac. But Hipparchus found that the Sun does not return to exactly the same place at the next spring equinox, but to a place about 0.014° earlier. He saw that the zodiac girdle must be slipping round the celestial sphere very slowly, carrying all the stars with it and leaving the celestial equator fixed to a fixed Earth. This motion of the whole sphere of stars round the ecliptic axis (not the usual north-south axis) takes 26 000 years for a complete revolution – yet it matters in astronomical measurements and has always been allowed for since Hipparchus first discovered it.



Precession of the equinoxes. Hipparchus discovered a slow motion of the star pattern around the ecliptic axis. Since his time, the Sun's position at the spring equinox has shifted from the constellation of Aries to that of Pisces.

Ptolemy's successful machinery (about AD 120) The mathematician and scientist Ptolemy reviewed the records, studied the machinery and produced a new model that did match the facts with considerable accuracy. It was the same as the previous epicycle scheme except that the Earth was set at a small distance from the centre of the main circle for each planet, and a new point (called the equant point) was marked at an equal distance on the other side. That equant point (Q in the diagram) was imagined to carry an arm that ran out to A, the end of the arm of the main circle. Instead of making the radius of the main circle, CA, revolve at constant rate, Ptolemy made the equant arm, QA, rotate at constant rate. You can see from the sketch that QA will change in length as A goes round the circle; so one has to imagine that arm sliding through the point A.



Ptolemy described his scheme in detail in a very important book, later called *'Almagest,'* and that book, and Ptolemy's model, remained the authority for describing and predicting the motions of Sun, Moon, and planets for upwards of a dozen centuries.

This machinery, complicated as it was, has the essential characteristics of good science; it runs by keeping things *constant**. The main circle has *constant radius*, the arm from the equant point Q revolves with *constant speed*, the Earth is in a *constant position*, at a *constant distance* off-centre; the radius of the sub-circle stays *constant* and revolves with *constant* speed.

To Ptolemy the planets were just bright stars moving in the star pattern. Their real distances from Earth were unknown and no one knew whether they were much nearer to us than the stars, or even which ones were nearer than others. The system could place Jupiter nearer than Mars or Mars nearer than Jupiter, equally easily. However, since Jupiter drifts eastwards through the star pattern much slower than Mars, it was assumed that Jupiter is much further away. The order of the planetary distances they decided upon agreed with what we know today.

EARLY MEASUREMENTS

Nowadays we can find out how far the Moon is from the Earth by radar (timing a pulse of radio waves to the Moon and back). Or, by placing a reflector on the Moon and timing a flash of laser light there and back, we can find the Moon's distance with amazing precision.

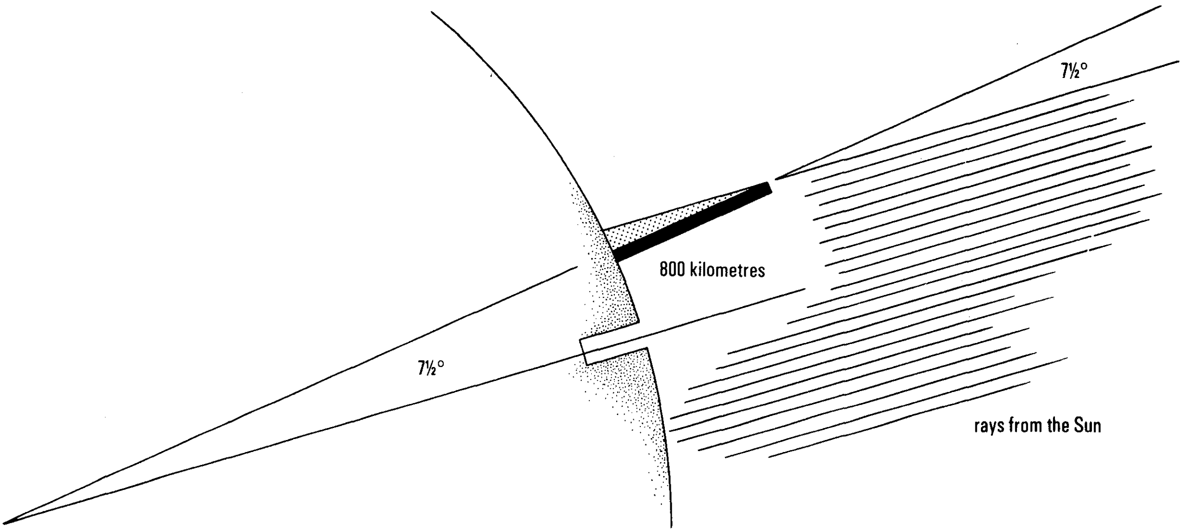
How did the Greeks make even rough measurements twenty-two centuries ago, with no lasers, no radar, no radio time signals, no telescopes, and only a small part of the world explored?

Even before Hipparchus and Ptolemy perfected their machinery, Greek astronomers at Alexandria had estimated the distance of the Moon, and therefore its size, by an ingenious method based on eclipse shadows. And they had attempted a rough estimate of the distance of the Sun.

Size of the Earth

Eratosthenes (about 240 BC) made an early estimate, using parallel rays of the Sun's light as a standard direction and measuring shadows at two stations a known distance apart.

He needed to measure the shadows at the same instant of time at both stations. So he chose Alexandria and Syene (Aswan), which was 5000 *stade* (thought to be about 800 km) further south, because a note in the Library at Alexandria by a traveller told him that at Syene at noon on Midsummer Day, sunbeams falling on a deep well go down to the water and are reflected straight up again.



* Scientists make descriptions of the behaviour of things in nature, and then make use of those descriptions in designing models and developing further knowledge. Many of those descriptions take the form of 'laws' which sum up the results of many experiments or observations. For example 'Springs stretch proportionally to load – up to a limit'. Such laws can be stated with the word *constant* as the key word in the account they give of nature. You will find that you can re-word almost any law in the sciences so that it has the word *constant* in it. For springs, the law becomes *stretch/load = constant*.

Therefore, the Sun must be vertically overhead at Syene at noon on that day. At noon on the same day of the year, Eratosthenes measured the shadow of a tall pillar at Alexandria and found that the Sun's rays made $7\frac{1}{2}°$ with the vertical. He assumed that *all* the Sun's rays reaching the Earth are parallel, so the Earth's radii, which have different directions at the two stations, must in fact make an angle of $7\frac{1}{2}°$ as you can see from the diagram.

Then, if 800 km of Earth's circumference subtends $7\frac{1}{2}°$ at the centre, what length subtends 360°? From the circumference, he calculated the radius of the Earth. *What radius do you get from this simple sum?*

Measuring the distance was difficult. Perhaps it was a military measurement made by pacing. Eratosthenes' error in the Earth's radius may have been as small as 5% – a remarkable success.

Experiment 22
Measuring the radius of the Earth

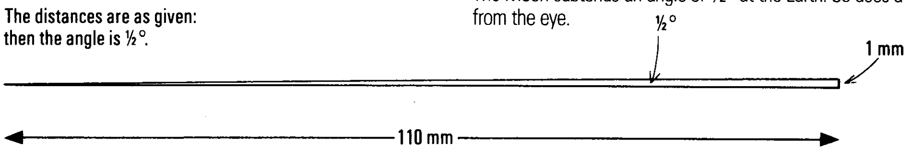
You can make your own estimate if your school cooperates with another school several hundred kilometres away, but near the same north–south line. Each school should set up a pole of known height, say 3 metres. The poles should be vertical, as shown by plumb-lines. Then pupils at each school observe the direction of sunlight at noon on the same day. They do that by measuring the shadow of the pole. Then the two teams compare notes. This is best done by telephone.

The size and distance of the Moon

Experiment 23
Estimating the ratio of the Moon's distance to its diameter

Look towards the full Moon and hold a small disk (such as a penny) out in front of you. Adjust its distance from your eye until it just obscures the Moon. If it needs to be further out than your arm can stretch, a stand and clamp will be needed to hold it – or you might stick it to the window pane.

The Moon subtends an angle of ½° at the Earth. So does a penny 2.2 m away from the eye.



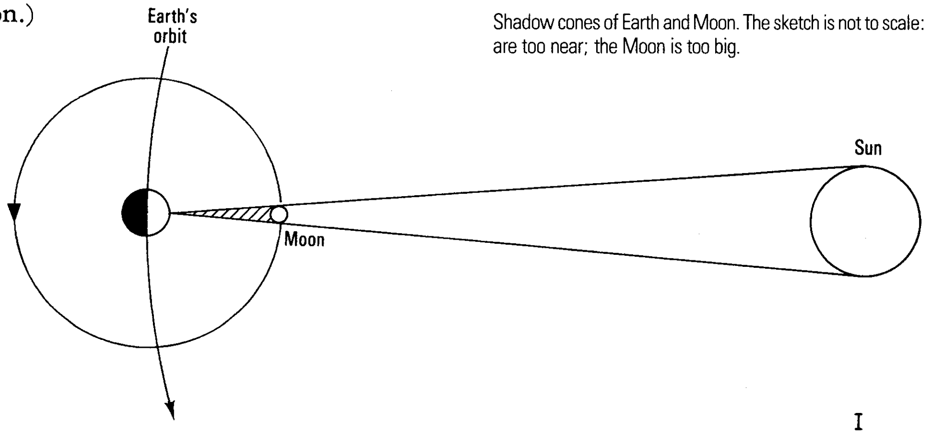
Ask a partner to measure the distance from your eye to the coin.

You will find that the coin is about 110 coin-diameters from your eye. By proportion, the Moon must be 110 Moon-diameters away.

By an odd chance, the Sun looks just about the same size as the Moon – so the Sun is about 110 Sun-diameters away.

(Since you should never look directly at the Sun, do NOT attempt the experiment with the Sun as well as the Moon.)

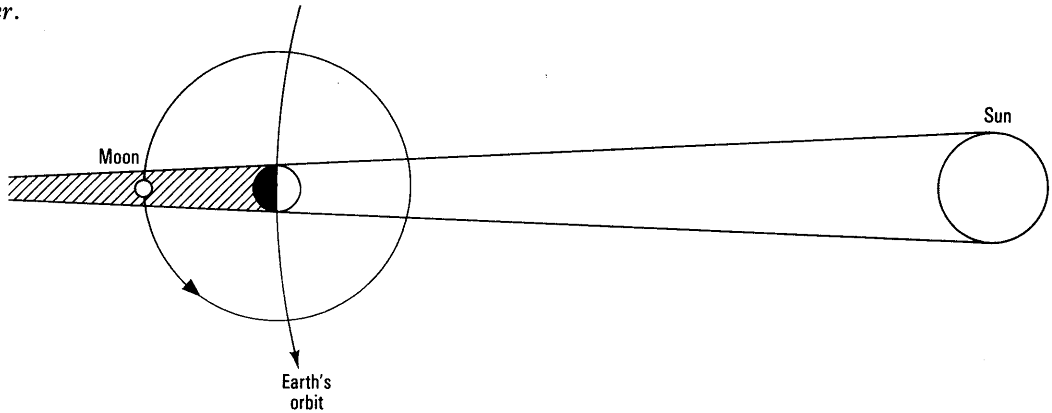
Shadow cones of Earth and Moon. The sketch is not to scale: the Sun and Moon are too near; the Moon is too big.



To find the Moon's actual distance we need another measurement as well. An early Greek method was to measure the time the Moon spends in a total eclipse and work out from that the size of the Earth's shadow in Moon-diameters.

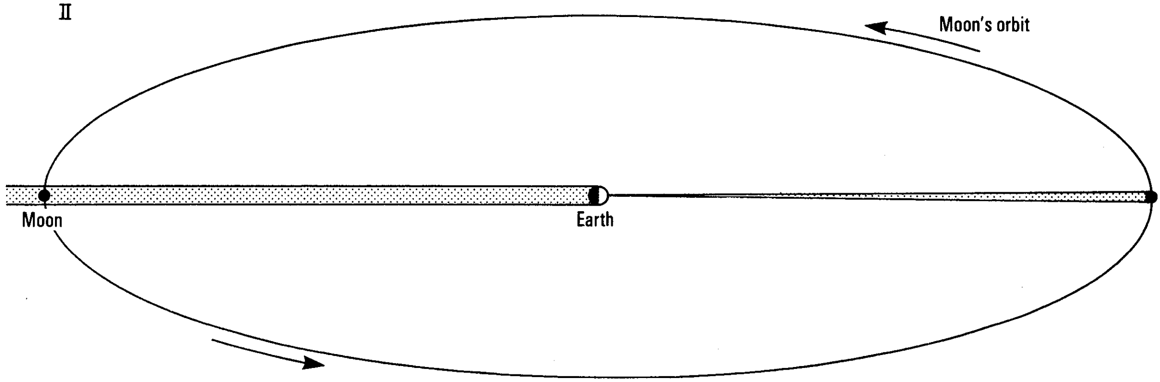
Diagrams to illustrate eclipses are often drawn with incorrect proportions, as in figure I. However, that figure does show how the Moon's shadow just tapers to a point by the time it reaches the Earth. We know that must be so because Sun and Moon *look* the same size; and, in eclipses of the Sun, the Moon just manages to blot it out.

The true proportions are shown in figure II. There you must imagine that you can see the Moon's shadow tapering to nothing at the Earth and the Earth's shadow also growing smaller, *with the same angle of taper*.



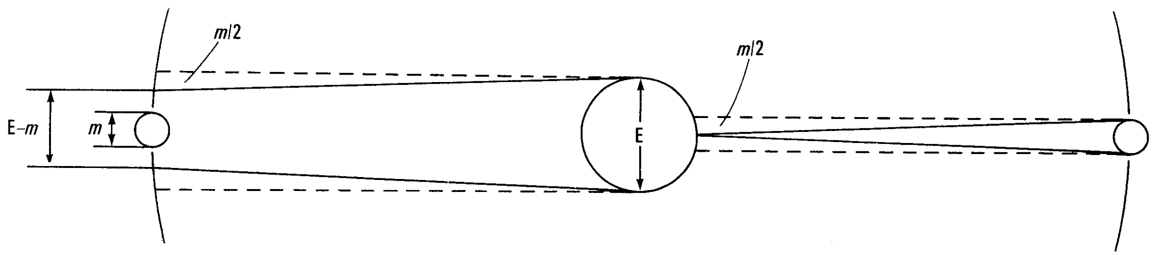
By watching a total eclipse of the Moon, the Greeks found that the Earth's shadow is $2\frac{1}{2}$ Moon-diameters wide, out at the Moon. That shadow has had the whole radius of the Moon's orbit in which to

II



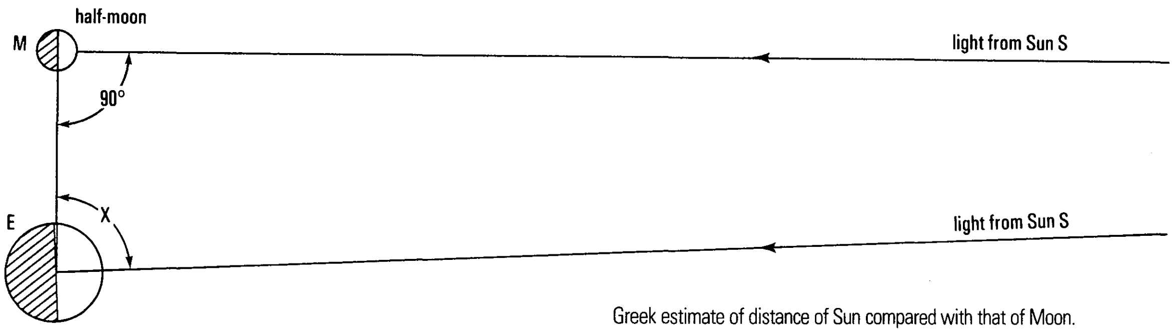
It is difficult to show how eclipses occur on a scale drawing. In this one the Sun is about 30 metres away to the right.

taper. Since we know that such tapering makes a shadow lose one Moon-diameter in that distance, we expect the Earth's shadow to be $3\frac{1}{2}$ Moon-diameters just behind the Earth. Therefore the Earth's diameter is $3\frac{1}{2}$ Moon-diameters. The Greeks, already knowing that the Earth's diameter is about 13 000 km, could then calculate the Moon's diameter. Multiplying that by 110 gave the Moon's distance, about 400 000 km.



Greek measurement of the diameter of the Moon (and hence its distance). The Sun is away to the right.

Estimating the Sun's size and distance Greek astronomers made a clever attempt, but the result was hopelessly inaccurate. They waited until they saw the Moon *exactly* at half-moon and tried to measure, at that instant, the angle between the Moon's direction and the Sun's direction. As you can see from the diagram, when the Moon is exactly at half-moon to an observer on the Earth, the angle at M must be 90°. If angle X is measured, all three angles of the triangle are known. Then one can draw a scale diagram, or use trigonometry, to find the proportion of ES to EM. The Greek estimate of angle X was 87°, but the correct angle is about 89.85° – much nearer to 90°. So the measurement was wrong by a factor of 20. This error in the Sun's distance (and therefore in the scale of the whole solar system) held for many centuries.



Greek estimate of distance of Sun compared with that of Moon.

ASTRONOMY AFTER PTOLEMY

By the fourth century AD scientific work in Alexandria was virtually over; the city was beset with religious strife and the conditions for rational thought were lost. Christendom was settling down into the Dark Ages.

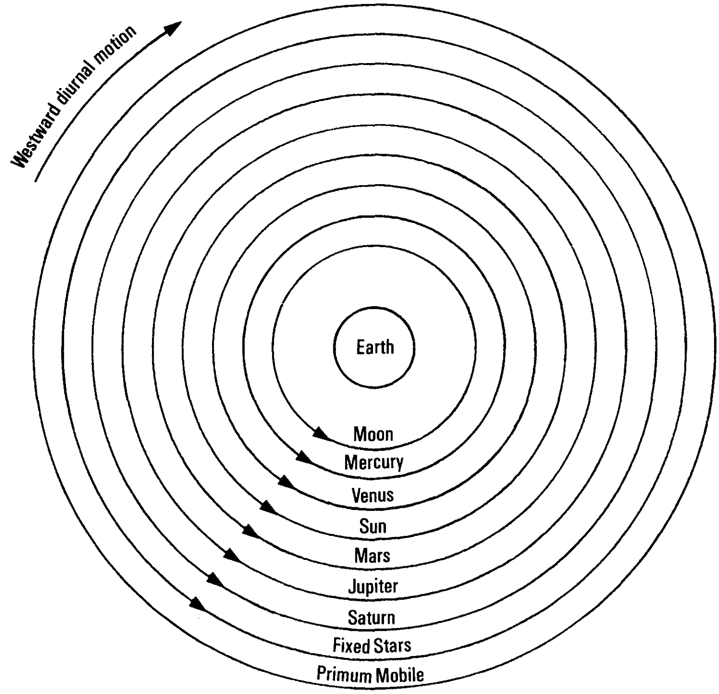
But around AD 750 a new school of astronomy and of other scientific studies came into being in Baghdad, a centre of the Arab world. Moslem astronomers made an important change to the picture of the universe they inherited from the Classical world. To the eight spheres carrying the seven 'planets' and the fixed stars, they added a ninth sphere or 'heaven', which helped them to give a better account of the precession of the equinoxes. This ninth heaven, the *Primum Mobile*, rotates every 24 hours. This view of a universe with nine revolving spheres or heavens was to become generally adopted in the west as well as in Islam.

After about AD 1100 the centre of activity shifted yet again – this time to Moslem Spain and, then, as the power of Islam waned, knowledge of such works as Ptolemy's *Almagest* seeped from Spain into Italy and France.

In the twelfth and thirteenth centuries, there was a great deal of interest in the 'world-picture' as European scholars began to rebuild the lost scientific tradition, using translations of the Arabic texts, which were themselves derived from the classical Greek works. A new set of planetary tables to replace those in *Almagest* was completed in 1252 and these *Alphonsine Tables* (named after King Alfonso the Wise of Castile who commissioned them) remained the prime source of information until after the time of Copernicus.

Speculation based on Ptolemy's model led to the development of a model of the universe made up of concentric spheres – seven for the Moon, Sun, and planets and, beyond the sphere of the fixed stars, the fastest moving sphere of all (*Primum Mobile*) all contained within an unchangeable region of perfection (the empyrean). The imperfect, lowly Earth lay at the centre and, in Dante's version, Hell was within it. This powerfully held picture did not prevent those interested in astronomy from continuing to work with the epicycles of Ptolemy's model. Indeed, several scholars considered the suggestion, first made by Aristarchus, that the rotation of the heavens was an optical illusion, resulting from the daily motion of the Earth.

So far the story outlined in this chapter has shown us how, long before the invention of the telescope, men had collected together vast quantities of observations of the stars and the planets; had mastered the art



The geocentric universe as generally accepted in the later middle ages.

of calendar making; had speculated about what they saw and had argued about a number of different mechanisms which might describe and perhaps explain the events they were watching in the sky. Even as late as the thirteenth century nearly everyone accepted the 'earth-centred' model which common sense suggested. To shift from this strongly held view to a 'Sun at the centre' system was too big a step to take; indeed it did not even seem to be necessary since the accepted description of the solar system was so satisfactory. To see the need for such a step – and then to make it – was to be the great contribution of Nicolaus Copernicus.

Progress Questions and Questions for this chapter appear on pp. 86–7 and 87–9.

CHAPTER 4
New developments

Ptolemy's effective model could reproduce the heavenly motions quite accurately. But it was a very complicated model indeed. Remember that the line ECQ in the diagram (page 47) can take different directions from the fixed Earth E for different planets, and the 'eccentric' distance EC can have a different value for different planets. So if you sketch Ptolemy's arrangement for the Sun and the planets all on one picture you will produce a very complicated drawing.

NEW SIMPLICITY: NICOLAUS COPERNICUS (1473–1543)

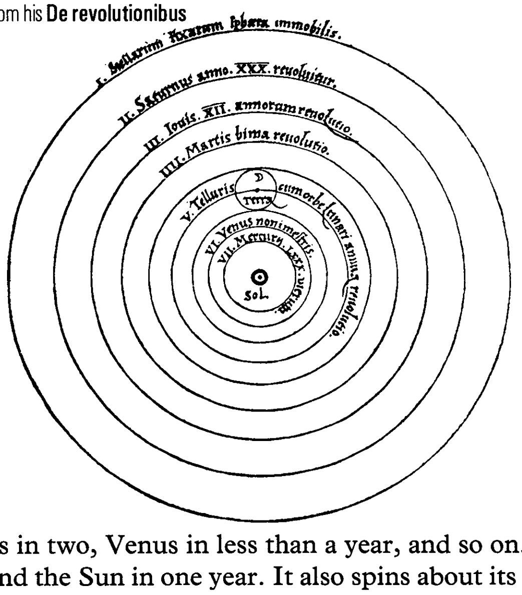
Nicolaus Copernicus was born in what is now Poland. He was brought up by his uncle who was bishop of the nearby cathedral and practically the ruling prince of the district. After school and university, Nicolaus went to Italy to study church law because his uncle planned to secure for him an administrative post as a canon in the church.

He stayed on in Italy, reluctant to leave because he enjoyed his life there and had developed a tremendous interest in astronomy, reading widely and studying all the early theories.

Eventually he was called back to Poland and he settled down to the job for which he had been trained – that of a secular canon administering the business affairs of the cathedral. But he continued to think about ideas for a simpler model of the heavens. He felt that the World must be simply made and not something as arbitrary, complicated, and unsymmetrical as Ptolemy's machinery of equants and epicycles.

His aim was to show that the movements of the Sun, Moon, and planets were made up of uniform, circular motions, related together in a regular way. He was convinced that the explanation of what we see happening in the sky had to be simple and economical. And his search led him to propose the Sun-centred system. The Sun is at a fixed centre and each planet moves round the Sun in a circular orbit –

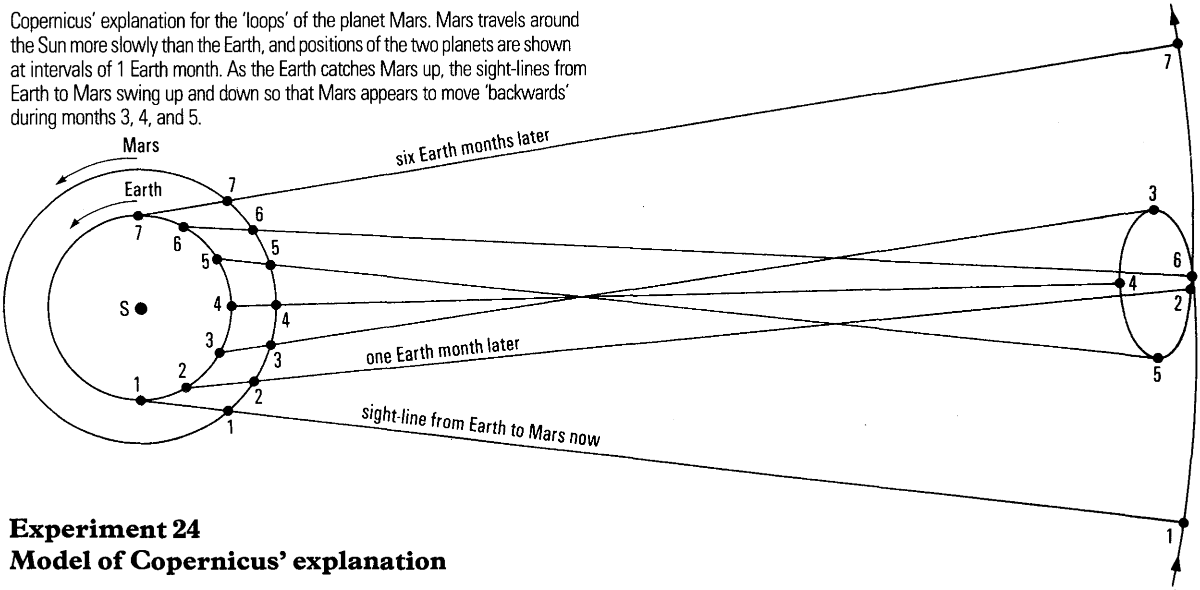
Copernicus' heliocentric system of the universe, from his **De revolutionibus orbium coelestium**, Nuremberg, 1543.
Ann Ronan Picture Library.



Jupiter in a dozen years, Mars in two, Venus in less than a year, and so on. The Earth itself is a planet, moving in a circular orbit round the Sun in one year. It also spins about its north-south axis making one revolution in 24 hours and this accounts for the daily motion of all the stars, the Sun, Moon, and the planets together. It was no longer necessary to think of the stars as stuck on a great revolving shell that whirled across the sky each night; the stars just hang in space while we watch them from our spinning Earth.

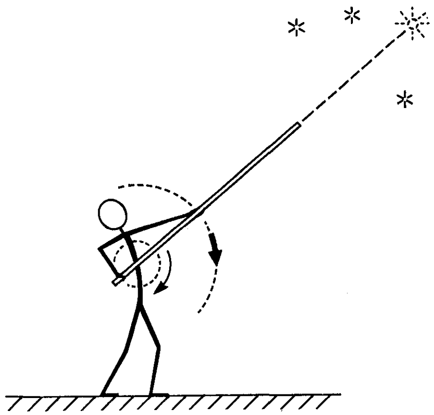
The looped paths of the planets If the system is as Copernicus suggested, the Earth's motion along its orbit will account for the 'loops' that we see in a planet's path through the zodiac. The planet is moving steadily along its circle but the motion of the Earth on which we are standing to observe the planet tilts our sight-line (the line from our eye out to the planet and beyond to the fixed stars) to and fro. That 'tilting' motion added to the planet's steady motion gives the planet's path a 'loop' at regular intervals of time.

Copernicus' explanation for the 'loops' of the planet Mars. Mars travels around the Sun more slowly than the Earth, and positions of the two planets are shown at intervals of 1 Earth month. As the Earth catches Mars up, the sight-lines from Earth to Mars swing up and down so that Mars appears to move 'backwards' during months 3, 4, and 5.



Experiment 24
Model of Copernicus' explanation

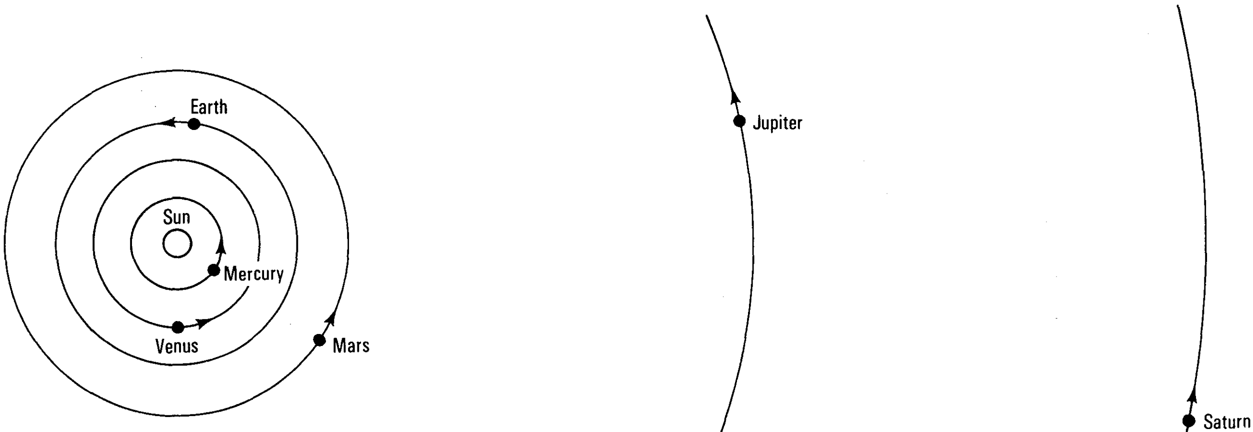
Try this yourself with a long pole. Pretend the Sun is just in front of your chest. Move your right hand round the 'Sun' in a vertical circle, fairly quickly, to represent the motion of the Earth in an orbit round the Sun. Stretch out your left arm and move your left hand round a larger circle, more slowly, to represent the motion of a planet, Mars or Jupiter, say. When you have practised making these two



movements, make them while you hold one end of a long pole in your right hand and let the pole slide through the fingers of your left hand. Then the pole represents the line-of-sight from an astronomer on Earth to the planet and on out to the distant stars. Watch the other end of the pole as you make these movements and imagine how the astronomer would see the planet moving through the pattern of stars.

Copernicus' solar system

The sketch shows Copernicus' scheme. So far, Copernicus was merely following the suggestions of the Greek astronomers. But now see what he added by thinking about his model and using some observations. One of the characteristics of a good theory or model of Nature is that it gives us new information. We pour ideas and facts into the building of a theory and then the theory gives us back new



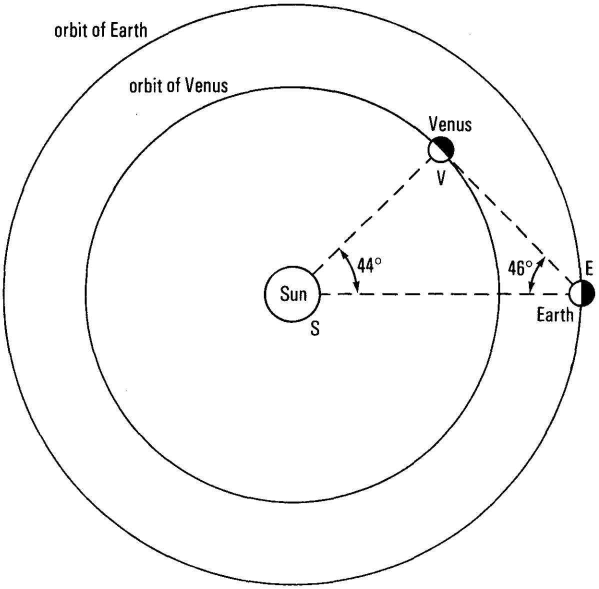
Copernicus' solar system.

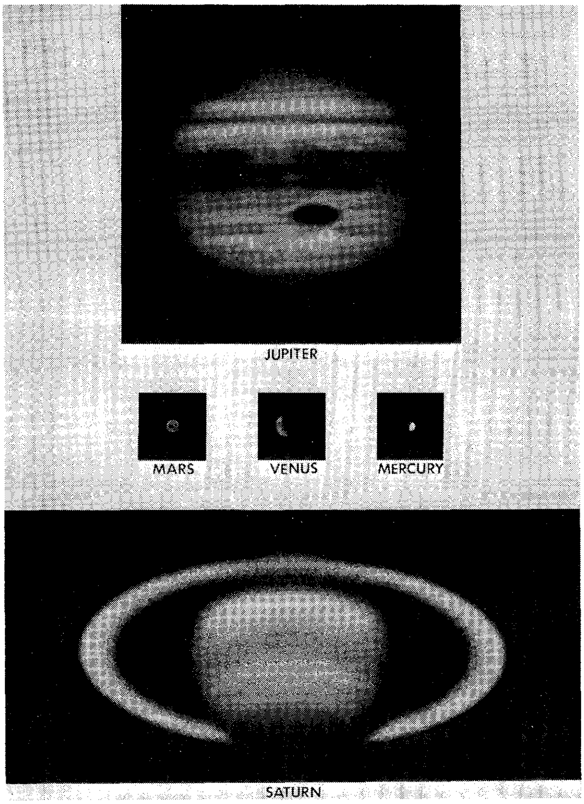
information – measurements or relationships – which follow from the assumptions we have made. Copernicus' theory did all that the earlier theories had done – and much more. It predicted the phases of Venus (not observed until the telescope had been invented). It gave the relative sizes of the orbits of the planets and therefore the order in which they were arranged about the Sun.

As we have seen the Greeks had assumed a relative order for the planets: but the epicycle system itself did not require any special order. The four spheres for Jupiter in Eudoxus' scheme could go outside the four for Mars, or they could go inside. Ptolemy's main circle and sub-circle for any planet could be enlarged to place any planet beyond any other planet.

But Copernicus' scheme allowed him to calculate the relative sizes of the orbits, so there was no doubt about the order in which the planets were arranged.

Estimating the relative radii of the orbits of Venus and Earth.





Relative sizes of five planets.
Lowell Observatory Photograpn.

To see how Copernicus did this, look at his method for Venus. We see that planet as a bright morning star or as a bright evening star, never very far away from the Sun. If you watch Venus carefully and make measurements you will find that Venus is never further away from the Sun than 46°. In the diagram, when Venus appears furthest away at V, the sight-line from Earth to Venus must just be a tangent to the orbit of Venus. Then the line EV is perpendicular to the radius SV. From the right-angled triangle, SV/SE must be the sine of 46°, which is 0.72. So the radius of Venus' orbit must be 72/100 of the radius of the Earth's orbit.

The same method was used for the planet Mercury. For the planets outside the Earth's orbit (Mars, Jupiter, and Saturn) the argument was a little more complicated but essentially the same. Then Copernicus could draw his scale model of the system. Here is his list of planets with the proportions of the orbit radii, taking the Earth's orbit radius as 100.

Mercury	39	Mars	152
Venus	72	Jupiter	520
Earth	100	Saturn	960

Although Copernicus could draw a scale model of the solar system, he did not know its real size at all accurately. For that, he needed a measurement of just one of the distances. All he had was a very inaccurate Greek estimate of the distance from Earth to Sun.

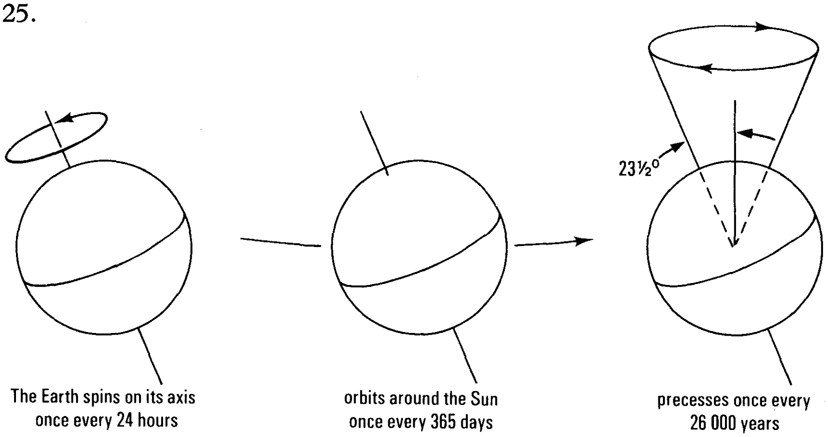
If you wished to make a scale model of the solar system you would need to know the sizes of the planets themselves and those were not measured until much later, when telescopes were available. But if you like to anticipate those measurements you might arrange the following for a rough model: place a beach ball to represent the Sun; then a grain of sand (about the size of a pin's head) 16 metres away to represent Mercury; then a pea at 30 metres to represent Venus and continue thus:

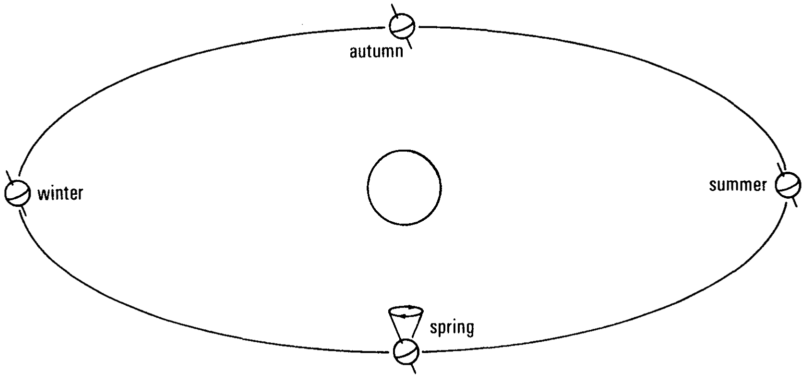
Sun	a beach ball	
Mercury	a grain of sand	16 m from 'Sun'
Venus	a pea	30 m
Earth	a pea	40 m
Mars	an apple pip	60 m
Jupiter	a table tennis ball	210 m
Saturn	a table tennis ball	380 m

You would place our Moon (a grain of sand) about 10 cm from the Earth.

Ecliptic Until now we have described the ecliptic as the Sun's path through the star pattern, but, to Copernicus, it was the plane of the Earth's yearly orbit round the Sun.

Precession Copernicus' model gives a simple description of the precession of the equinoxes. It is that the Earth's north-south axis, about which the Earth spins daily, slowly swings round a $23\frac{1}{2}°$ cone, taking 26 000 years. The axis of that cone is the axis of the ecliptic (that is, an axis perpendicular to the ecliptic). But Copernicus could give no reason for this motion, any more than could the Greeks. You may see Demonstration 25.





Copernicus' great book Copernicus was eventually persuaded to publish a small booklet describing his scheme; but he was hesitant about publishing a scheme so different from the one held by most people. However he finally put all his work into a great book.

In that book he described his system, gave his reasons in support of it, worked out tables to show how it could be used for predictions, and added a chapter on spherical trigonometry. By now he was an old man and in poor health. A cautious editor added a preface saying that the scheme was a hypothesis and not necessarily true. Nothing could be further from Copernicus' own view. He was almost certainly convinced that his scheme represented God's work, endowed with great simplicity.

When the book was finally printed, Copernicus was dying. It is said that the first copy was rushed across Europe to him and that he touched it on the day he died.

The book was called *De revolutionibus orbium cœlestium*, meaning '*Concerning the Revolutions of the Heavenly Spheres*'; we regard it still as one of the great books of science.

Copernicus wrote in Latin, the international language of scholars at the time. Nevertheless, his book had very little effect for about fifty years. Then the implications of a system in which a spinning Earth moved in orbit round a central Sun began to be realized.

Copernicus' scheme was Sun-centred (or heliocentric), and it is the one we accept today. We now know that the planets' orbits are ellipses and not circles but with that small change, Copernicus' model seems to us to be better than earlier models because it is (*i*) simpler and (*ii*) in agreement with the rest of scientific knowledge.

(*i*) Scientists use models or theories like maps* to help them find their way, or to describe their explorations, or to direct another scientist on his way. We like to choose the *simplest* model that suits our purpose and we do not worry too much whether it is true, so long as it fits the facts. Ptolemy's scheme for the heavens fitted the facts, and in making tables or calculations for navigation we might still use a Ptolemy pattern of 'things as seen from the Earth'. But to travel in a space probe among the planets with that sort of model would not be sensible; a Copernican model would be better.

(*ii*) When we come to Newton's general theory, we find that the Copernican model fits in well with the rest of our scientific knowledge, whereas a Ptolemaic (or 'geocentric') system, with the Earth at the centre, would still need special machinery to keep it going – machinery quite different from the machinery of science on the Earth.

HIGHER FIDELITY: TYCHO BRAHE (1546–1601)

The next developments of astronomical theory owed much to an astronomer with tremendous skill and success at observing. Until then observations had been gathered and recorded in a rather haphazard way. Astronomers made observations when it was convenient, and though they took reasonable care, their

* If you visit or live in London, you will find the map of London's Underground very helpful. On that map, in many colours, the lines run straight up, or down or across with a few at 45°, and even the River Thames follows a simple course. If you look at a map of bus routes instead, you will see all the crooked complexity of the streets. That map can be useful too. But if someone asks you 'Which is the right map?' you would call it a silly question and say that it depends on what you want the map for. Theories in science are maps of our thinking and knowledge. Which theory – or which model – is the right one depends on what we want to use it for. We try to choose the simplest one.

records were not always very accurate. Tycho Brahe spent his life making fine instruments and using them with great skill and tremendous enthusiasm, to measure the positions of the planets on a systematic timetable of work. As a result his student and successor, Kepler, could discover precise, reliable laws of planetary motion which then served as the foundations for Newton's theory. What fired Tycho with that enthusiasm for measurement?

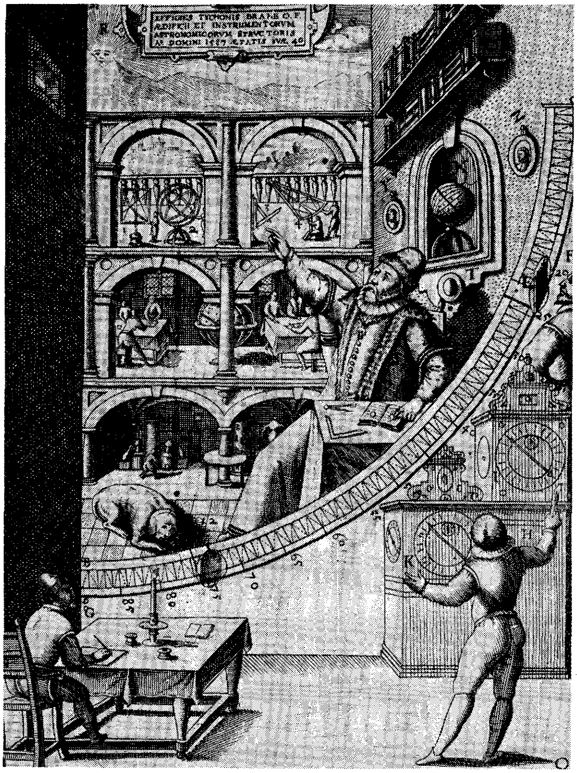
Tycho's family were nobles close to the Court of Denmark and Tycho was brought up by an uncle with intellectual interests, who valued good education. At thirteen he went to the University to learn philosophy and law; but there he became fascinated by astronomy.

The eclipse Astronomers had predicted an eclipse of the Sun. When it happened at the predicted time, young Tycho was thrilled, not just with the wonder of the eclipse but with the idea that astronomers could predict it. He decided that astronomy was to be his life's work.

After his university studies, his uncle sent him on a tour of foreign travel with a tutor to continue his study of law. But much of his time was spent in astronomical studies and observations.

The clashing planets Then another astronomical event changed his outlook. He calculated that the planets Jupiter and Saturn would soon *seem* to pass very close to each other as they moved through the star pattern. That 'clashing' of two planets is called a 'conjunction'. It could be predicted with the help of the planet records which had been published in the Alphonsine Tables in 1252 or with the help of the records to which Copernicus' researches had contributed. To Tycho's great disappointment, the Alphonsine Tables were a whole month in error for this conjunction whilst Copernicus' Tables were wrong by a few days. He was angry at such inaccuracies and he grew more and more determined to set things right. He decided to measure the motions of the planets with such care and skill that he would be able to make really accurate predictions. As a boy of seventeen he realized what other astronomers had missed: that a connected series of precise observations was needed to establish astronomical theory.

Eventually he joined other astronomers in Germany and began to make the huge instruments that were necessary for accurate observing. To measure each planet's celestial latitude and longitude accurately



Tycho's mural quadrant. An observer at F is sighting a star through a pin-hole and a marker at a window. The pin-hole can move along a huge brass arc (radius about 2 m) with its centre at the open window in the southern wall. The wall within the arc was painted to show Tycho observing, students working, and some of the larger instruments.
Ann Ronan Picture Library.

required instruments with scales so large that each degree on the scale of angles could be subdivided into small fractions. Such instruments had to be both large and robust if they were to be reliable.

The great observatory: Uraniborg The king of Denmark, hearing of Tycho's growing fame abroad, offered to provide him with a magnificent observatory if he would work in Denmark. So, using royal endowments and his own fortune, Tycho built a palatial observatory on an island near Copenhagen.

He spent twenty years there, building up a tremendous record of accurate observations, all made with naked eyes, using instruments which he designed and constructed in the workshops of the observatory.

Towards the end of that time there were strong complaints about Tycho's management of the royal estates on the island and eventually he was forced to close the observatory and to leave the island. To find a new royal patron, he published a book describing his instruments, from which one picture is shown on page 58. The Holy Roman Emperor Rudolph II, then living in Prague, invited Tycho to be Imperial Astronomer and Astrologer. So Tycho moved with many of his instruments to a castle near Prague. There, though his health was failing, he carried on observing and recording.

A young mathematician, Johannes Kepler, wrote to Tycho and asked if he might join him. Tycho welcomed him and finally bequeathed many of his great records to him. Those records catalogued the motions of the Sun and the planets with an accuracy quite unknown before.

JOHANNES KEPLER (1571–1630)

Johannes Kepler who had joined Tycho Brahe as a 'research assistant' was given the task of finding the orbit of Mars from Tycho's records. The two men worked together from early in 1600 until Tycho died in October 1601, forming a strange contrast: Tycho, a rich, vigorous aristocrat, with great mechanical and experimental skills; Kepler, a poor scholar with great mathematical gifts. They had in common a profound interest in astronomy and a consuming determination to pursue that interest.

Kepler was fascinated by puzzles concerning numbers and sizes; and he was determined to find the mathematical scheme underlying the behaviour of the planets. His mind burned with questions: *Why are there only six* planets? Why do their orbits have just the proportions and sizes they do? Are the times of the planets' 'years' related to their orbit sizes?*

Orbit sizes Kepler's first question 'Why only six?' is characteristic of the time. Nowadays we should just hunt for a seventh; but then there was a magic in numbers.

Kepler tried to find geometrical patterns that would predict the relative proportions of planetary orbits.

After many trials Kepler imagined a cube sitting in a sphere, its eight corners just touching the sphere, and another sphere inside the cube. The radii of those two spheres gave him just about the right proportion for the orbits of Saturn and Jupiter. Using the other four regular solids to space spheres apart, he had a scheme of five solids, bounded by six spheres, which predicted the ratios of the planetary orbit sizes reasonably well.†

You might laugh at Kepler's mystical scheme of solids; yet to him it was a wonderful discovery and good theory, in keeping with the spirit of the time. The only objection was that the measurements of orbits given by the Copernican scheme did not fit the pattern of solids accurately. Kepler himself was obliged to thicken the spherical shells between the solids; but many theories throughout the ages have had to adopt minor modifications to escape criticisms of inaccuracy. It was then that Kepler decided to visit Tycho Brahe.

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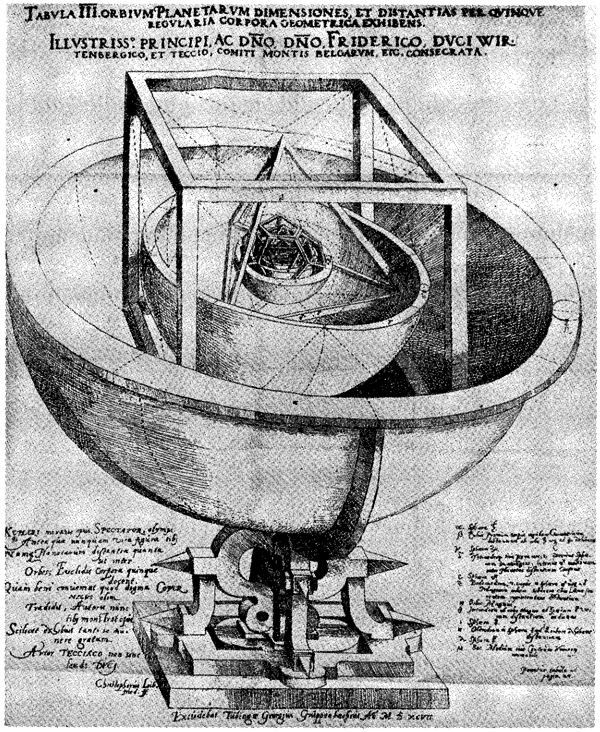
* The Ptolemaic system counted *seven* planets (including Sun and Moon but excluding Earth) and even had reasons to show that seven must be right, as a lucky number. On Copernicus' system only *six* planets were known: Mercury, Venus, Earth, Mars, Jupiter, Saturn.

† A regular solid is a shape with all edges equal, all face angles equal, all corners the same and all faces the same. There are only five: cube, tetrahedron, dodekahedron, eikosahedron and octahedron.

Kepler's scheme. The relative sizes of the planetary orbits are shown by the bowls separating one solid from the next. The bowls were just thick enough to accept the eccentric orbits of the planets.
Ann Ronan Picture Library.



Mars, the difficult planet

Working with Tycho and continuing after his death, Kepler tried repeatedly to find the shape of the orbit of Mars.

We now know that the orbit of Mars is an ellipse which is very close to a circle – the ratio of the maximum radius to minimum radius is only 1.0043:1.0000. Yet the observed motion of Mars differed enough from simple motion round a circle with constant speed to show up clearly in the observations and to make Mars the difficult planet.

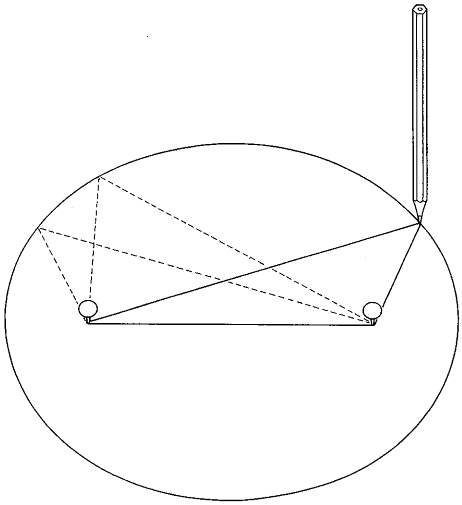
Kepler was sure that the Copernican heliocentric system would turn out to be the true model. Under the influence of the Greek tradition, he tried circular orbits with the Sun a short distance off centre and the planet carried round by a constant-speed arm from another point (like an equant) a small distance off centre. He made dozens of trials with different amounts and directions of eccentric placing. In each trial he used some of Tycho's observations to determine the circle, then continued the motion of his theoretical planet and predicted its position at some later date; then he compared that with Tycho's observation.

Scheme after scheme failed to fit but, after many trials, Kepler found an eccentric-circle scheme that fitted well. Delighted, he made one further test and found that his predicted direction for Mars differed from the observed position by 8 minutes of angle (0.13°).

Might not the observations be wrong by this amount? Would not 'experimental error' take the blame? No. Kepler knew Tycho, and he was sure Tycho was never wrong by that amount. Tycho was dead, but Kepler trusted his record. He bravely set to work to go the whole weary way again, saying that upon these 8 minutes he would yet build a theory of the universe.

Plotting Mars' orbit It was now clear that a circular orbit could not be made to fit the facts. Kepler realized that he must obtain an accurate picture of Mars' real orbit from the observations – not an easy task, since we observe only the apparent path of Mars from a moving Earth. The true distances were unknown; only angles were measured, and they gave a foreshortened compound of Mars' orbital motion and the Earth's. So Kepler attacked the Earth's orbit first – by a method which Einstein once said was Kepler's real mark of genius. Once he had found the Earth's true orbit to be an ellipse, Kepler returned to the orbit of Mars and found that to be an ellipse as well. The Sun was at one focus of each ellipse. This was a thoroughly revolutionary statement. Kepler had accepted that the Sun was not just the innermost body in the system, but it was also the controller of the system, exerting a force over its family of planets. Kepler had brought physical reality into the story of the heavens.

Experiment 26
Drawing an ellipse
If you have not tried drawing an ellipse yourself, try it now. Use two drawing pins and a loop of thread about 25 cm long.



Stick the two drawing pins in a board (not pressed far in) about 10 cm apart. Slip the loop of thread over them. Insert a pencil point in the loop and pull the thread taut. Then move the pencil to draw an ellipse, always keeping the thread taut.

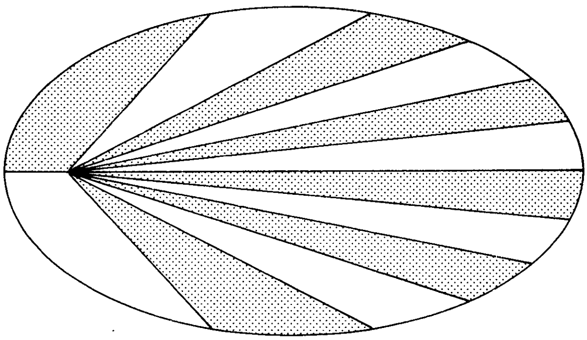
Kepler's laws

Kepler found that the same rule must hold for the other planets. Thus he had discovered the first of his three great laws. (You may see a rough illustration of motion round an ellipse: **Demonstration 27**.)

Law I The orbits of the planets are ellipses

In the course of trying different orbits for Mars, Kepler discovered another guiding rule, now called his Second Law.

Law II Constant areas and variable speed He tried Ptolemy's spoke, an arm from the equant point, sweeping round with constant speed and carrying the planet along the orbit. He could not find a choice to agree with the facts; instead he found that an imaginary line, running straight from the Sun to the planet, does *sweep out area* at a constant rate.



Kepler's discoveries. An ellipse with the Sun at one focus fits the orbit. The line from the Sun to the planet sweeps out equal areas in equal times. All the sectors shown have equal areas; the planetary orbits are much closer to circles in shape than in this figure.

This must mean that the planet's speed along the orbit is changing. How does it change? Sketch an orbit, an ellipse with the Sun at one focus, and make several sectors, all of the same area, as in the sketch here. You can see that when the arm from the Sun to the planet is long, the planet's speed is slow, when the arm is short the planet's speed is fast.

Experiment 28
Pulling a 'satellite' in

Take the rubber bung on the string you used in **Experiment 6** and whirl it as slowly as you can in a vertical circle. Then let the string wrap round your finger.

As with Ptolemy and the Greeks before him, something had to stay constant in the machinery, or it was useless as a scientific theory. Kepler replaced constant speed by constant rate of sweeping out area.

Law III Connecting the motions of all the planets Kepler continued to brood on one of his early questions: what connection is there between the sizes of the planets' orbits and the times of their 'years'?

Here is a table of measurements giving modern data which are more accurate than those Kepler had. Can you see any relation connecting orbit radius and the time a planet takes to go round its orbit? Suppose that radius and time went up in the same proportion from planet to planet so that values of ORBIT RADIUS/TIME OF REVOLUTION were the same for all. Is that so? As R almost doubles from Mercury to Venus, T almost triples. As R grows almost ten times from Earth to Saturn, T grows about 30 times. Simple proportion will *not* do.

Planet	Radius of planet's orbit, R, in km	Time of revolution (planet's 'year'), T, in days
Mercury	5.785×10^7	87.97
Venus	10.81×10^7	224.7
Earth	14.95×10^7	365.3
Mars	22.78×10^7	687.1
Jupiter	77.76×10^7	4333
Saturn	142.58×10^7	10 760

Is there something which you could work out for Jupiter's orbit size and orbit time, again for Mars' orbit size and orbit time, again for Earth's orbit size and orbit time, and so on, and get the same result for each planet? This was the problem with which Kepler wrestled for a very long time, trying different combinations such as R/T (which as we saw, will not succeed), R^2/T and many other ratios. At last he found that R^3/T^2 does succeed.

Here is the full story, using modern data. The test of Kepler's guess is shown in the last column.

Planet	Radius of planet's orbit, R (km)	Time of revolution (planet's 'year', T (days)	R^3 (km)^3	T^2 (days)^2	$\dfrac{R^3}{T^2}$ $\dfrac{(\text{km})^3}{(\text{days})^2}$
Mercury	5.785×10^7	87.97	1.936×10^{23}	7739	2.502×10^{19}
Venus	10.81×10^7	224.7	12.63×10^{23}	50 490	2.501×10^{19}
Earth	14.95×10^7	365.3	33.41×10^{23}	133 400	2.504×10^{19}
Mars	22.78×10^7	687.1	118.21×10^{23}	472 100	2.504×10^{19}
Jupiter	77.76×10^7	4333	470.18×10^{23}	18 770 000	2.505×10^{19}
Saturn	142.58×10^7	10 760	2898.5×10^{23}	115 800 000	2.503×10^{19}

Kepler was overjoyed and published this law as well as his others. He was a mathematical speculator. He looked for connections among planetary data and found some that he considered successful. His three great laws were clear, simple and powerful. We still hold them as descriptions that fit the facts very accurately.

Law I The orbit of each planet is an ellipse with the Sun at one focus.
Law II The radius (arm) from Sun to planet sweeps out equal areas in equal times as the planet travels in its orbit.
Law III For all planets, R^3/T^2 has the same value.

For these laws we may call Kepler the law-giver of the heavens.

CONVINCING PUBLICITY: GALILEO GALILEI (1564–1642)

The brilliant teacher Galileo did much to prepare physics for Newton's development. He insisted on making theory realistic by tying it to experiment and putting the laws of physics into mathematical form as far as was possible. He was a great mathematical codifier and arguer, who seemed content to quote rough experiments in support of his arguments. He argued in a clever way: he first learned his opponents' views and arguments, then expressed those arguments even more clearly and convincingly than his opponents could. When they rejoiced at what looked like his clear understanding of their story, he turned round and demolished it with his own powerful arguments. In doing that he often made bitter fun of his opponents and annoyed them very much.

In sorting out mechanics from mystical speculation, Galileo arrived at the law we now know as Newton's First Law by an ingenious argument (sketched in the next chapter). He knew about motion with constant acceleration and had the beginnings of Newton's Second Law in his thoughts. So he laid the foundation, by argument and experiment, for Newton's relationships between force, mass, and motion.

Teaching the Copernican system While Kepler was at work on the orbits of the planets, Galileo was teaching the Copernican system with great enthusiasm. As a teacher of tremendous power Galileo was able to put the case for Copernicus so clearly that for the first time readers far and wide understood and saw its full meaning. And when he built his telescope he showed Jupiter's moons going round Jupiter and said that it was a scale model of the Copernican system itself.

His lecturing and writing made clear what Copernicus' book had given to only a very few scholars, that the Earth is just an ordinary planet like the rest and not a wonderful, special, privileged central home for all-important Man. The Earth is ordinary. And his telescope showed that the Moon is ordinary too.

All this was a violent and disturbing attack on established thinking and the central position given by scholars to the Earth and to Man. It was an attack on the Church teaching of the Ptolemaic system and on the general public's idea of heaven as a comfortable future home outside the sphere of the stars. If the Earth spins and the stars are at rest, a starry sphere is no longer required and the stars can be situated far out in space at many different distances leaving no place for a heaven. That was a very disturbing suggestion.

Contest between science and church In 1633, after a long trial, Galileo was forced by the Inquisition and the Church to recant his view of the universe and his support for the Copernican model. He had brought into the open the differences between authoritarian Churchmen and independent scientists. But his tactless manner and powerful arguments had brought great troubles upon him, and, in some ways, on science too. His biographers differ in their views about his conflict with the Church, according to their own feeling about authority.

Some paint him as almost a martyr, threatened by a bigoted Inquisition, suspected, persecuted, imprisoned, and forbidden to teach the great truths he had helped to discover – with the Church as the villain of the piece.

Others show Galileo bringing his troubles on himself by his hot-headed arguments and his exasperating manner of setting people right; they see him as ungrateful towards the Church which listened to his teaching and honoured him with pensions, and they point out that his conflict with the Church arose directly from his attack on scriptural science – in which he was meddling in the Church's rightful province. They say that Galileo's essential mistake was his insistence that the Copernican scheme was *true* and not just an interesting hypothesis; treating it as a model would have been acceptable.

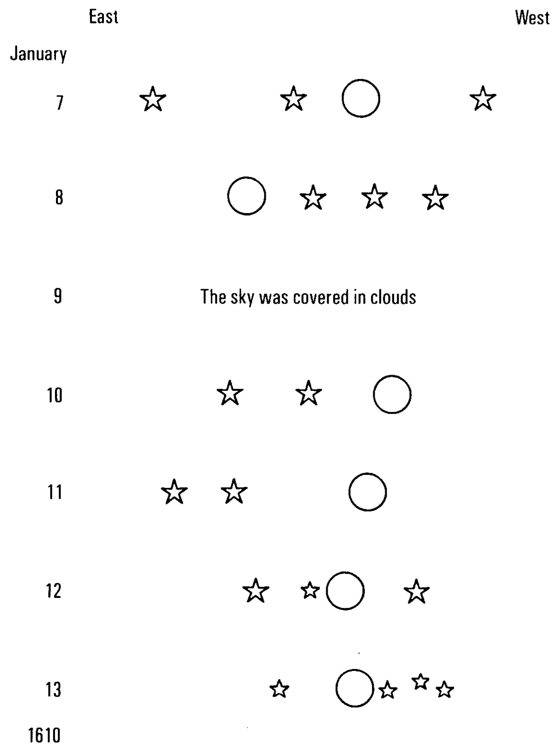
Telescopes In the middle of his teaching life, Galileo heard rumours of an optical instrument that would make distant things look closer. He at once designed a telescope himself and made a small, but weak one. Then he made larger and stronger telescopes, always grinding the lenses from blocks of glass himself.

When he turned his telescopes on the heavens, he saw many surprising things, some of them very disturbing to the accepted view. He saw the Milky Way resolved into a cloud of tiny stars. He saw that the Moon was rough, with mountains and craters. This was a shock, for it was believed that the Moon was a smooth, shining sphere.

He saw spots on the Sun – again damaging to the view that the heavens were perfect.

He saw the planet Venus as a bright crescent, changing to other phases as it moved round the Sun – a series of changes that would be very difficult to account for with the Ptolemaic machinery.

Jupiter When he first looked at Jupiter through his telescope, he noted some small stars near it. Then, the next night, he found that the pattern had changed.



Jupiter seemed to have moved the wrong way relative to those stars. Waiting impatiently through a cloudy night, Galileo then saw the pattern change again. Soon it was clear; the small stars were moons moving round Jupiter. Delighted, Galileo published a full description and claimed Jupiter and its moons as a model to support his strong arguments for the heliocentric system which Copernicus had described. You can see those moons for yourself with strong field glasses or a small telescope.

THE DEVELOPMENT FROM COPERNICUS TO NEWTON

Before Copernicus' book was published in 1543 the 'common-sense', earth-centred model of the universe was the one which men accepted. And for a further fifty years his arguments for a system with the Sun at the centre had very little effect. But then Galileo's powerful arguments, ably supported with the new evidence he found when he turned his newly invented telescope on the skies, made men begin to accept Copernicus' revolutionary world picture.

Galileo also developed and taught, in unfinished form, the new view of force and motion that Newton was to use in his theory and that we use to this day. Kepler extracted precise, reliable laws of planetary motion; but he gave only vague suggestions for the mechanisms of forces to produce such motion.

The world of philosophers, scientists, and other thinkers was soon alive with questions about this heliocentric system about which people then knew so much but understood so little. It was in this climate of active discussion, with scientific societies being formed to exchange ideas and experiments, that Newton grew up and, as a young man, took astronomy to his heart.

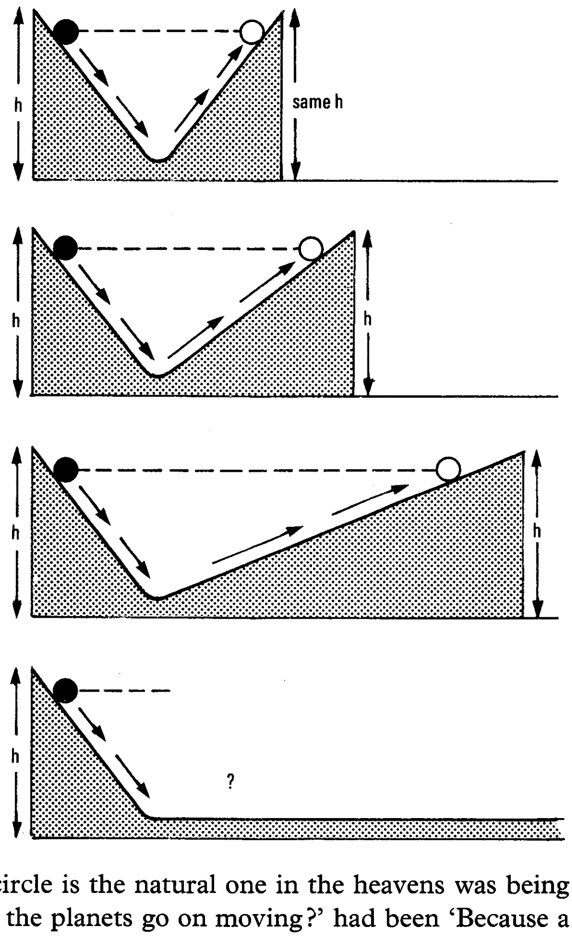
Progress Questions and Questions for this chapter appear on pp. 89 and 90–1.

CHAPTER 5

The Grand Theory: universal gravitation

SIR ISAAC NEWTON (1642–1727)

In the second half of the seventeenth century, scientific discussion and experiments were popular, respectable, and interesting; scientific societies like the Royal Society of London flourished; good telescopes and microscopes had been devised so that the quality of observations and of measurements had improved. There were new mathematical tools for scientists to use; Descartes had invented graph-plotting and Galileo had showed how to put physical knowledge into mathematical form.



Galileo's thought-experiment. He thought that a ball, rolling or sliding down a hill without friction, would run up to the same height on an opposite hill. Suppose that opposite hill was horizontal. Would the continuing motion continue for ever along the tangent or for ever parallel to the Earth's surface?.

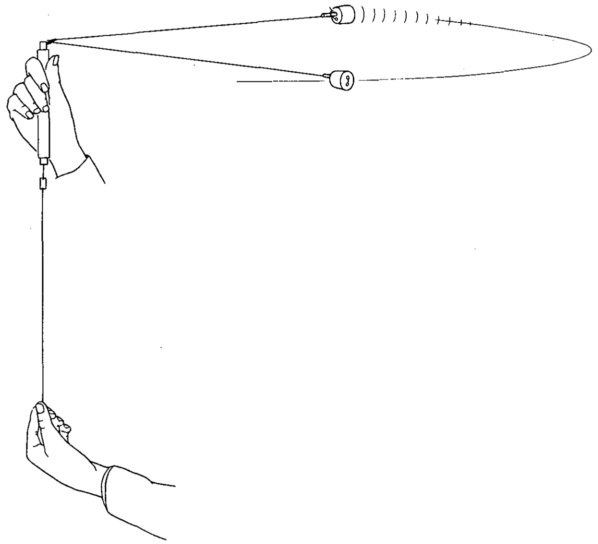
In astronomy, the old view that motion round a circle is the natural one in the heavens was being questioned. The old answer to the question 'Why do the planets go on moving?' had been 'Because a force continues to push them along'. But Galileo had suggested that *no* force was necessary to keep an object moving with constant velocity. Newton took this into his first law.

Newton's First Law Newton's answer to 'What force pushes the planet along?' was 'No force is needed for that, the motion just continues. But an inward force is needed for the curved orbit, pulling the planet away from the simple straight line tangent.'

You may see **Demonstration 29 Illustration of planetary motion with a dry ice puck**. But you may make your own illustration by repeating part of **Experiment 6**.

Experiment 30
Illustration of planetary motion with the centripetal force kit

Take the rubber bung, thread, and glass tube from the centripetal force kit. Hold the free end of the thread in one hand and the tube in the other and whirl the bung round above your head. What happens as you pull the thread a little harder? A little less hard?



Newton's early guess Newton, then a young man of 24, guessed that gravity might provide the inward force to keep the planets in their orbits. He said, 'I began to think of gravity extending to the orb of the Moon. . . . From Kepler's rule . . . I deduced that the forces which keep the planets in their orbs must [be] reciprocally as the squares of their distances* from the centres about which they revolve; and thereby compared the force requisite to keep the Moon in her orb with the force of gravity at the surface of the Earth, and found them to answer [agree] pretty nearly.'

But then he hesitated because he saw a difficulty which we shall describe later about the gravitational pull of the whole Earth. He put the work aside for many years and turned his attention to developing mathematics and experimenting on light and colour.

The appeal to Newton Twenty years later, Kepler's clear simple rules for the orbits of the planets were still without an explanation and this had become an important problem in scientific circles. Several people saw that a body moving in a circular orbit should have an acceleration towards the centre. A few (among them Huygens and Hooke) knew that this acceleration was v^2/R. But ideas of force and motion were still not fully clear. Some people saw that Kepler's Law III fitted with gravitation spreading straight out from the Sun. But Laws I and II remained unexplained. In about 1684, the astronomer Halley, despairing of all the talk in London, journeyed to Cambridge to ask Newton whether an inverse square law of attraction could account for the elliptical orbits of the planets.

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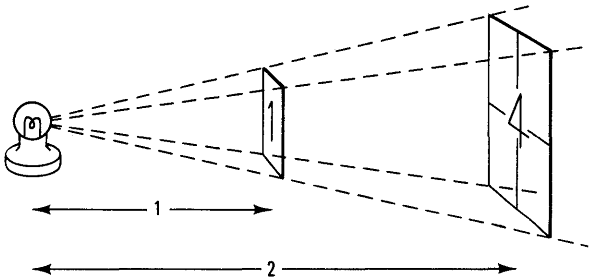
* Newton is describing an inverse-square law for the pull of gravity similar to the inverse square law for the light from a small lamp. That gives illumination which varies as $1/(\text{distance})^2$ in clear air as you can see from the sketch.



Who was Newton? Newton was a professor of mathematics living quietly in Cambridge, interested in problems in chemistry and in religion. He was already known as a brilliant scientist and mathematician, presently to be recognized as one of the greatest scientific thinkers ever known. He not only connected Kepler's Laws with the laws of ordinary machines on Earth but expanded his idea of universal gravitation into one of the grandest theories in all physics.

As we have seen he had started to think about this problem in his early twenties. But he had put his solution away and had gone on to study white light and to break it up with a prism into its component colours and to invent the calculus for his own use. And at the age of 26 he had been appointed to the most distinguished professorship of mathematics in Europe.

So when Halley brought him the problem of elliptical orbits, Newton said he had already solved the problem and that inverse square law gravity would make a planet follow an ellipse. And he knew the interpretation of Kepler's Second and Third Laws also. He could not find his notes, but soon sent fuller notes to London. His friends pressed him to publish his work but he was reluctant to do so. However, persuasion won and he put his work into a great book that set forth his whole gravitational theory: *The Mathematical Principles of Natural Philosophy*, which we still call by its Latin name, the *Principia*.

The *Principia* did far more than just explain Kepler's laws by force of gravity. It set forth a theory that provided a whole family of explanations and predictions. It gave a sense of many things in nature being linked together by one consistent scheme. Newton cleared up our knowledge of earthly mechanics and heavenly motions at the same time and gave us language with which to talk about our knowledge. The book was a work of genius and Newton's fame spread abroad. In England, his fame was recognized by special honours; he was elected to Parliament, he was made Master of the Mint, he was knighted. He was elected President of the Royal Society and he held that position for 24 years to the end of his life.

Motion round an orbit: centripetal acceleration An object moving with constant velocity just continues along a straight line. As you know from Chapter 1, an object moving in a circle has an acceleration even if it is not moving any faster. That is an inward acceleration, v^2/R. Your experiments showed that this means that there is an inward force, mv^2/R. That force must be provided by some real agent: if there is no force, there can be no orbit. Newton applied this idea to the Moon's motion.

Newton and his theory

There is a story that when Newton was sitting in his orchard at home an apple falling from a tree started him thinking about vertical fall and universal gravitation. The truth of the story is uncertain but here we shall choose an apple as our specimen object near the Earth.

Then, as you have read in his own account, he began to think about the same Earth's gravity stretching all the way out to the orbit of the Moon. He asked: could the Earth's gravity that pulls a falling apple also pull the Moon and hold it in orbit? He saw that, to fit the facts, gravity must be *much* weaker out at the Moon.

He tested his idea by calculating the Moon's acceleration towards the Earth. The data are:

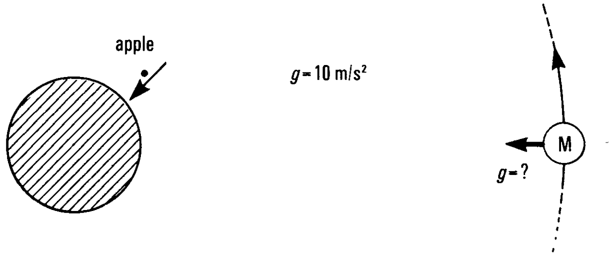
$$\begin{aligned}\text{Radius of Moon's orbit} &= 60 \times \text{radius of the Earth}\\ &= 3.84 \times 10^8\ \text{m}\end{aligned}$$

$$\text{Time taken by the Moon to go round its orbit} = 27.3\ \text{days}^{\star}$$

$$\begin{aligned}\text{The speed of the Moon } (v) \text{ along the orbit} &= \text{circumference/period}\\ &= 2\pi R/T\\ &= 2\pi(3.84 \times 10^8\ \text{m})/(27.3 \times 24 \times 3600\ \text{s})\\ &= 1022\ \text{m/s}\end{aligned}$$

⋆ 27.3 days is the true time taken by the Moon to make one complete orbit, judging its direction by the fixed stars. However, since the Earth is also moving in the same direction once round the Sun in a year, the Moon has to travel further to return to the same position *relative to the Sun*. That takes about $29\frac{1}{2}$ days – a full lunar month.

$$\text{Inward acceleration of Moon} = v^2/R$$
$$= (1022\,\text{m/s})^2/(3.84 \times 10^8\,\text{m})$$
$$= 0.0027\,\text{m/s per second}$$



So the Moon's actual acceleration towards the Earth is about 0.0027 m/s^2 – far smaller than the acceleration of the apple at the Earth's surface (9.8 m/s^2). If gravity does produce the Moon's acceleration, it must be much weaker at the Moon. The simplest scheme for that would be to halve the gravity when the distance doubles. But that does not fit this result. The Moon is 60 Earth radii away. Compared with an apple which is one Earth radius away from the centre of the Earth, that is 60 times further. It would give $\frac{1}{60} \times 9.8$ or 0.17 m/s^2 at the Moon.

Another simple scheme is the inverse square law. If gravity does thin out with an inverse square law, the apple's acceleration should decrease to a value at the Moon of $9.8/60^2$ m/s^2. If you work that out, you will find it very near to the acceleration that Newton calculated from $a = v^2/R$.

Newton now had a satisfying test of his guess of inverse square law gravity. He also had a test that the inward force he thought necessary to hold a body in an orbit was mv^2/R.

Newton's doubt We have already seen that Newton then hesitated and put his idea to one side. The Moon is 60 Earth radii away, much the same distance from all parts of the Earth – the extremes are 59 and 61 and an average of 60 will serve. But the apple is very near and some parts of the Earth are a very short distance from it while other parts are far away. Attractions which follow an inverse square law are *much* smaller at greater distances. How could he add up the effects of all the rocks and oceans of the whole Earth pulling on an apple, so that he could compare the resultant with the pull on the moon? He needed to concentrate the whole Earth, *in imagination*, at a single attracting point. But how deep in the Earth would that point be? That was probably the puzzle which worried Newton. But, later on, when he had invented the calculus to deal with this sort of problem he arrived at the surprising result that a sphere attracts as if all its mass is concentrated at its centre. Then he knew he could safely consider the apple to be one Earth radius away and compare that with the Moon at 60 Earth radii.

Universal gravitation Newton assumed that each piece of matter attracts each other piece of matter with an inverse-square force and his test on the Moon's acceleration supported this.

He also assumed that the attractions are proportional to the masses. If we release a large stone and a small one together, they fall with the same acceleration. They have different masses but the same acceleration. Therefore, applying $F = ma$, we are sure that the Earth must pull those stones with forces proportional to the masses. If one stone is ten times as massive as the other the Earth pulls it with ten times the force, making the acceleration the same for both.

So Newton guessed at his law of gravitation in the form

$$F = G\frac{M_1 M_2}{d^2}$$

where G is a universal constant.

The gravitation constant, G, is quite different from g. G is a constant for all bodies in the universe, but g is the local acceleration due to the Earth's gravity (or it is the field strength of the Earth's gravitational field at a point, measured in newtons/kilogram).

Nevertheless G and g are related to one another. Since the force on a stone m at the Earth's surface is mg we can write

$$F = mg = G\frac{Mm}{R^2}$$

where M is the mass of the Earth and R is its radius. Cancelling m

$$g = G\frac{M}{R^2}$$

The great general theory: Newton's assumptions and deductions

To build his theory, Newton started with simple, clear assumptions chosen with a careful eye on experimental knowledge of the real world. He assumed:

LAW I Any object remains at rest, or continues to move with constant speed in a straight line, if it is left alone; that is, if there is no RESULTANT force acting on it.

LAW II A force acting on a mass makes it accelerate in the direction of the force; and

$$\text{FORCE} = \text{MASS} \times \text{ACCELERATION}$$

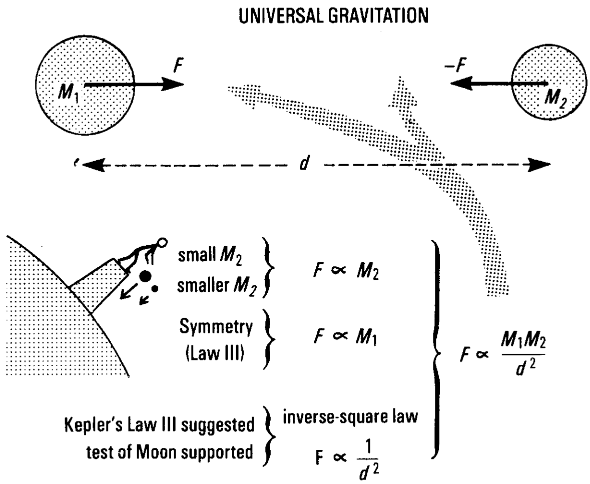
$$\text{or} \quad \text{FORCE} \times \text{TIME} = \text{CHANGE OF MOMENTUM } (mv)$$

LAW III Action equals reaction. Whenever one object pushes or pulls another, the other exerts an equal and opposite push or pull – whether the objects are at rest, or moving with constant speed, or accelerating.

LAW OF UNIVERSAL GRAVITATION

Every object in the universe attracts every other object with a force which is proportional to each of the masses concerned, and inversely proportional to the square of the distance between them.

$$F = G\frac{M_1 M_2}{d^2}$$



From those laws as a starting point, Newton was able to explain some things already known and to predict many others. This was the work he put into the *Principia.*

A list

Here is a concise list of the outcomes of Newton's theory: details of each are given later. He derived, or explained, or predicted the following:

1. THE MOON'S MOTION round the Earth is controlled by the Earth's inverse square law gravity (Newton's original test).
2. KEPLER'S LAW III The ratio (orbit radius)^3/(planet's year)^2 is the same for all planets.
3. KEPLER'S LAW I The planets' orbits must be ellipses with the Sun at one focus.
4. KEPLER'S LAW II A line drawn from the Sun to the planet sweeps out equal areas in equal times: shown to be necessary for *any* 'central' force.

5. A PLANET'S MOONS The rule, R^3/T^2 = constant, applies to all the satellites of a planet, but with a different value of the constant for each owner of satellites (e.g., all Jupiters' moons; all Earth satellites).
6. RELATIVE MASSES of Earth and Sun, Earth and Jupiter, etc., estimated through Kepler's Law III. (This estimate can be made for any two bodies which have satellites.)
7. COMETS, until then lawless and mysterious, follow elliptical orbits according to Kepler's Law I, as members of the solar system. Times of comets' return predicted successfully.
8. THE SHAPE OF THE EARTH must be an oblate spheroid (bulge at the equator); amount of bulge estimated. Surveys soon after confirmed this unexpected prediction.
9. SMALL DIFFERENCES OF g PREDICTED, due to the shape of the Earth and due to the Earth's spin: both make g slightly smaller at the equator than at the poles.
10. OCEAN TIDES, due to differences of Moon's attraction. (Two tides in 24 hours explained.) Similar tides due to the Sun are smaller. Added to the Moon's tides, these make the large 'spring' tides, twice a month; subtracted, they make 'neap' tides. The relation with the phases of the Moon was also explained.
11. MASS OF THE MOON estimated by treating the ocean tide as a satellite of the Moon.
12. PRECESSION OF THE EQUINOXES Shown to be a gyroscopic motion due to the gravitational pulls of Sun and Moon acting on the equatorial bulge of the spinning Earth. The 26 000 year period predicted roughly.
13. IRREGULARITIES OF THE MOON'S MOTION The elliptical orbit of the Moon shows several small changes in the course of time, all of them now explained as due to small differences of the Sun's gravitational pull as the Moon moves nearer and further in the course of the month. Newton predicted several and tested some.
14. PERTURBATION OF PLANETARY ORBITS Each planet is affected slightly by the gravitational pulls of other planets. Newton started the prediction of these small perturbations.
15. DISCOVERY OF NEPTUNE Long after Newton's death, when the planet Uranus had been discovered, it showed small residual perturbations from its expected orbit (in addition to the effects of known planets). From these Adams and Leverrier predicted the location, mass, and orbit of an unknown planet that could produce these tiny perturbations. Then the planet was seen: a triumph of Newtonian theory.

Detailed discussion of the outcomes of Newton's theory

It is good to look at a list summarizing Newton's achievements. But just making a list is not very good science. A scientist will want details. So if, as we hope, you are reading this as a scientist, you should see how some of these predictions were made. In the following pages each prediction is described in more detail. Some of the descriptions will seem difficult; and we expect different readers to choose different items for study – there is no need to try them all.

1. THE MOON'S MOTION This is accounted for by inverse square law gravity, which at the Moon's distance of 60 Earth radii is predicted to be 3600 times weaker than at the Earth's surface. That agrees with the actual acceleration, v^2/R, calculated from the Moon's distance and the time to go round the orbit.

2. KEPLER'S LAW III For any circular orbit, the force that is needed is mv^2/R inward. Some real agent must provide that force. The force provided by the Sun's gravitational attraction is

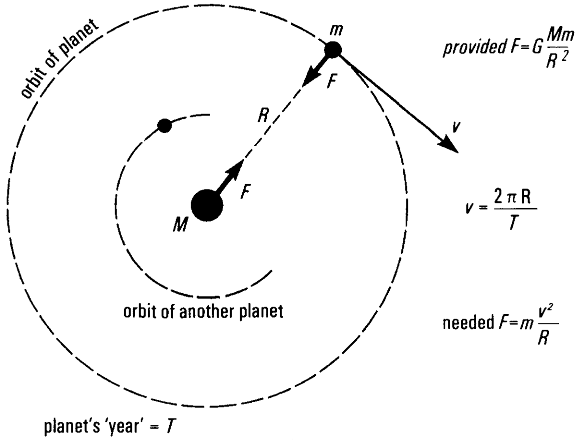
$$G\frac{Mm}{R^2}.$$

For a circular orbit suppose a planet of mass m moves with speed v in a circle of radius R round a Sun. This motion needs an inward resultant force on the planet, mv^2/R, to produce the inward acceleration, v^2/R. If the gravitational attraction between the Sun (of mass M) and the planet just provides this force,

$$\text{then} \quad G\frac{Mm}{R^2} = \frac{mv^2}{R}$$

$$\text{But } v = \frac{\text{circumference}}{\text{time of revolution}} = \frac{2\pi R}{T} \text{ where } T \text{ is the time of one revolution.}$$

$$\therefore \quad G\frac{Mm}{R^2} = m\frac{(2\pi R/T)^2}{R}$$



$$\therefore \quad G\frac{Mm}{R^2} = \frac{4\pi^2 mR^2}{T^2 R}$$

To look for Kepler's Law III, collect all Rs and Ts on one side; move everything else to the other.

$$\therefore \quad \frac{R^3}{T^2} = \frac{GM}{4\pi^2}$$

What does that tell you about R^3/T^2?

It is equal to the gravitational constant G multiplied by the Sun's mass M divided by a constant number $4\pi^2$. What will happen if we calculate R^3/T^2 for another planet also owned by the Sun?

This is Newton's derivation of Kepler's Law III from his simple assumptions. Look back at the table of measurements and values of R^3/T^2 in the account of Kepler's work. With any other law of force R^3/T^2 would not be the same for all planets. An inverse cube law, for example, would make R^4/T^2 the same for all and values of R^3/T^2 would *not* be the same for all. The inverse square law *must* be the right law.

The orbits of the planets are independent of the planets' masses. The mass m of the planet does not appear in the equation. That tells us that several planets of the same mass could all follow the same orbit with the same motion. You might have foreseen that – it is another form of the simple experiment of dropping a large stone and a small stone together.

3. KEPLER'S LAW I It was one of Newton's great achievements to show that with inverse square law gravitation from the Sun, a planet's orbit would be an ellipse with the Sun at one focus. Unfortunately his mathematics is too difficult to be of use here so we must ask you to take Newton's proof on trust.

4. KEPLER'S LAW II Newton showed that Kepler's law of 'equal areas in equal times' will hold for *any* type of planetary motion provided the force on the planet is always directed *straight towards the Sun*. It does not have to be an inverse square law force: any 'central' force will do. But, once again we shall ask you to take Newton's proof on trust.

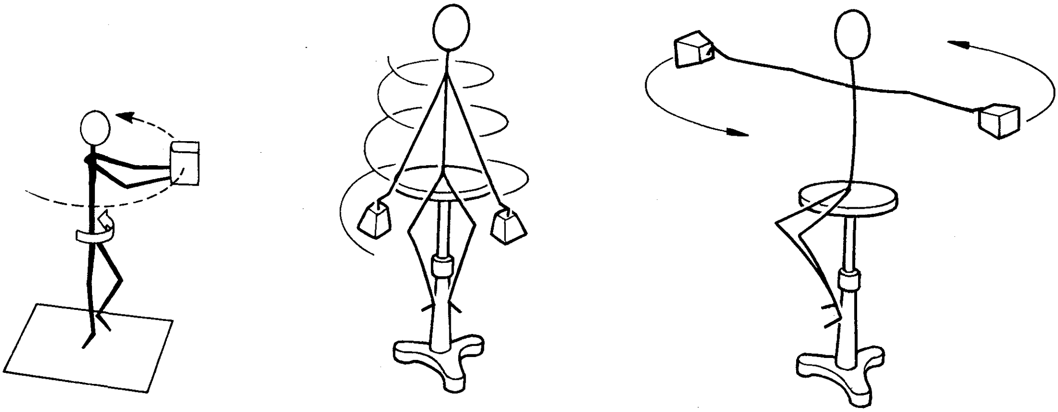
Experiments to illustrate Kepler's Law II You have already tried an experiment which illustrates the law (Experiment 28). The 'planet' in that experiment moves faster when it is a shorter radius – as you would expect from the Law – because your inward pull is practically central.

Experiment 31

Hold a book or some other massive object at arm's length while you spin on your heels, or better, on a revolving stool. Then, while you are spinning, pull the object in to your body.

You may see the same effect when a high diver, a skater, or a ballet dancer changes from slow spin to fast spin by pulling in arms or legs.

5. A PLANET'S MOONS The rule, R^3/T^2 = constant, applies to all satellites but the value of the constant depends on the mass of the planet. Here are the actual measurements for Jupiter's four largest moons.

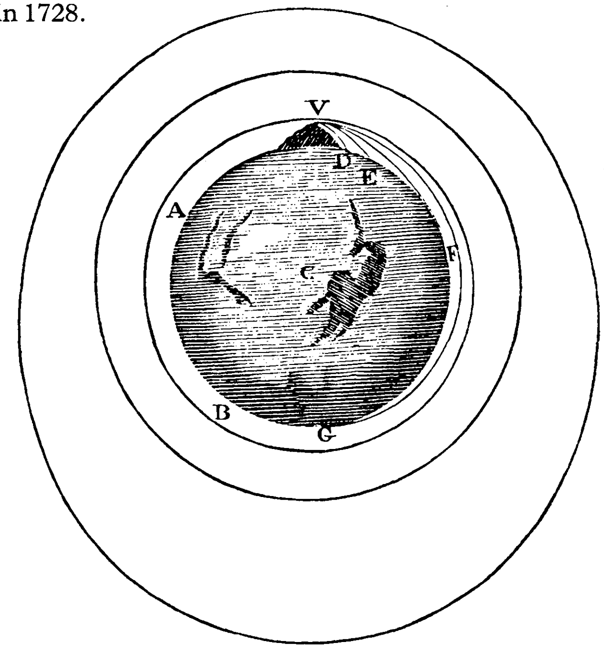


Does Kepler's Law III apply? If it does, Galileo's use of Jupiter and its moons as a model of the solar system was justified.

Name of satellite	Distance from Jupiter in kilometres (R)	Time of revolution in hours (T)	Calculations for test of Law III		
			R^3 (km)^3	T^2 (hours)^2	$\frac{R^3}{T^2}$ (km)^3/(hours)^2
Io	421 910	42.46	7.51×10^{16}	1802.9	..?..
Europa	671 260	85.23	30.25×10^{16}	7264.2	..?..
Ganymede	1 070 800	171.71	122.8×10^{16}	29 484	..?..
Callisto	1 883 700	400.54	668.3×10^{16}	160 430	..?..

Earth satellites Any object that is held in orbit round a massive body by gravitational attraction is called a satellite. The planets are all satellites of the Sun; Jupiter's moons are his satellites; the Moon is an Earth satellite. Even a cricket ball, after it leaves the bat, is an Earth satellite, for a limited time. We now have 'artificial' Earth satellites – high up, practically free from air friction – placed in orbit by Man.

Newton saw the possibility of such artificial satellites, though he never thought it could be achieved. He pictured a gun on a mountain top firing projectiles out horizontally, faster and faster until one could go right round the Earth and hit the gun from behind. The picture shows the sketch he put in his *The System of the World*, published in 1728.



Ann Ronan Picture Library.

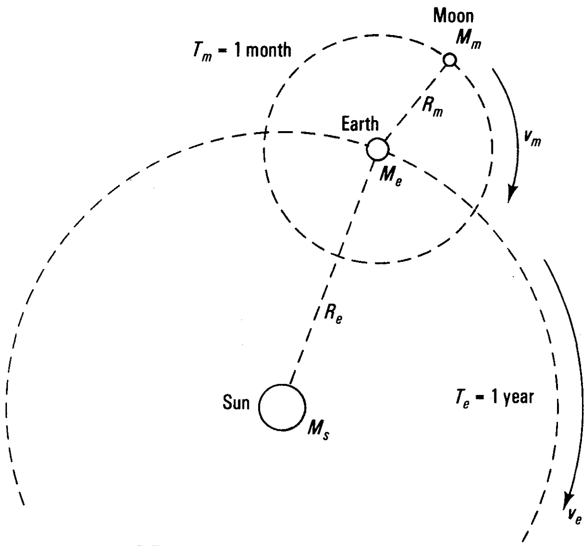
The slow projectile falls to the ground nearby; a faster one goes further before it reaches the ground. Each of them falls towards the ground down from the horizontal tangent that it would follow without gravity. The path is sharply curved for the slow one, not so sharply for the faster one; and if we fired one sufficiently fast it could fall away from the tangent just as much as the surface of the Earth curves away. Then the projectile would continue round the Earth, always at the same height above the ground, until it returned to its starting place.

Orbit time If the satellite is near to the Earth, only a few hundred kilometres up, $v^2/R = g = 9.8 \text{ m/s}^2$, where R is the radius of orbit, a little more than 6 400 000 metres. Remembering that the circumference of the orbit is $2\pi R$, you can calculate the period. You will find your result close to the 90 minute period of real satellites which keep close to the Earth.

If the satellite is further away, you can still calculate its period T for its orbit radius R, or *vice versa*, by going through a calculation just like Newton's test when he compared the Moon and the apple. Or you can use that calculation in a ready-made form by appealing to Kepler's Law III. The satellite you wish to know about is an Earth satellite; so is the Moon. Therefore R^3/T^2 must be the same for both, and you know R and T for the Moon.

Many Earth satellites have elliptical orbits. In that case, as Newton showed, R in Kepler's Law III is the average of the ellipse's largest and smallest 'radii'.

Problem Suppose a communications satellite is to hover over one spot on Earth, to act as a relay station for television. It must have a circular orbit with a suitable orientation and it must have exactly the right period. *What period must it have?* Use Kepler's Law III and the fact that the Moon takes 27.3 days to go once round the Earth, to find how far from the Earth such a satellite must be.



6. RELATIVE MASSES OF THE PLANETS Newton could estimate the relative masses of the Sun and a planet or of any two planets with satellites. He could not check these relative values, but this was a good case of theory providing new numerical knowledge. The calculations for the Sun and the Earth can be carried out as follows. The subscripts $_s$ and $_e$ and $_m$ refer to the Sun, the Earth, and the Moon.

Earth as satellite of the Sun For the Earth's motion around the Sun in its yearly orbit Kepler's Law gives

$$\frac{R_e^3}{T_e^2} = \frac{GM_s}{4\pi^2}$$

$$\therefore\ M_s = \frac{4\pi^2}{G}\left[\frac{R_e^3}{T_e^2}\right]$$

Moon as a satellite of the Earth For the Moon's motion round the Earth in its monthly orbit

$$\frac{R_m^3}{T_m^2} = \frac{GM_e}{4\pi^2}$$

$$\therefore\ M_e = \frac{4\pi^2}{G}\left[\frac{R_m^3}{T_m^2}\right]$$

Therefore, dividing one equation by the other

$$\frac{M_s}{M_e} = \frac{R_e^3/T_e^2}{R_m^3/T_m^2} = \frac{R_e^3}{R_m^3}\cdot\frac{T_m^2}{T_e^2} = \left[\frac{\text{Distance of Sun}}{\text{Distance of Moon}}\right]^3\left[\frac{1\text{ month}}{1\text{ year}}\right]^2$$

With the known values of these times and orbit radii, the ratio of the Sun's mass M_s to the Earth's mass M_e can be calculated. You should put in the numbers, just as Newton did. But it would be sad if you felt compelled to calculate that with great precision. Remember 'Rough estimates for good general knowledge: great precision when there is a special need.'

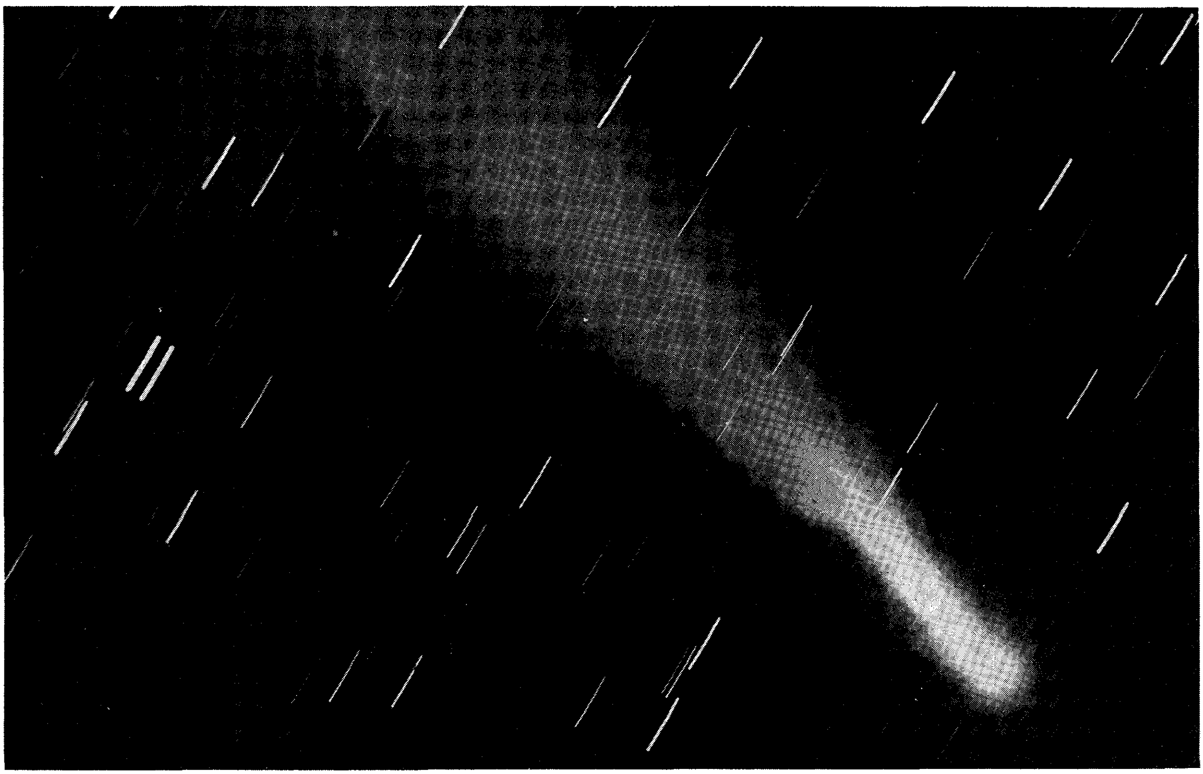
Taking orbit radii in kilometres, we have 150 million for the Sun and 380 000 for the Moon, making a ratio of about 400 to 1. There are 13 moon-months in a year. Now make your own estimate of the ratio of the mass of the Sun to the mass of the Earth. You will then see why the Earth is unlikely to upset the orbits of other planets to any great extent.

Newton could make similar estimates for other mass ratios, so long as the two bodies each owned satellites. And he found that great Jupiter, which is by far the biggest of the planets, has only one thousandth of the mass of the Sun – even that won't disturb the orbits of other planets by very much.

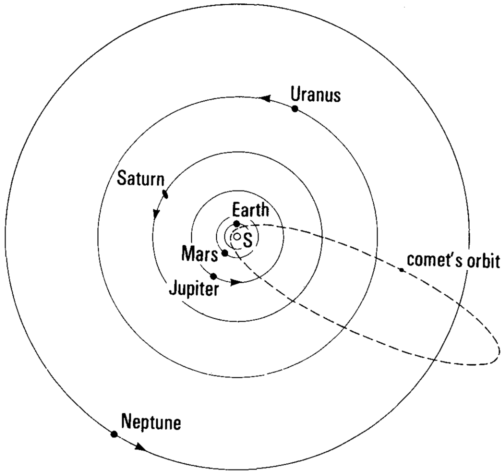
Where a body had no satellite, the estimate could not be made. And yet he managed to estimate the mass of the Moon as a fraction of the mass of the Earth! See below.

7. COMETS Occasionally, a bright object quite different from a star or planet appears in the sky and moves through the star pattern in the course of months, looking like a brush of bright shining material. This is a

Comet Morehouse (1908 III), taken on 30 September 1908. Time exposure. **Royal Greenwich Observatory.**



comet and, when big ones appear, people cannot fail to see them and be impressed. It is not surprising that such comets excited awe and even fear and, up to Newton's day, they were thought to be very mysterious. Newton used observations of several comets to show that each moves in a long ellipse that fits with Kepler's laws. They come visiting from very far out, probably from some reservoir of broken up material outside the outermost planets. So Newton welcomed them as members of the solar system.



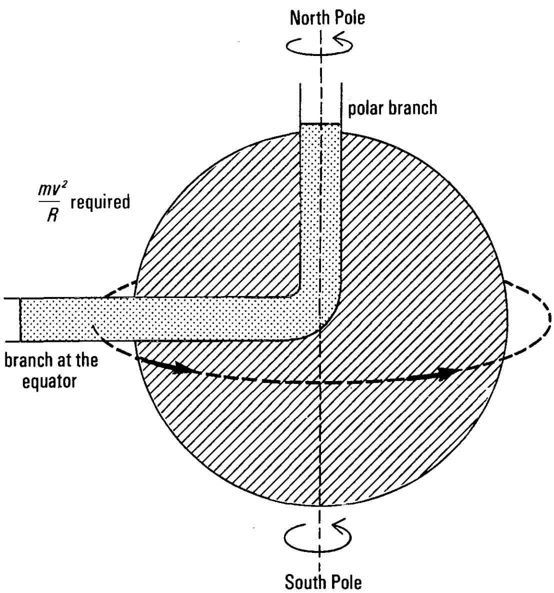
The solar system showing the elliptical path of Halley's Comet around the Sun.

Small ones are observed by telescope every year; but large ones are rare. The comet seen by Halley in 1682 is perhaps the best known. Its orbit time was deduced as 76 years and it returned, within a month of prediction, in 1759. It returned yet again in 1835 and 1910 and we may expect it once more in 1986.

We now believe that comets are made mostly of fine dust, ice, and gas, shining by reflected sunlight, so that we see them when they are near the Sun.

8. THE SHAPE OF THE EARTH: AN OBLATE SPHEROID Until Newton's day the Earth was thought to be a perfect sphere. Newton predicted that it must be flattened at the poles and bulging at the equator – a spheroid.

He had realized that a spinning sphere of a liquid, water perhaps, would maintain a tremendous equatorial bulge. And he thought about the shape the Earth would have if, long ago, it had been 'pasty'. He came to the conclusion that it would take the 'equilibrium' shape required for a spinning liquid body. A simple form of his argument runs like this:



Imagine that a pipe of water runs through a spinning spherical Earth from the North Pole to the centre, turns through a right angle, making an elbow, and runs out to the equator. If this were filled with water, just to the Earth's surface at the Pole, where would the water surface be in the equatorial branch of the pipe?

At the centre of the Earth, where the elbow of the polar pipe is, the water pressure at the bottom of the polar pipe is due to the weight of the water in the polar pipe; and this pressure pushes round the elbow at the centre and out along the other branch. The water in the equatorial branch pushes back, pulled towards the centre by the weight of water in that branch. But these two forces on the water in the equatorial branch must be unequal. They must differ by enough to provide an inward centripetal force to act on the water in that branch, which is being carried round by the Earth as it spins. The weight (inward) of the water in the equatorial branch must be larger than the outward push from the water at the elbow by the amount needed for the mv^2/R force.

Therefore, the water column in this equatorial branch must be taller than the water column in the polar branch. The equatorial branch must extend out beyond the spherical surface to carry the extra height of water.

Newton calculated the extra height and found that $22\frac{1}{2}$ km would be required. He argued that the Earth, at an early pasty stage, would bulge out by about this distance. Surveys not long after Newton's time showed that the Earth does have the kind of shape that Newton predicted and more careful surveys have confirmed this, with some modifications.

Problem Look at Jupiter through a good telescope, or at the photograph on p. 55. Although Jupiter is covered with clouds, astronomers know that it is spinning and can estimate its rate of spin. How?

Experiment 32

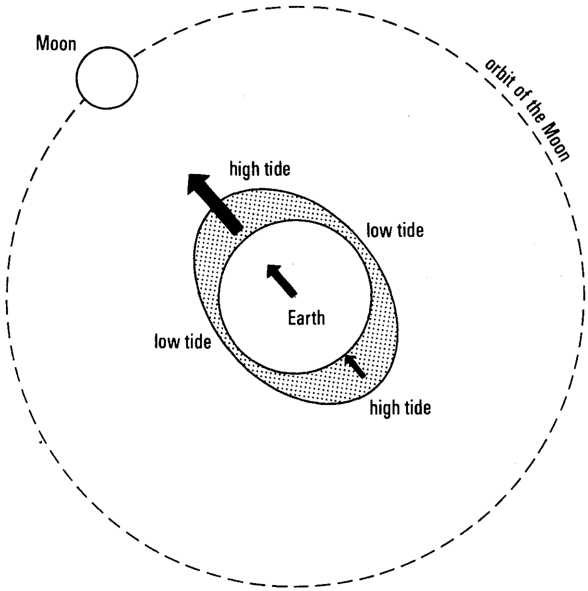
Make your own model of a spinning Earth. Take a strip of very thin paper about 20 cm long and 2 cm wide. Make it into a loop by joining the two ends together with tape or paste. Very carefully, push the point of a pencil through the centre of the join – a small cut in the paper may help. Now push the pencil through this tightly-fitting hole and across the loop. Where the point of the pencil meets the other side of the loop, make a hole just a little wider than the pencil. Push the pencil through that loosely fitting hole and then try rolling the pencil quickly to and fro between the palms of your hands.

9. DIFFERENCES OF g, THE ACCELERATION DUE TO GRAVITY Both the equatorial bulge and the spinning of the Earth have slight effects on the apparent value of g, the acceleration due to gravity at the surface of the Earth. Newton predicted that the acceleration of free fall would be slightly smaller at the equator than at the poles.

Suppose we are measuring free fall in a laboratory on the equator. There we are a little further from the centre of the Earth than at the pole, so gravity would be a little weaker, by about 0.2 per cent. Also at the equator a falling object is orbiting the Earth's axis with the rest of the laboratory, so a little of the Earth's pull on it is used to give it the necessary centripetal acceleration. This also makes gravity seem slightly weaker, about 0.3 per cent less.

These effects were quite unexpected at the time, but later surveys have confirmed the prediction roughly. However, there are additional local differences which depend on the nature of the rocks below the surface and on local mountain masses. Some of these effects are of great interest to geologists and to prospectors for oil and minerals.

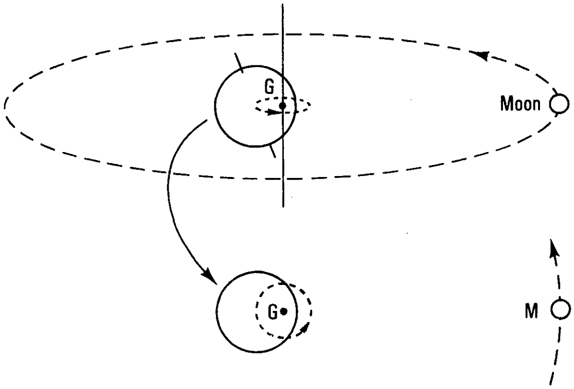
10. TIDES Newton showed that tides can be explained as being due to differences of the gravitational pull on the ocean exerted by the Moon. This was one of the greatest achievements of his theory because it linked well-known events on Earth with the story he was building up concerning gravitation and the heavens.



The extra large pull on the ocean nearest to the Moon raises one high tide. The extra small pull on the ocean furthest from the Moon lets the water flow away into another high tide.

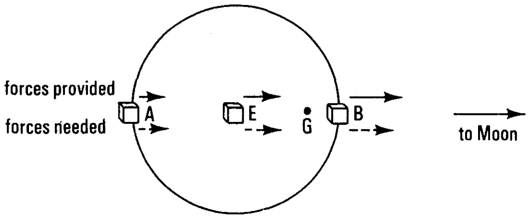
The Moon and the Earth pull each other. The pull of the Earth holds the Moon in its orbit. This gravitational pull provides the force mv^2/R which each piece of the Moon with mass m needs to keep it in orbit.

But the Moon also pulls the Earth with an equal and opposite force. That pull keeps the whole Earth moving in a small monthly orbit round a 'centre of mass' point for the Earth and Moon together. This point is 4800 km from the centre of the Earth towards the Moon. (The radius of the Earth itself is about 6000 km.)



The centre of the Earth E moves round that centre of mass G in a circle of radius 4800 km. And all the other parts of the Earth make similar circles at the same time. Every piece of mass m at a distance r from the centre of mass G needs a force mv^2/r towards G to keep it in orbit.

The gravitational pull of the Moon provides just the right force on a mass m at E, the centre of the Earth. But the Moon's pull gets less as distance from the Moon increases. At places on the Earth (A) furthest from the Moon the pull is a little weaker; at places (B) nearest the Moon the pull is a little stronger. These differences in the pull of the Moon make the water of the oceans pile up in two humps: one hump



furthest from the Moon where the water is not pulled 'inward' quite enough; a second hump nearest the Moon where the water is pulled 'outward' a little too much.*

Those humps are the ocean tides. In mid-ocean, they are only about a metre high. This is far less than the $22\frac{1}{2}$ km bulge of the Earth's equator because this monthly motion around the centre of mass is much slower than the Earth's daily spin.

The Earth's daily spin carries the land masses round to meet these ocean humps in turn. Then those humps of water go sloshing up on every shore in turn, and back again, making two high tides in 24 hours.

If you live near the sea, you know that high tide does not occur at the same hour each day. This is because the Moon travels round the Earth in the same direction as the Earth's daily spin and it takes a little more than 24 hours to be in the same position in the sky again. So you must wait a little more than 24 hours to meet the same hump of water that is opposite the Moon.

You will also know that tides on the seashore are larger than one would expect in some places and smaller in others. This is due to the patterns of the land and sea boundaries. For example, at La Rance in north-west France peak tides of over 13 m occur. This is the site of a tidal power station producing an average 65×10^6 W of electrical power throughout the year.

Spring tides and neap tides As well as tides made by differences of the Moon's pull there are also two humps of ocean made by differences of the Sun's pull on water furthest from the Sun and nearest to the Sun. These are smaller than the humps made by the Moon, because the distance across the Earth's diameter does not make such an important difference in the Sun's gravitational pull. The gravitational field of the Sun is much stronger than that of the Moon because the Sun has a very much bigger mass; but the *differences* in Sun's pull are smaller than the *differences* in the Moon's pull.

The humps of tide made by the Sun will fall on top of the humps made by the Moon when the Sun is in the same direction as the Moon, that is, at new Moon. They will also fall on top of one another at full Moon, when the Sun is just opposite the Moon. At each of these two times there will be extra large tides, Moon-tide plus Sun-tide. These are the large spring tides, every fortnight.

Halfway between spring tides, when the directions of the Sun and Moon are at 90° (half Moon), the smaller humps made by the Sun will fall on the low-tide troughs between the humps made by the Moon. Then there will be smaller tides, neap tides, which are Moon-tide minus Sun-tide.

11. MASS OF THE MOON We promised to show how Newton found a 'satellite' for the Moon, and could therefore estimate the Moon's mass. He realized that the two humps of water that we call the tides could be regarded as a satellite of the Moon and that therefore it must be possible to estimate the mass of the Moon.

From the measurements of spring tides and neap tides in open ocean Newton could separate out the tide made by the Sun from the tide made by the Moon:

$$\begin{aligned} \text{Spring tide} &= \text{effect of Moon} + \text{Sun} \\ \text{Neap tide} &= \text{effect of Moon} - \text{Sun} \end{aligned}$$

Simple algebra, first adding two equations and then subtracting them, gives the two separate effects. Knowing the size of the ocean humps due to differences of the Moon's attraction, Newton could treat them as a satellite of the Moon and roughly estimate the mass of the Moon.

Nowadays, we can give the Moon a satellite, a spaceship flying round it; and by watching that we can measure the Moon's mass very well.

12. PRECESSION OF THE EQUINOXES Precession is the slow, conical motion of the Earth's spin-axis round the axis of the ecliptic. That was how Copernicus described the slow, creeping motion which the Greek, Hipparchus, had discovered. That motion carries the Earth's axis round in about 26 000 years, making a cone of half-angle $23\frac{1}{2}$°.

Newton showed that this motion is a necessary consequence of gravitation and the Earth's spin. A *spherical* Earth whether spinning or not, would keep its axis pointing in a constant direction among the stars as it followed its orbit round the Sun. But an Earth with an equatorial bulge will suffer *extra* gravitational pulls exerted by the Sun (and by the Moon) on the parts of the bulge. Since the Earth's

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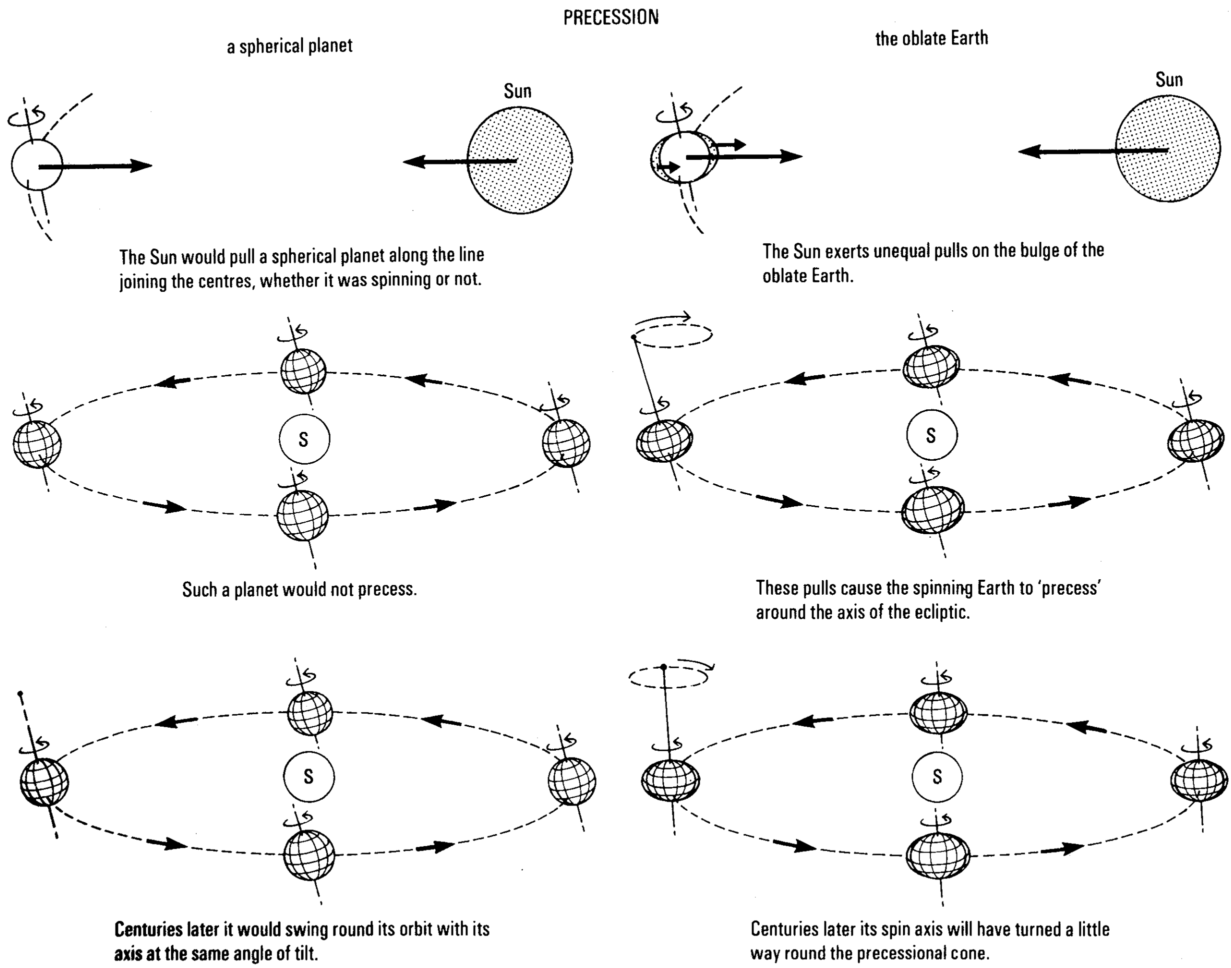
* Actually the high tide humps are delayed by about six hours by inertia, tidal friction, and the effects of rotation.



spin-axis is tilted and not at right angles to the Earth's orbit these extra pulls make a rocking force which tries to change the tilt of the Earth's spin-axis.

But, because the Earth is spinning, the rocking force does not change the tilt of the Earth's spin-axis as you would expect: instead it makes the spin-axis slew round with a conical motion.

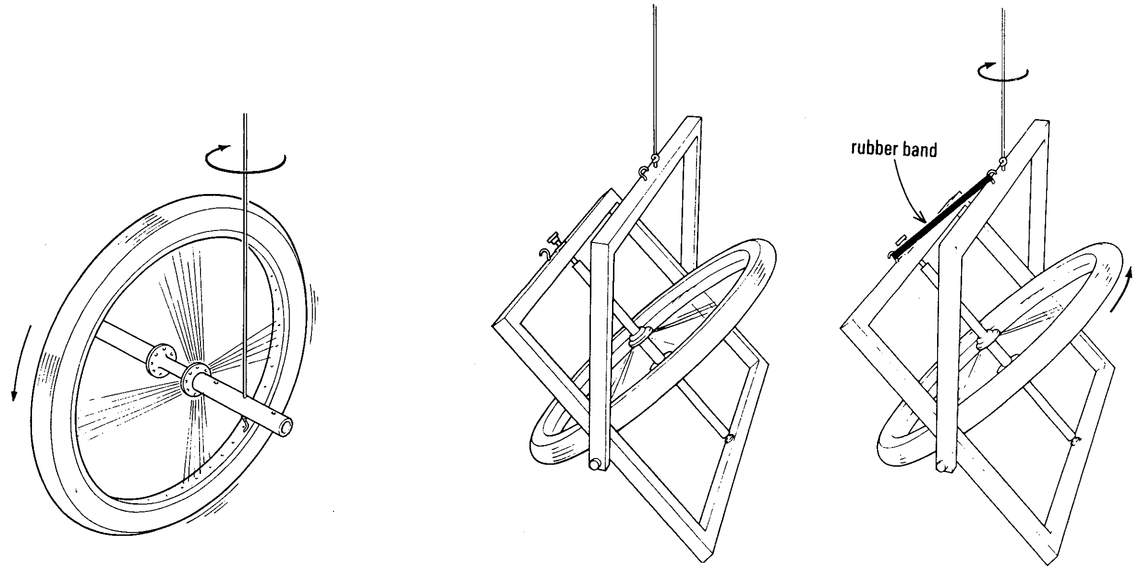
You can see that happen with a toy spinning top which is placed on the floor leaning over a little. It does not fall over but swings round with a conical motion.

The details of Newton's explanation and calculation are too difficult to give here: you need the advanced mechanics that deals with spinning motion and predicts the behaviour of spinning tops and gyroscopes. Nevertheless, the basic physics is still Newton's laws of motion.

Demonstration 33 Precession of a gyroscope
See this with a large wheel hung up as in the sketch or with a small flywheel.

Demonstration 34 Model to illustrate the precession of the Earth
Watch this important demonstration carefully; the wheel, spinning rapidly, represents the spinning Earth; and the massive rim of the wheel represents the Earth's equatorial bulge. Suspended as in the first sketch the wheel spins without changing the direction of its axis. Then the rubber band is installed; its pull represents the Sun's gravitational pull on the Earth's bulge. Watch the effect.

13. IRREGULARITIES OF THE MOON'S MOTION The Moon's elliptical orbit round the Earth changes its elliptical shape slightly as time goes on and it moves slowly round in its own plane; and the Moon shows



small extra monthly and yearly accelerations. All these changes from the simple orbit are produced by the small differences of the Sun's gravitational pull. As the Moon goes round the Earth, it is sometimes a little nearer to the Sun and it feels a little extra pull from the Sun. And a fortnight later it is a little further from the Sun, and feels a slightly smaller pull. Those differences cause the changes mentioned. Newton predicted several of them and was able to test some of his predictions.

Understanding of such small changes of the Moon's orbit is important for two reasons:

(i) They are part of our testing of Newton's theory of universal gravitation; we want to test the theory as completely as we can and let no tiny discrepancy slip through unexplained.

(ii) In Newton's day, and after, navigators badly needed a clock that would keep reliable time during a long sea voyage. Such a clock would enable them to compare the local noon-time with the noon-time at their original port and so to find their longitude. The need was so great that, in 1714, Parliament offered a large prize for a reliable solution. Two schemes competed for this prize:

(a) timekeeping by precise observations of the Moon's position among the stars;

(b) a seaworthy clock which could carry Greenwich time on a long voyage.

Both schemes proved workable – thanks to the extensions of Newton's work on the Moon's motion and Harrison's invention of a chronometer with a good balance-wheel and escapement (1759). Eventually, Harrison was awarded the first prize for this chronometer.

14. PERTURBATIONS OF PLANETARY ORBITS Universal gravitation meant that, in addition to the Sun's holding pull, each planet must be pulled by neighbouring planets with tiny disturbing forces. The larger planets must pull neighbouring planets a little out of their simple Kepler orbits. Newton could calculate that the Sun is 300 000 times more massive than the Earth and 1000 times as massive as Jupiter. So, for comparable distances, the Sun's great gravitational pull far outweighs the deflecting forces due to the other planets. Yet those forces do have small measurable effects which we call perturbations.

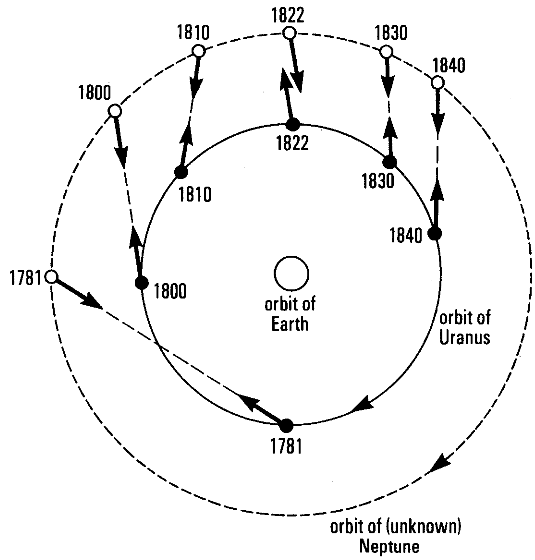
Newton started the calculation of perturbations, particularly the effect of Jupiter's attraction on the orbit of Saturn. Later mathematicians continued the work and we can now make full allowance for all inter-planetary attractions – and we find close agreement with observation.

These tiny modifications to the orbits of the planets added their testimony for the general theory, but they also led to one of the finest triumphs of Newton's work – the discovery of an unknown planet.

15. THE DISCOVERY OF NEPTUNE A century after Newton's death, planetary perturbations led to the discovery of an entirely new planet – by the application of pure Newtonian theory.

One additional planet had been found by direct observation in 1781. The astronomer Herschel noticed a 'star' which looked larger than its neighbours, and then he found that it moved. It proved to be a planet, which was named Uranus. Measurements showed that it was twice as far from the Sun as Saturn; its orbit fitted with Kepler's Law III.

But, as time went on into the early 1800s, precise observations of the new planet showed that it was not quite following a Kepler ellipse. The perturbing forces due to Jupiter and Saturn were carefully calculated and allowed for. There were still small deviations left unexplained and, although these were small, they were too big to blame on 'errors of observation'.



Uranus and Neptune. Uranus was discovered in 1781. From 1781 to 1822 it was travelling faster than predicted by Newton's theory. From 1822 it was travelling more slowly. This led to the discovery of Neptune in 1846: Neptune's pull had first speeded Uranus up a little and then had slowed it down.

Here was a new challenge: why did Uranus seem to disobey Newton's theory, even by a little? Some wondered whether gravitation did follow the inverse square law exactly; others wondered about another unknown planet pulling on Uranus. That was ingenious, but it posed a very difficult problem. It is hard enough to work out the effect of one known planet on another. Here was the reverse problem, with one of the participants quite unknown; a blind man's buff reaching out a thousand million kilometres into space to locate an unknown planet, of unknown mass, at an unknown distance, with only rough hints of its direction.

Two young astronomers, Adams in England and Leverrier in France, took up the suggestion of an unknown planet as the cause of the perturbations and attacked the problem with great courage and skill. Working independently of one another, the two men solved the problem and were in a position to ask observatories to look for the new planet in a specified position in the heavens. The actual discovery was made by astronomers working in the Berlin observatory and was soon confirmed by observatories all over the world.

The new planet, discovered by the application of pure theory, was named Neptune. In the present century a further planet, Pluto, has been located.

Exploring a field of force Newton and Kepler were using the planets to explore the Sun's gravitational field of force, to show that it was an inverse square law force all the way from the innermost planet Mercury to the outermost known planet – and beyond, using the testimony of the comets. Two centuries later, Rutherford and his colleagues used alpha particles from radioactive substances to explore the field of force inside atoms. And, in a way which corresponds to Kepler's Law III, the alpha particles told them that atoms are almost entirely hollow with a tiny central nucleus exerting an inverse square law electrical force. We shall discuss this in Chapter 10.

Newton's insight

'Hypotheses non fingo' – 'I do not feign hypotheses' – Newton wrote at one time. He meant that he would not invent unnecessary details in his description of nature, or pretend to explanations that could never be tested. Yet, in later writings, he offered many a keen guess: at the nature of light, at the properties of atoms, etc.

He was aided in reaching his great successes by his extraordinary gift of concentrating on a problem in reasoning. This concentration and his power of bringing every piece of information and every mathematical tool (whether old or newly invented) to bear on it, enabled him to make surprising guesses about nature – he guessed right more often than mere chance would account for. This was not good luck, but intense thinking. He guessed correctly at universal gravitation. He made a guess, on scanty evidence, at the mass of the Earth itself – a guess which could not be tested then but had to wait for Cavendish's experiment.

Again he devised a theory of light: tiny particles travelling fast in straight lines to make sharp shadows; but he added a wave-like behaviour to guide them into interference patterns. For many years, scientists laughed at this strange mixed scheme. Now, 200 years later, we have clear evidence that light does behave both as waves and as particles. Once again, Newton had made a wise guess.

The mass of the Earth Newton argued that the solid ground of the Earth must be denser than water, or it would float up into many more mountains than we have now. Furthermore, regions near the centre of the Earth must be more dense than the outer rocks, on account of the intense pressure there. He knew something of the effect of pressure, because he knew the size and mass, and thence the average density of Jupiter whose huge gravity would make great internal pressures. He guessed that the average density of the whole Earth was between five and six times the density of water (we now know it is $5\frac{1}{2}$ times!).

A century after Newton, the actual mass of the Earth could be estimated from the results of Cavendish's experiment; and we now take the mass of the Earth to be about 6×10^{21} tonnes.

By using Newton's method of comparison we then find that the Sun's mass must be 2×10^{27} tonnes. The Sun continually radiates light both visible and invisible; we know nowadays that the energy of that radiation itself has mass, which we can calculate by using $E = mc^2$. The Sun loses mass at a rate of about 4 million tonnes per second; yet it is so small a fraction of the Sun's total mass that we expect it to make little difference for a very long time.

Is the theory true?

The factual information that goes into the building of a theory comes from experiment and is presumably a true summary of actual behaviour. But scientists feel uncomfortable when they are asked if the rest of the structure is *true*; the assumptions, the pictures, the models, and the imaginative ideas which all form part of the machinery that we call a theory. Scientists today would rather say that they value theory because it is fruitful and useful and because it gives a sense of connected knowledge.

As our knowledge grows, we often have to change our theory, modifying it, sometimes remaking it altogether. But at any given time our theory serves as a map of our knowledge, to guide our work and to help us in discussing it with others.

When someone first learns science, he expects science to *explain* many things, to give scientific reasons for things that happen. And most people continue all their lives to expect scientists to give the 'true' explanation of things. Yet, in fact, science cannot give the final reason, the true story underlying everything. Science can only show that some new, unfamiliar event or behaviour is another form of something we already know. We link the unknown with the familiar known things. For example, we say a lightning flash is a large electric spark; or we say the force holding the Moon in orbit is like the force of gravity on an 'orbiting' cricket ball. And sometimes science can collect together many different things and give one story to cover them all. Newton's great theory did both those things.

Newton himself knew that an inverse square law field of force would account for Kepler's laws, and many things besides; but he said clearly that he did not know the *cause* of gravitation. He suggested that it must be some kind of influence that spreads out from every piece of matter, and penetrates matter freely, but that was only a description of observed properties. He insisted that he did not know its ultimate cause. Modern scientists agree. Science is not able to push its explanations so deep.

Newton's theory and its explanations Newton used mathematics to deduce many things from a few laws; but his treatment was quite different from the deductive methods of the Greeks and their followers.

Newton did not just invent imaginary machinery. He devised his theory with the help of guesses from experiments and observations; then he drew from that theory many predictions; *then* he tested as many of those predictions as he could by experiment and measurement. (Some of them, of course, were things already known, so they passed the test at once.)

Thus Newton's theory was a framework of thought and knowledge, tied to reality by experiment and clear definitions, able to make predictions which in turn were tested by experiment.

A theory, as Newton used it, 'explained' a number of mysteries by referring them to a few familiar pieces of physics that we can work with in a laboratory on Earth.

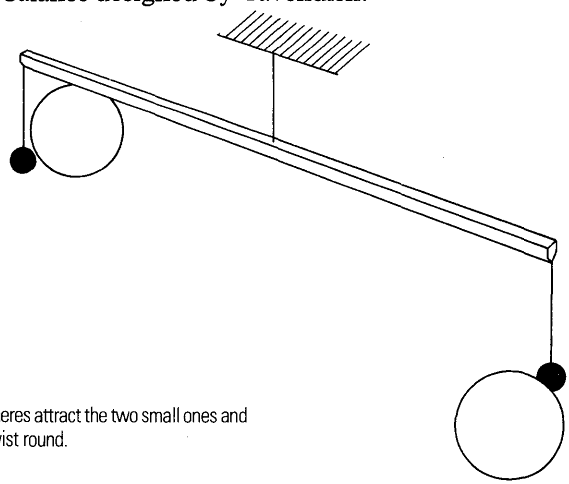
Scientists value a theory when it is fruitful, that is, when it makes successful predictions. We expect a good theory to make many predictions from few assumptions.

If we needed to add one or two extra assumptions for each additional prediction we extract from a theory, we should be disappointed: we might just as well have everything in Nature run by demons, a whirling demon for each planet, a boxing demon with pounding fists for gas pressure, a down-only demon to pull each falling stone downward, and a floating demon to push a rising balloon upward. By endowing each demon with suitable behaviour, we could 'explain' everything that we observe in Nature. And that is just how things were explained (with pleasanter or more mysterious words instead of demons) by pre-scientific thinkers centuries ago.

The essential advantage of scientific theories and the explanations they give is that they are *economical.* They help us to organize our knowledge, to simplify it, to put it to use, and to suggest new ideas and new applications.

A sequel to Newton: measuring the gravitation constant

Newton knew that the gravitational attractions between man-sized objects in a laboratory on Earth must be extremely small – perhaps too small for man ever to measure. But a century later those tiny forces were being measured – a mountain pulling a pendulum ever so little out of the vertical, a large lead ball pulling a small one on a very delicate balance designed by Cavendish.



Cavendish's balance. The two large lead spheres attract the two small ones and pull the beam, so causing the balance to twist round.

The table shows the results of many, varied experiments to measure G, the gravitation constant, approaching a constant value as accuracy improved. Notice the variety of materials and shapes and distances and masses: then you can see how the converging of the results assures us of Newton's Law of universal gravitation on Earth – while planets and comets carry the assurance out through the whole solar system.

Newton's Law of Gravitation today

The laws of gravity and of motion which together made sense of the motions of the planets and their moons are also the laws that we need to plan the journeys of artificial satellites and space probes.

Calculating the angle and speed at which a space probe should leave the Earth, and fixing the rockets that adjust its path, so that it will arrive close by a planet over 150 million kilometres away, are very complicated tasks. Both the Earth and the planet at which the space probe is aimed are moving all the time, and their gravity adds to the Sun's gravity to give a gravity force which changes in size and direction as the space probe and the planets all move. In fact, space travel would be impossible if it were not for powerful computers: only with their help can we do the sums in time. But the basic laws with which the computer programmes work are those of Newton.

The laws of gravity are still one of the main areas of research for physicists interested in the structure of the universe. One of the recent foci of interest has been the very strong gravity effects that can arise if matter shrinks. A really big object could be compressed by its own gravity: but once it squeezed itself in, the gravity effect would be bigger. For example, the force on a rock on the surface of a huge object would increase as the radius of the object became smaller. This could lead to more squeeze, resulting in smaller size, larger forces, more squeeze, and so on. So objects that are big enough could suffer a catastrophic collapse, being squeezed so much that all atomic structure would break down. Instead of nuclei and electrons, we would then have solid nuclear matter. Such bodies are thought to exist. They are called neutron stars (because all the protons and electrons have combined to give neutrons).

However, in such extreme conditions Newton's laws start to break down. Einstein showed how to rewrite the laws of gravity with his General Theory of Relativity. This theory makes many quite new predictions that were not in Newton's scheme at all. For example, according to this theory, light rays are bent when they pass near a massive body. Also, bodies which have suffered catastrophic gravity collapse might, if they are massive enough, prevent all radiation from leaving them (so they are invisible), and could have other, more complex effects on the basic laws of space and time. These are the black holes – so called because they absorb completely any matter or radiation that comes near them.

Measurement of *G*

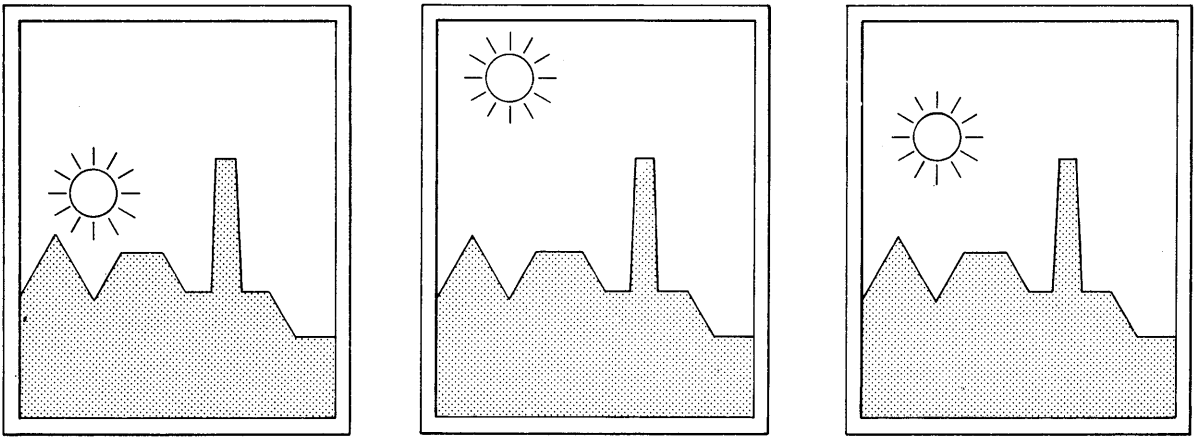
Date	**Experimenter**	**Attracting mass**	**Attracted mass**	**Approximate distance apart in m**	**Result *G* $\times 10^{-11}$ N m^2/kg^2**
1740	Bouguer	Mountain	Pendulum	10^4	12
1774	Maskelyne	Mountain	Pendulum	10^4	7 to 8
1854	Airy	Outer shell of the Earth	Pendulum	6×10^6	5.7
1887	Preston	Mountain	Pendulum	10^4	6.6
1798	Cavendish	Lead ball (167 kg)	Lead ball (0.8 kg)	0.2	6.75
1881	von Jolly	Lead ball (45 000 kg)	Metal ball (5 kg)	0.5	6.46
1895	Boys	Lead ball (7 kg)	Gold ball (0.0012 kg)	0.08	6.66
1898	Richarz & Krigar-Menzel	Lead cube (10^5 kg)	Copper ball (1 kg)	1.1	6.68
1942	Heyl & Chrzanowski	Steel cylinder (66 kg)	Platinum ball (0.1 kg)	0.1	6.67

Progress Questions for Chapter 3

The Sun

1. What do you see the Sun do each day? Where does it rise? And where does it set? When is it at its highest in the sky? In which direction is it when it is at its highest? Does it rise (or set) in the same place in winter and summer? Does it climb as high in the winter as it does in the summer? Is its path the same all through the year?

2. These sketches were made from the same window in spring, summer, and winter. Which is which? Explain how you can tell.



A 11.00 a.m. B 11.00 a.m. C 11.00 a.m.

3. Wait until a sunny day. Make a drawing of the nearby trees and chimney pots to your south. Mark the position of the Sun on your drawing each hour. How does it move across the sky, and up and down in the sky?

The Moon

4. How does the Moon move as you watch it at night? Where does it rise? Where does it set? When have you seen the Moon in daytime? How does its shape change?

5. Suppose you look at the Moon every night at the same time for two months. What changes in its position and in its shape would you see?

6. Watch the Moon for a few hours during one night. Make a drawing of the nearby trees and chimney pots to your south. Mark the position of the Moon on your drawing at each hour. Mark the time on each position. Add one or two bright stars as well.

Stars

7. You may wish to use books in the library to help you answer this. Draw sketches of the following groups of stars: (*i*) the Plough, (*ii*) Cassiopeia, (*iii*) Cygnus (the Swan). Then draw a star chart to show how these groups of stars fit round the Pole star.

8. Does a particular star group appear in the same place in the sky at the same time every night of the year?

Planets

9. Sometimes the planet Jupiter can be seen high in the sky at night, very white and bright. Why can the planet Venus, also a bright one, not be seen high in the sky? Explain.

10. You may wish to use books in the library to help you answer this.

a. Write out a list of the names of all the planets, in order going out from the Sun.

b. Find out and write down *three* facts about each planet.

c. Copy and complete: The planet nearest the Sun is called . . ? . . The two planets furthest from the Sun are called . . ? . . and . . ? . . The planet . . ? . . has four large moons and the planet . . ? . . has one moon. The planet . . ? . . has 'rings' which astronomers think are made of . . ? . .

Eclipses

11. Eclipses of the Sun happen quite often, but each eclipse can only be observed by people on a small patch of the Earth's surface. What causes the Sun to be eclipsed?

The shape of the Earth

12a. You have a small lamp a metre or so away from a wall. You hold a flat disk (a round table mat, for example) between the lamp and the wall, so that you get a shadow. Draw the shapes of the shadows you get as you turn the disk round. Now do the same for a sphere (a ball, or an orange).

b. Look at the photograph of an eclipse of the Moon. The Earth cuts off the Sun's light so that the dark patch is the Earth's shadow. (*i*) Look at the edge of the shadow; is it curved or flat? (*ii*) The Earth's shadow is *always* this shape: what shape does that suggest for the Earth itself – flat disk or sphere?

13a. You watch a friend walk away along a long straight road. He gets smaller and smaller. Make a series of drawings to show him as he goes away.

b. If you watch a ship carefully as it sails away, you will see that it disappears bit by bit – hull first. Make three sketches to show this happening. What does this suggest about the shape of the Earth?

14. As far as you can tell from looking around you at the landscape the Earth *is* flat. Long ago men believed that it really was flat.

a. Aristotle, who lived about 340 BC, gave two pieces of evidence why men should believe that the Earth was a round ball. What were they?

b. We can give more evidence for this today – from space flights for example. What extra, modern evidence can you think of which would support Aristotle's idea?

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Questions for Chapter 3

Sun and Moon

15. On a clear, cloudless day – or night – the sky above us looks like a hemispherical bowl, upside down above us with ourselves at the centre: a bright blue bowl by day, a black bowl by night. Inside this bowl, but above us, we see objects that clearly belong to the Earth – clouds and man-made objects such as aircraft. The Sun, Moon, and stars are obviously farther away. Perhaps they are part of the bowl. And there are the interesting objects we call planets.

a. Certainly to us on Earth, the Sun is the most important and necessary of all these objects. Why?

b. An important thing to us about the Moon is that it produces tides. What evidence is there that the Moon, rather than the Sun or stars, is chiefly responsible for the rise and fall of the sea?

c. What practical usefulness to us do the stars have?

16a. Which *looks* the larger, the Sun or the Moon?

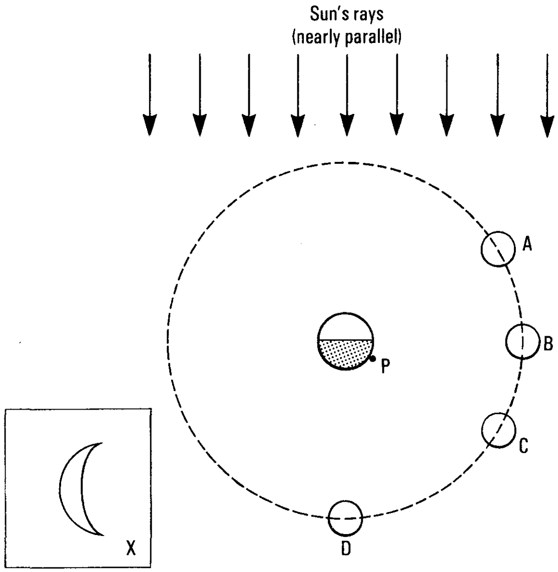
b. What evidence is there, which men could have known about 3000 years ago, that the Sun is farther away than the Moon?

17a. How far away from your eye must a penny (2 cm across) be so that it looks the same size as the Moon? (The diameter of the Moon makes an angle of $\frac{1}{2}°$ at the eye and so does the diameter of the Sun.) Give your answer to the nearest few centimetres.

b. You are told that the Moon is about 400 000 km and the Sun about 150 million km away. Calculate their diameters.

18. You know what the Moon looks like when seen at 'full' on a clear night. What would the Earth look like to an astronaut standing on the Moon at this time and looking towards the Earth? Write a few lines comparing what he would see of the Earth with what you see of the Moon.

19a. An observer at P, in the 'night-time' portion of the Earth, looks at the Moon. Draw diagrams to show the shape of the Moon, as he sees it, when it is (*i*) at A; (*ii*) at B; (*iii*) at C; (*iv*) at D. (Draw diagrams like the one at X. The others will have different shapes and will not be the same as X. You may assume that, even for position D, Sun, Moon, and Earth are not exactly in line.)

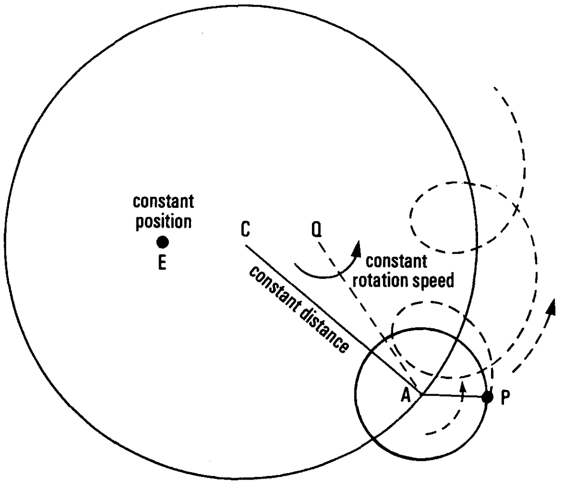


b. Whereabouts, on the sketch, would the Moon be if it is not visible from anywhere on Earth?
20a. Why is the Pole star important to us?
b. Sketch the star group called the Plough and show how it helps in finding the Pole star.
c. The Sun, Moon, and most of the stars rise in the east, move westwards across the sky, and set in the west. But some stars (not planets) can be seen moving eastwards across the sky. How do you explain this? Whereabouts are they, with respect to the Pole star?
21. Explain why the star pattern revolves approximately 15° every hour in the same night; and 30° from midnight to midnight a month apart.
22. The Sun appears to move 'eastwards' among the constellations by about 1° a day.
a. What do you think is meant by move 'eastwards' among the constellations?
b. Why is the 'eastward' movement about 1° a day?

Planets
23. If you had been an observant person living three thousand years ago you might have picked out four stars as behaving differently from the rest. These are some of the ones we now call planets. Which planets were they likely to be? Write half a page or so explaining in what way they are different, and describe how they differ. You might use headings: Apparent movement among the other stars; position in the sky where seen; brightness.
24. Supposing you look through a small telescope such as an amateur astronomer might use. What is there especially striking you would notice,
a. if you looked at Venus at different times during the year?
b. if you looked at Jupiter (Galileo was the first to see this)?
c. if you looked at Saturn?

Theories or models
25. There are several pieces of evidence for believing the Earth is round.
a. Suppose someone asks you what evidence there is. What would you tell him?
b. Give some reasons that might have been known to, or discovered by, the Greeks two thousand years ago. Illustrate your answer by sketches where this is helpful.
c. Mention, if you can, some further reasons, belonging to this century.
26. Suppose you could meet and talk with a Greek student of your own age living in the year 500 BC. What reasons might he or she give for supposing that the Earth is at rest, immovable in space? And what might you reply?

27. Look at the figure on page 34.
a. Why is the Pole star specially marked?
b. What do you understand by 'horizon plane' and by 'celestial equator'?
c. What is meant by 'zenith'? Where would it be on the figure?
d. What is the angle between the zenith direction and the horizon plane?
e. Would the horizon plane be the same as in this figure for a person living in Japan? Explain your answer.
f. Copy the sketch and add to your copy the plane of the ecliptic. What evidence do you have for placing the plane of the ecliptic at an angle to the plane including the celestial equator?
28. The arrangement of one crystal sphere for each of the heavenly bodies did not account for their observed motions very well. So Eudoxus had four spheres for each planet. What reasons can you give for including the third and fourth spheres?



29. The diagram shows Ptolemy's scheme for one planet P which imitated very closely the motion of the planet round the Earth E. The features of his system were 'fixed Earth, constant radii, rotation with constant speed'.
a. Use this diagram to describe how Ptolemy explained the observed motions of the planet round the Earth.
b. Explain the three features mentioned above.
c. On what occasions will the motion of the planet be 'retrograde' (moving westwards among the stars)?

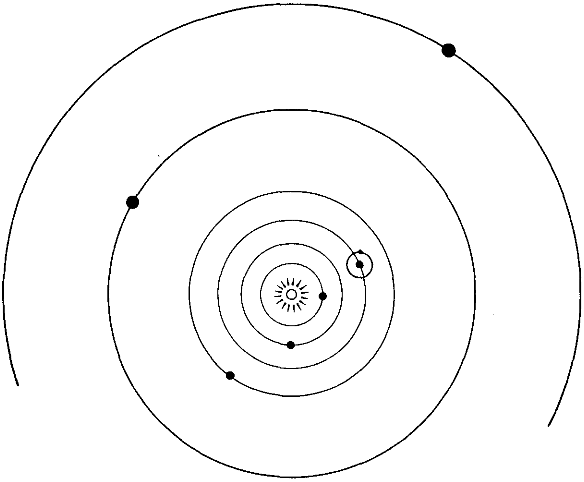
Progress Questions for Chapter 4

Copernicus' solar system
30. Copy and complete:
The Earth travels round the . . ? . . once every . . ? . .
This motion gives us [day and night/the seasons].
The Earth spins on its axis once every . . ? . .
This motion gives us [day and night/the seasons].
The Sun and stars look as though they move across the sky once every . . ? . .
The Moon goes round the . . ? . once every . . ? . .
31. Galileo built one of the first telescopes. What did he see with it that supported his teaching of Copernicus' solar system?

Questions for Chapter 4

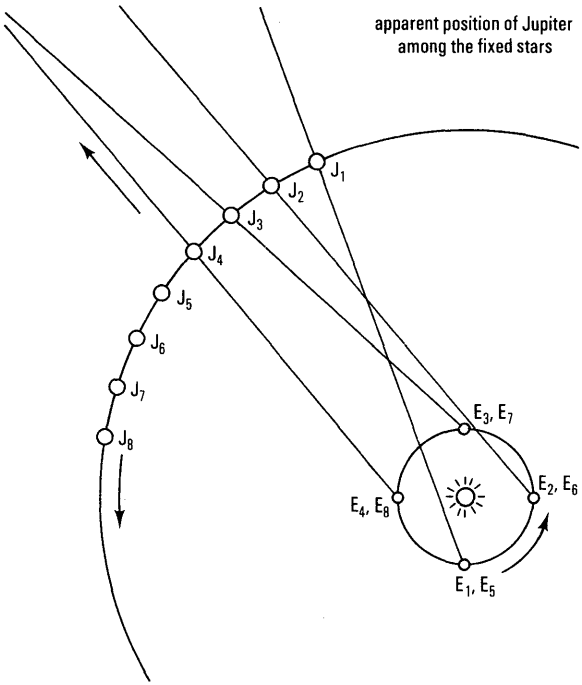
Copernicus' scheme

32a. Copy the diagram and mark S (for Sun), M (Mercury), V (Venus), E (Earth), m (Moon), Mars, Jupiter, and Saturn. (Exact radii do not matter, but make your copy look something like the diagram.)
b. Where would you put Uranus on this scheme?
c. What did Copernicus know about the speeds of the planets – that is, on his model, are they moving faster farther from the Sun, or all at the same speed, or slower the greater the distance?



The Copernican system.

33a. What are the main differences between the Copernican scheme of the previous sketch and the systems of Pythagoras, Eudoxus, and Ptolemy?
b. How did Copernicus explain the apparent 24-hourly rotation of the stars?
34. Copy the diagram about the same size but on a large sheet of paper so that you have plenty of space to continue the sight lines such as E_2J_2 further out to a 'sphere of fixed stars' far out at the edge. Use the same



sizes as here for the orbits of Earth and Jupiter. Continue the sight lines and mark the apparent positions of Jupiter among the fixed stars. Use your diagram to explain the fact that Jupiter sometimes appears to move westwards (retrograde) against the background of the fixed stars. (Note: This diagram has been drawn roughly to scale both for distances and for speeds of the planets.)

35. How would Copernicus explain that the westward (retrograde) motions are seen only when Sun and planet are 'in opposition', that is, on opposite sides of the Earth?

36. How, on Copernican theory, do you explain the following?

a. Mars appears brighter at some times of the year than others.

b. Venus is invisible when it is closest to us (two reasons).

37. Explain, with the help of a diagram, why Venus shows 'phases' like the Moon (see the photographs on page 93). Why does Venus at full look so much smaller than when it is seen as a 'new moon'?

38a. What sort of observations concerning heavenly bodies are explained equally well by the systems of Ptolemy and Copernicus? (Give some examples.)

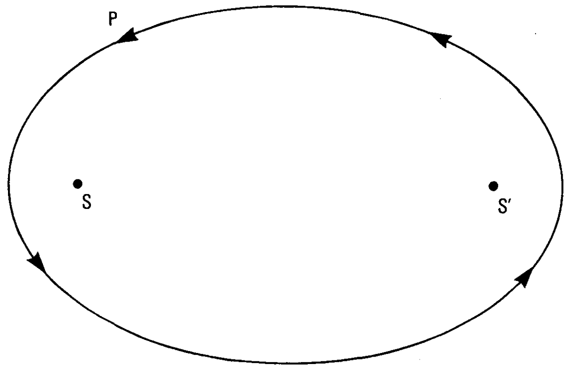
b. In what respects is the Copernican system superior to that of Ptolemy?

Kepler's ellipses

39a. Draw an ellipse. Take a length of strong cotton or thread not more than 20 cm long and tie it into a loop about 9 cm long when stretched out straight. Put a piece of paper on wood or wallboard and push two drawing pins into it – about 8 cm apart. Loop the cotton round the pins and place the point of a pencil in the loop. Push the pencil round, keeping the thread taut. A little practice is necessary. Slope the pencil slightly outwards so that the thread does not slide underneath. Then try drawing other ellipses with the pins (foci) at different distances apart.

b. If you use only one pin, what do you get?

c. If SS′ is 8 cm and the length all round the loop is 18.4 cm, what is SP + S′P? Why? The 'major' axis of the ellipse is the 'big diameter' through SS′: prove that the major axis also equals SP + S′P.



Galileo's discoveries

40a. How did Galileo's discovery of Jupiter's moons support the Copernican view as against that of Ptolemy?

b. Mention two other things besides the satellites of Jupiter that Galileo saw through his telescope and which were disturbing to the traditional view of the heavens.

Progress Questions for Chapter 5

41. Name the scientist who did each of the following things:

a. Used Jupiter and its moons as a model to support Copernicus' picture of the solar system.

b. Made precise observations of planets, systematically, without using a telescope, so that Kepler was able to extract his laws.

c. Discovered that planets move in ellipses not circles.
d. Explained that the Moon moves round its orbit because it is falling under Earth's gravity.
42. Tycho Brahe, Kepler, Copernicus, Galileo, and Newton: all these men contributed to Newton's theory in some way. For each man, find out the following and write a short note on what you find:
a. Where he lived.
b. When he lived and the names of three other famous people alive at the same time.
c. What he did for a living.
d. How he contributed to astronomy.
e. Three other facts that interest you about him.
f. For Galileo and Newton, what other important scientific work they did.

Questions for Chapter 5

The Moon's motion
43. The Moon, of mass m, rotates in an orbit round the Earth with radius R. Let v be its orbital speed, and let g be the value of the Earth's gravitational acceleration at the Moon. Then we can write

$$mv^2/R = mg$$

a. What does mv^2/R represent? What does mg represent? Why can they be put equal to each other?
b. If T is the time for one revolution of the Moon round the Earth, then $T = 2\pi R/v$. Why is this?
c. Show by algebra that $T^2 = 4\pi^2 R/g$.
d. Use the last equation to calculate T for the Moon taking R to be 400 000 000 m and g to be 10 m/s^2.
e. Did you get a result of about 11 hours? Could this be a correct value for the period of one revolution of the Moon round the Earth?
f. The answer to **e** is incorrect because we assumed that g is the same whatever the distance from the Earth. Clearly g must diminish with distance. Newton's assumption was that g is inversely proportional to the square of the distance. If g is 10 m/s^2 at the Earth's surface, what is g at the Moon, 60 times as far from the centre of the Earth? (Hint: at 60 times the distance away, the inverse square law would reduce the force by a factor of $1/60^2$.)
g. Use your new value for g to calculate T for the Moon. Does this result agree with observation?

Gravitational attraction
44. Jack and Jill are attracted to each other. Could any noticeable part of this attraction be gravitational?
a. Calculate the gravitational attraction they have for each other when they are 2 metres apart, given that the mass of Jack is 70 kg and of Jill 60 kg. G is 6.6×10^{-11} N m^2/kg^2.

Express your answer in newtons. Make a rough estimate of how this answer compares with the weight of the tiniest piece of paper you could tear off.

(*Note.* This question is not silly. It shows the great difficulty of measuring gravitational forces between objects in the laboratory, even if those objects are as dense as lead i.e. far denser than Jack and Jill.)
b. Taking the question more seriously than it deserves, and remembering the shape and size of Jack and Jill, say what you think is meant when we say they are 'two metres apart'?

Newton's projectiles
45. An artificial satellite is lifted by rockets to 3000 km above the Earth's surface, and is then fired horizontally (i.e. at 90° to the radius of the Earth). The intention is to give it exactly the speed needed to make it follow a perfectly circular orbit. But, as a result of a miscalculation, although it is fired horizontally, it is given too big a speed.
a. Draw a diagram with the Earth represented by a circle about the size of a 2p coin, and sketch in an orbit like one you think the satellite might possibly follow – make sure, at any rate, that it is an orbit which Kepler would not consider impossible.

sizes as here for the orbits of Earth and Jupiter. Continue the sight lines and mark the apparent positions of Jupiter among the fixed stars. Use your diagram to explain the fact that Jupiter sometimes appears to move westwards (retrograde) against the background of the fixed stars. (Note: This diagram has been drawn roughly to scale both for distances and for speeds of the planets.)

35. How would Copernicus explain that the westward (retrograde) motions are seen only when Sun and planet are 'in opposition', that is, on opposite sides of the Earth?

36. How, on Copernican theory, do you explain the following?

a. Mars appears brighter at some times of the year than others.

b. Venus is invisible when it is closest to us (two reasons).

37. Explain, with the help of a diagram, why Venus shows 'phases' like the Moon (see the photographs on page 93). Why does Venus at full look so much smaller than when it is seen as a 'new moon'?

38a. What sort of observations concerning heavenly bodies are explained equally well by the systems of Ptolemy and Copernicus? (Give some examples.)

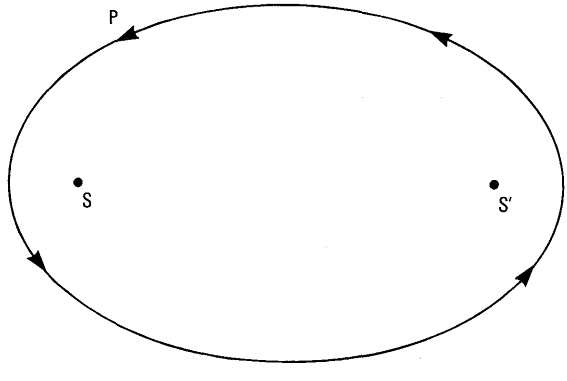
b. In what respects is the Copernican system superior to that of Ptolemy?

Kepler's ellipses

39a. Draw an ellipse. Take a length of strong cotton or thread not more than 20 cm long and tie it into a loop about 9 cm long when stretched out straight. Put a piece of paper on wood or wallboard and push two drawing pins into it – about 8 cm apart. Loop the cotton round the pins and place the point of a pencil in the loop. Push the pencil round, keeping the thread taut. A little practice is necessary. Slope the pencil slightly outwards so that the thread does not slide underneath. Then try drawing other ellipses with the pins (foci) at different distances apart.

b. If you use only one pin, what do you get?

c. If SS′ is 8 cm and the length all round the loop is 18.4 cm, what is SP + S′P? Why? The 'major' axis of the ellipse is the 'big diameter' through SS′: prove that the major axis also equals SP + S′P.



Galileo's discoveries

40a. How did Galileo's discovery of Jupiter's moons support the Copernican view as against that of Ptolemy?

b. Mention two other things besides the satellites of Jupiter that Galileo saw through his telescope and which were disturbing to the traditional view of the heavens.

Progress Questions for Chapter 5

41. Name the scientist who did each of the following things:

a. Used Jupiter and its moons as a model to support Copernicus' picture of the solar system.

b. Made precise observations of planets, systematically, without using a telescope, so that Kepler was able to extract his laws.

c. Discovered that planets move in ellipses not circles.
d. Explained that the Moon moves round its orbit because it is falling under Earth's gravity.
42. Tycho Brahe, Kepler, Copernicus, Galileo, and Newton: all these men contributed to Newton's theory in some way. For each man, find out the following and write a short note on what you find:
a. Where he lived.
b. When he lived and the names of three other famous people alive at the same time.
c. What he did for a living.
d. How he contributed to astronomy.
e. Three other facts that interest you about him.
f. For Galileo and Newton, what other important scientific work they did.

Questions for Chapter 5

The Moon's motion
43. The Moon, of mass m, rotates in an orbit round the Earth with radius R. Let v be its orbital speed, and let g be the value of the Earth's gravitational acceleration at the Moon. Then we can write

$$mv^2/R = mg$$

a. What does mv^2/R represent? What does mg represent? Why can they be put equal to each other?
b. If T is the time for one revolution of the Moon round the Earth, then $T = 2\pi R/v$. Why is this?
c. Show by algebra that $T^2 = 4\pi^2 R/g$.
d. Use the last equation to calculate T for the Moon taking R to be 400 000 000 m and g to be 10 m/s^2.
e. Did you get a result of about 11 hours? Could this be a correct value for the period of one revolution of the Moon round the Earth?
f. The answer to **e** is incorrect because we assumed that g is the same whatever the distance from the Earth. Clearly g must diminish with distance. Newton's assumption was that g is inversely proportional to the square of the distance. If g is 10 m/s^2 at the Earth's surface, what is g at the Moon, 60 times as far from the centre of the Earth? (Hint: at 60 times the distance away, the inverse square law would reduce the force by a factor of $1/60^2$.)
g. Use your new value for g to calculate T for the Moon. Does this result agree with observation?

Gravitational attraction
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(*Note.* This question is not silly. It shows the great difficulty of measuring gravitational forces between objects in the laboratory, even if those objects are as dense as lead i.e. far denser than Jack and Jill.)
b. Taking the question more seriously than it deserves, and remembering the shape and size of Jack and Jill, say what you think is meant when we say they are 'two metres apart'?

Newton's projectiles
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a. Draw a diagram with the Earth represented by a circle about the size of a 2p coin, and sketch in an orbit like one you think the satellite might possibly follow – make sure, at any rate, that it is an orbit which Kepler would not consider impossible.

b. Write a few sentences discussing the various things that might happen if the satellite were given too small a horizontal velocity. (Note. Remember, when fired horizontally, it has no vertical velocity.)

Kepler's Equal Area Law

46a. Sketch a diagram of a planet moving in an ellipse round the Sun and use it to explain what is meant by 'arm (or line) from the Sun to the planet sweeps out equal areas in equal times'.

b. Describe some simple illustrations of Kepler's Law II, applied to spinning objects that you have seen. Say what was done, and what happened.

c. Newton showed that Kepler's Law II applies to *any* planetary motion *provided that the controlling force . . ? . .*

Models

47. Here are two statements about models for astronomy, each with a question to answer.

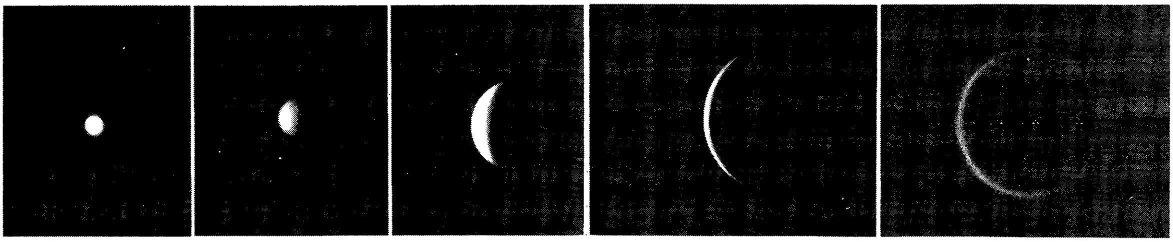
a. The schemes of Eudoxus and Ptolemy are very good models. Why?

b. But the Newtonian scheme is a much better kind of model. Why?

General questions

48a. Why is the planet Venus sometimes called the Evening Star and sometimes the Morning Star?

b. When farthest from the Sun, what does the planet Venus look like when viewed through a telescope?



1910 SEPT 27 | 1910 JUNE 10 | 1927 OCT 24 | 1919 SEPT 25 | 1964 JUNE 19

Five phases of Venus. *Lowell Observatory Photograph.*

c. When you see Venus looking like a crescent Moon, the planet looks very much bigger than when you see it as a bright round disk. Why?

49. Mercury is a planet that is rarely seen, appearing very near the horizon at sunset or sunrise. Why is it rarely seen? Suggest one or two reasons.

50. Kepler's Law II (equal areas) reminds us that when a planet is pulled in nearer to the Sun it moves much faster. Describe the application of this law to each of the following:

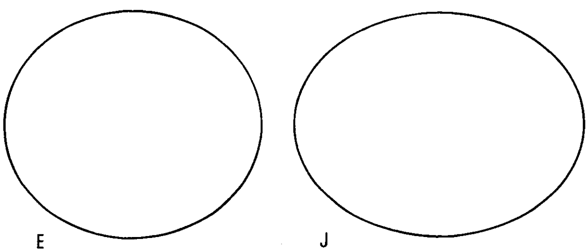
a. A diver who has taken off from a high board and is doing a somersault.

b. A skater who wants to spin very fast standing on one toe.

c. A shrinking Earth. Suppose owing to cooling or some other cause, the Earth were to shrink a little. What change would you expect to notice apart from the change of size?

51. Suppose the Moon were suddenly completely removed from the solar system. What would our ocean tides then be like (if any)? Explain.

52. The sketches E and J show the Earth (as seen from another planet) and Jupiter (as seen from Earth). Assume that the sketches are made from photographs taken with large telescopes, arranged with different magnifications to give pictures the same size. Look carefully at the shapes of the two pictures. The difference is exaggerated. What can you infer (conclude) about Jupiter?



53. Before the time of Newton, comets were regarded with awe.
a. How did Newton show that comets are just members of the solar system?
b. What later observations were used to test Newton's idea and showed he was correct?
54. Suppose an amateur astronomer claims that he has discovered a small planet. It is, he says, so small and dark that it has escaped notice so far. He has observed it carefully, finds that it moves in a circular orbit, and takes three years to go once round its orbit. Comment on his claim.
55. In deriving or predicting one of Kepler's Laws for the solar system the following equations are written:

$$v = 2\pi R/T$$
$$mv^2/R = GMm/R^2$$

and the conclusion is $R^3/T^2 = GM/4\pi^2$.
a. Explain briefly what the first equation means. (What does it say, where does it come from?)
b. Explain briefly what the lefthand side of the second equation means.
c. Explain briefly what the righthand side of the second equation means.
d. Which of the three things mentioned in **a, b, c,** involves one of Newton's three laws of motion?
e. The conclusion is a statement of one of Kepler's Laws. State that Law in clear words – that is, describe its meaning.
f. The Sun's planets and Jupiter's moons all pursue almost circular orbits. R^3/T^2 for one of the moons of Jupiter is about 1/1000 of R^3/T^2 for the Earth's orbital motion. What can you infer (conclude) from that?
56. Which of the following do you consider the two most important aspects of Newton's theory?
It used very simple laws.
It was more accurate than anything before.
It was very difficult, using great mathematics.
It was economical, collecting many things under one explanation.
It was fruitful, predicting many unexpected things.
Give your own reasons in support of your two choices.
57. A theory is neither a collection of facts nor wild irresponsible imagining. Mention (*i*) some facts (experimental knowledge) that Newton put into his theory, (*ii*) some guesses that he made to start his theory, (*iii*) one or two results that agreed with things already known, (*iv*) one or two unexpected results that made the theory seem useful.
58. Both the Sun and the Moon cause ocean tides, but those made by the Sun are smaller than those caused by the Moon. Comment on *each* of the following suggested reasons for the effect of the Sun being smaller.
(*i*) The Sun is less massive.
(*ii*) Gravity is less effective for a big thing like the Sun.
(*iii*) Although the Sun pulls much more than the Moon, the difference of pull between ocean nearest the Sun and ocean farthest from the Sun is much smaller than the difference of pull of the Moon.
(*iv*) The Moon goes round the Earth once a month but the motion of the Earth round the Sun is much slower, taking a whole year.
59. Suppose the Earth is not spinning at all, and never has been spinning. Would gravity (*g*) at the Equator be the same as gravity at the North Pole?

One of your neighbours, A, says 'yes' because without any spin none of the gravity is 'used up' in keeping an object at the Equator moving round in a circle. Another neighbour, B, says 'Oh, but the Earth is not a sphere, it is a spheroid, flattened at the poles, and that makes a difference to gravity.' What do you say, and why?
60. Up to the time of Newton, scientists, including Galileo, explained the Moon's circular motion round its orbit, and similar motions for the planets, by saying 'Above the Earth, motion in a circle is *natural* motion'. Was that wrong, bad, misleading, comforting, useful . . .? Give your opinion. Why do we now prefer Newton's view?

- -

61. *(Nuffield O Level Examination question, November 1977)**
At midnight on a certain day the constellation of the Plough appeared as shown above. Three hours later the Plough had moved.

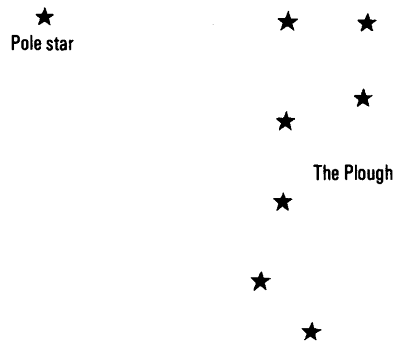


Fig. 1

(*a*) Draw a rough sketch to show the original and the new positions of the constellation.

(*b*) Calculate the angle that the Plough moves through in the 3 hours.

(*c*) Would a planet ever be seen in the constellation of the Plough? Give a reason for your answer.

(*d*) How would the ancient Greek astronomers have explained the movement of the constellations?

(*e*) (i) What is the modern explanation of the movement of the constellations?
(ii) What evidence is there in support of this modern explanation?

(*f*) Draw a sketch to show the path that Jupiter appears to follow when moving across the sky in the course of 1 year.

(*g*) How was the way we see Jupiter move explained on Ptolemy's system of epicycles?

(*h*) What is the explanation of the motion of Jupiter which we accept today?

62. *(Nuffield O-Level Examination question, June 1979)**
Fig. 2 shows the arrangement of the planets Venus, Earth, and Mars relative to the Sun.

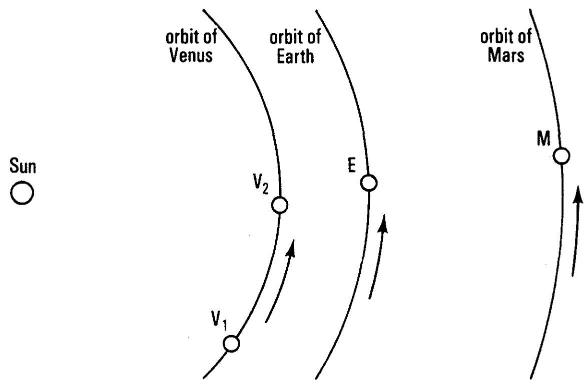


Fig. 2

(*a*) Draw diagrams to show how Venus appears when at the two positions *V*1 and *V*2 in Fig. 2, as seen through a telescope on the Earth.

(*b*) Explain why the brightness of Mars varies when seen from the Earth.

(*c*) Venus is sometimes called the Morning Star and at other times the Evening Star. Copy Fig. 3 and mark on it the position of Venus when it is the Evening Star ($V3$) and the Morning Star ($V4$).

(*d*) Galileo observed some small bright points of light near Jupiter which changed in position and number. How did he explain these observations?

(*e*) The orbits shown in Fig. 2 are circular. It is known that the orbits are not circular. What is the shape of an orbit? Where is the Sun placed relative to it?

(*f*) Draw a sketch to show how the orbit of a comet differs from that of a planet.

(*g*) Kepler's second law states that the line drawn from a planet or a comet to the Sun 'sweeps out equal areas in equal times'. Use this law to explain why comets are visible for only a short time.

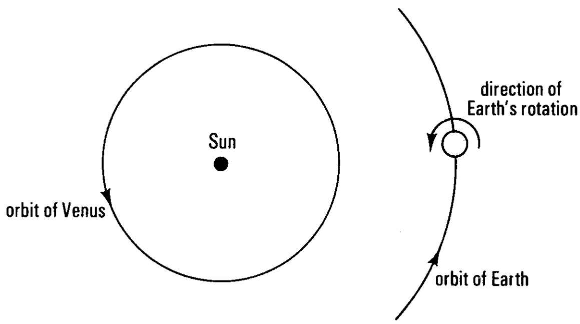


Fig. 3

(*h*) Kepler's third law states that for the planets moving around the Sun, R^3/T^2 is a constant. What do R and T stand for?

(*i*) Newton's law of gravitation accounts for Kepler's third law. What does Newton's law state?

CHAPTER 6

Oscillations: simple harmonic motion

You have seen several things that vibrate or swing to and fro: the ticker-timer, the wig-wag, and often enough a pendulum – probably without thinking about the details of its motion. These motions which we call oscillations, all have the same programme of speeds and accelerations. It is a type of motion that is very common and very useful in science.

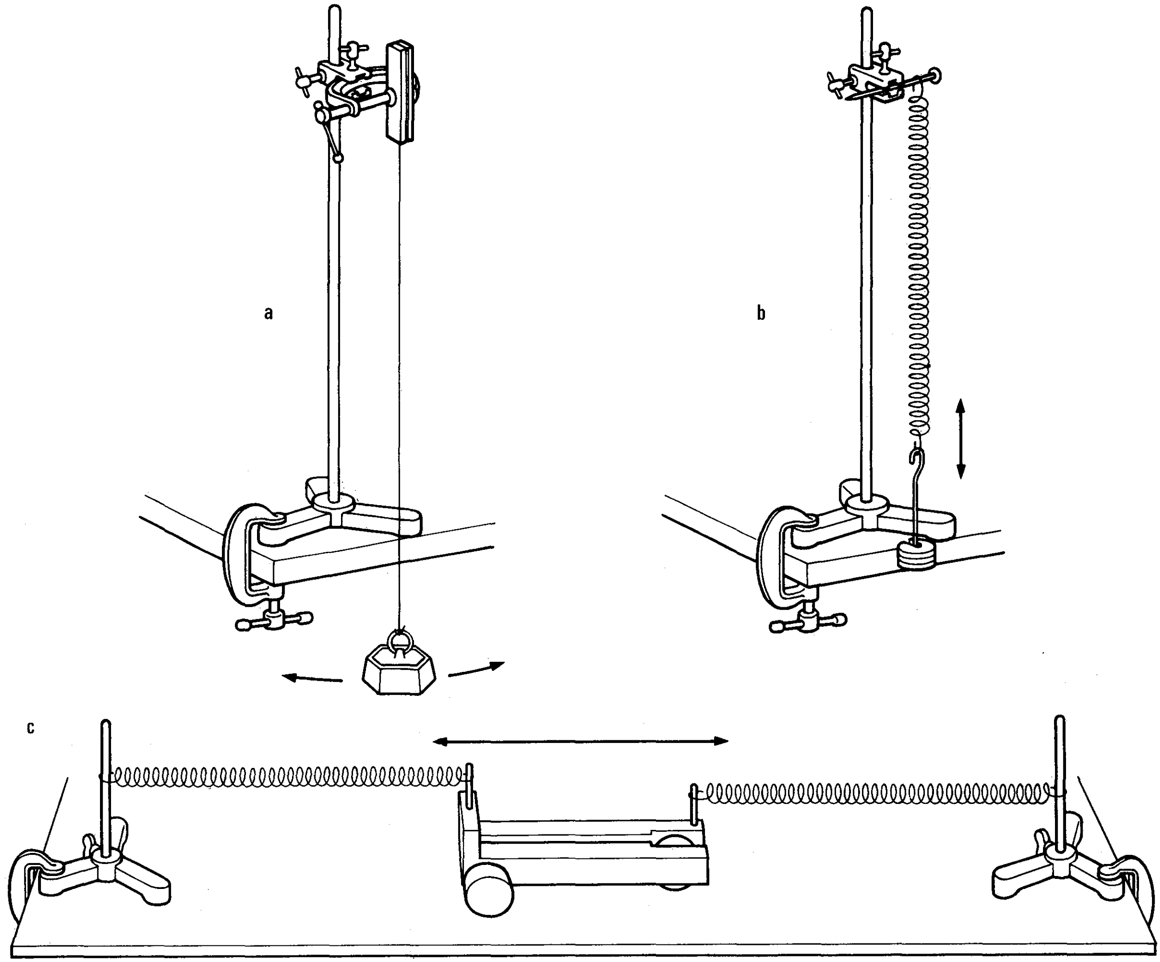
Experiment 35
Oscillations

Watch the motion of each of the three arrangements sketched. Find out what you can about them without being told or reading about them beforehand.

a. *Pendulum* Clamp the top of the thread between two metal strips as jaws. Attach the clamp to a stand fixed firmly near the edge of the bench. Pull the bob aside and let go. Watch the motion.

b. *Loaded spring* Hang a spring of steel wire from a firm support. Attach a load of about 400 grams to the lower end of the spring. Raise the load a short distance and let go. Watch.

(*Note:* A load hung on a spring has two simple motions, a bouncing up and down and a pendulum swing to-and-fro sideways. If you investigate the bouncing motion, you may find it does not last long



but changes into a to-and-fro pendulum motion. You can discourage that change by inserting a length of string between the bottom of the spring and the load.)

c. *Trolley controlled by springs* Clamp two small stands to the bench, about 60 cm apart. Place the trolley between them and connect the ends of the trolley to the stands with two stretched steel springs. Move the trolley by hand a short distance towards one stand and let go. Watch its motion – also listen to it.

Simple harmonic motion You may see many examples of that common type of motion. And you may *hear* some examples because it is the motion which occurs in musical instruments when they are producing a pure musical note. So we call it simple *harmonic* motion, S.H.M. for short.

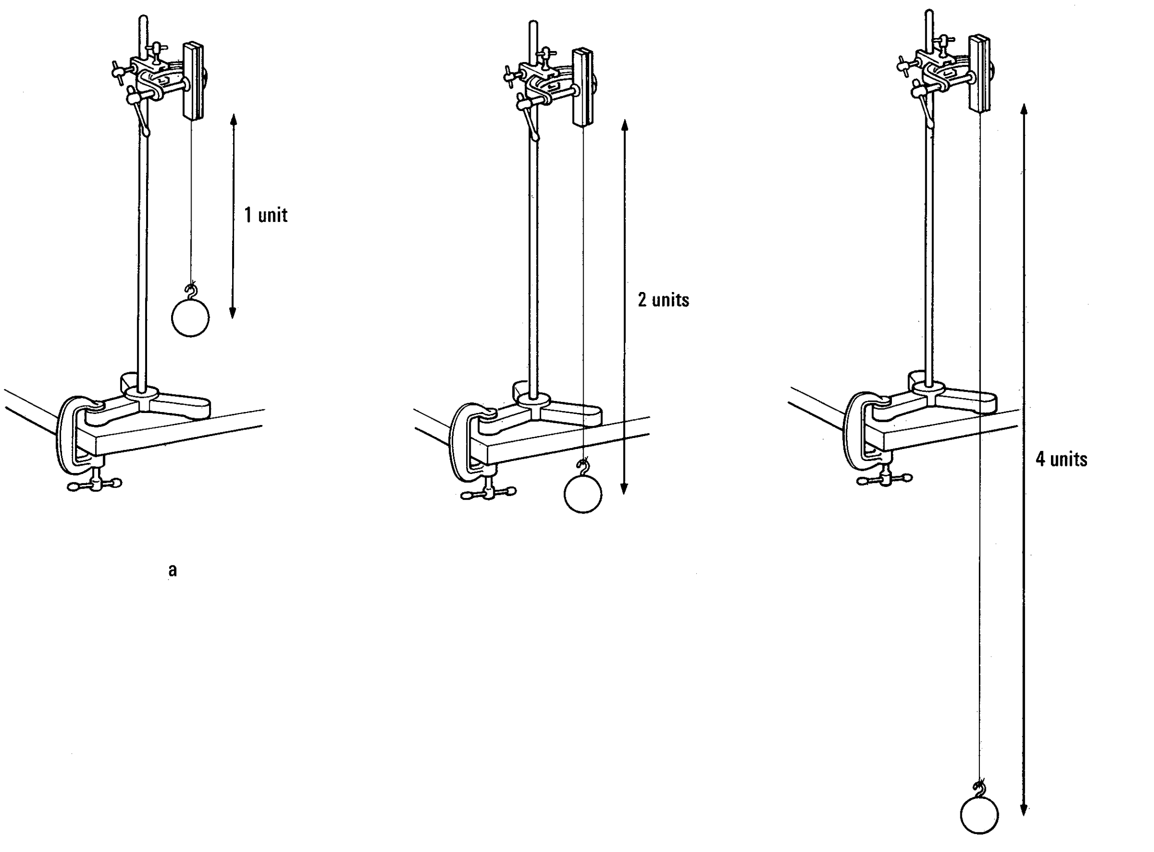
We call the time taken for one complete cycle of any repeating motion the *period* of the motion. For example, the period of a pendulum is the time for one 'swing-swang'.

We call the number of complete cycles the motion makes in one second the *frequency*. The motions you have just looked at have a very small frequency, such as 0.5 cycle per second – or, to use the modern unit 0.5 hertz, or 0.5 Hz. The pulse generator in the millisecond scaler timer has a frequency of 1000 Hz. The frequency of the electrical oscillations in a radio aerial for broadcasting ranges from a few hundred thousand hertz to a hundred million or more for very high frequency (V.H.F.).

If you do advanced physics for A-Level, you will find that you can calculate the frequency of the S.H.M. of a pendulum and a loaded spring, and many other things, from simple measurements of length or mass and springy forces. And we can analyse *any* repeating motion – ocean tides, sound waves, motion of the Moon, electron waves in atoms, and many more – into a whole set of S.H.M. components. (Have you seen an early example of that analysis?) Before you learn details of simple harmonic motion, you should look at a number of examples, such as those in the sketches.

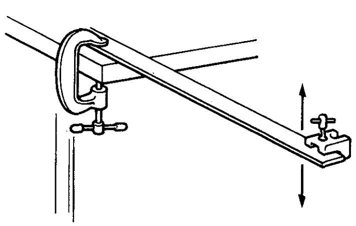
Demonstration 36a
Examples of simple harmonic motion

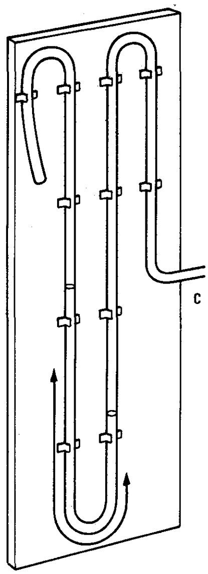
a. Pendulums of lengths in proportions 1 : 2 : 4.



a

b





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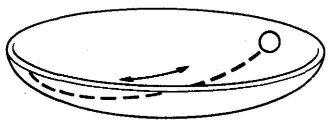
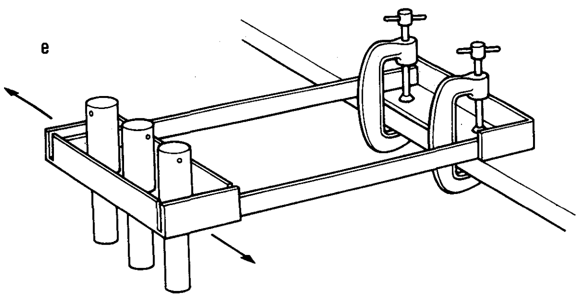


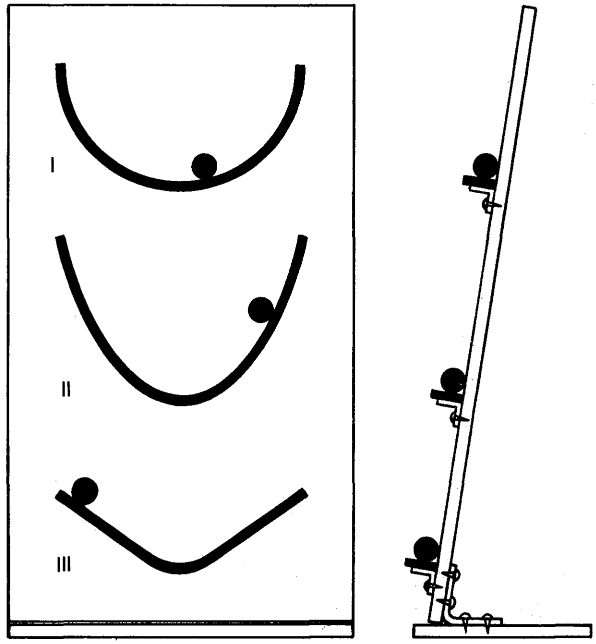
e



b. Bending beam: a metre stick like a very large ticker timer blade.
c. Water in a large U-tube.
d. Ball rolling in a bowl.
e. Wig-wag (or inertia balance).

Demonstration 36b
An interesting comparison

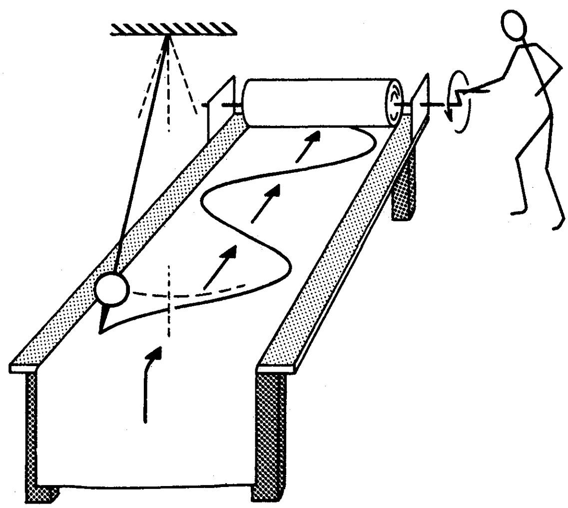
A ball rolls on three shapes of rail. If you see this, there will be three shapes: circle, parabola, and open vee. Listen to the sound of the ball scraping



along the slanting back-board. What can you say about each of these motions? Are they all simple harmonic?

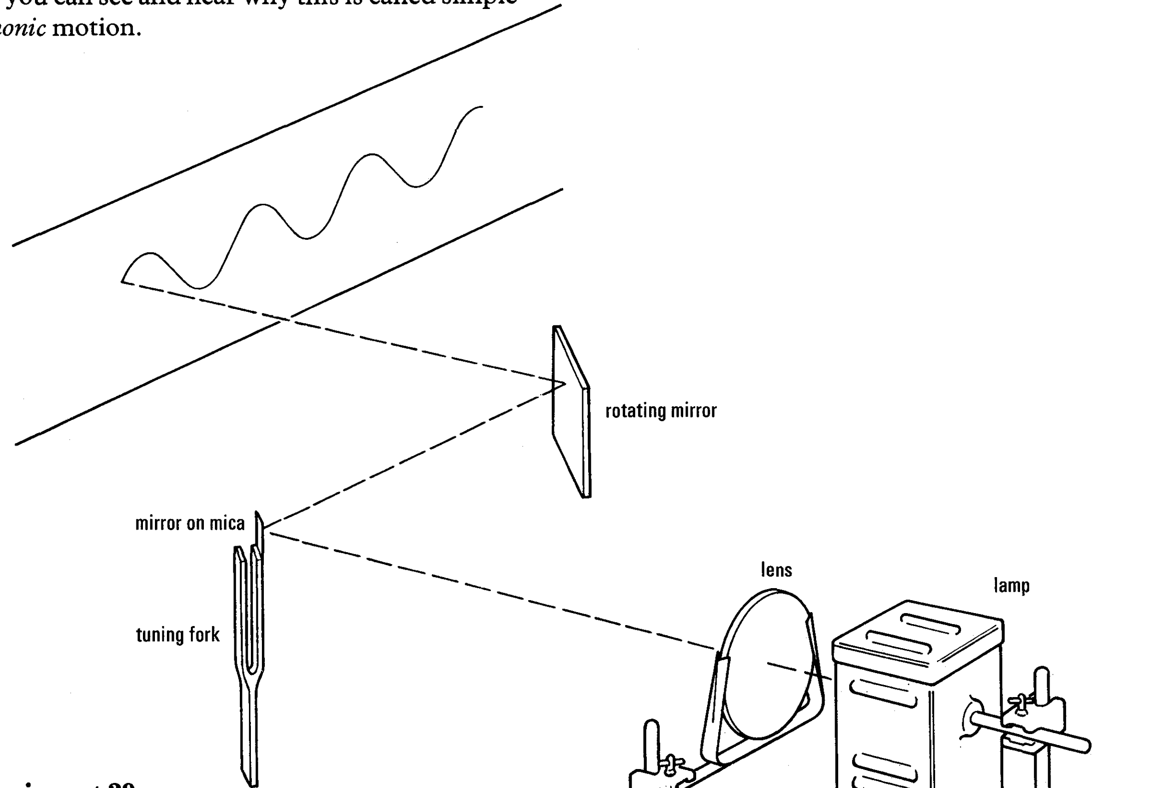
Demonstration 37
Time-graph of simple harmonic motion

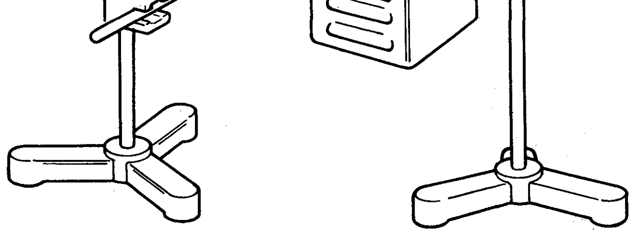
Suppose an object moves to and fro with S.H.M. Guess what the graph of that motion plotted against time would look like. Then see the demonstration sketched.



Demonstration 38
The motion of a musical tuning fork

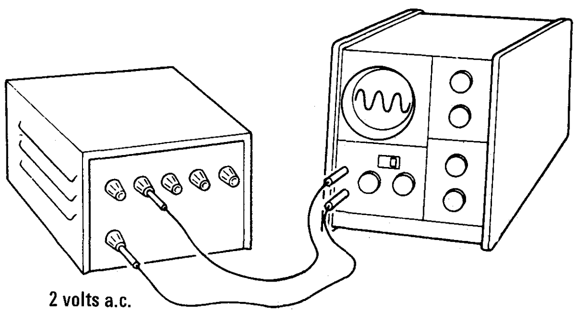
Now you can see and hear why this is called simple *harmonic* motion.





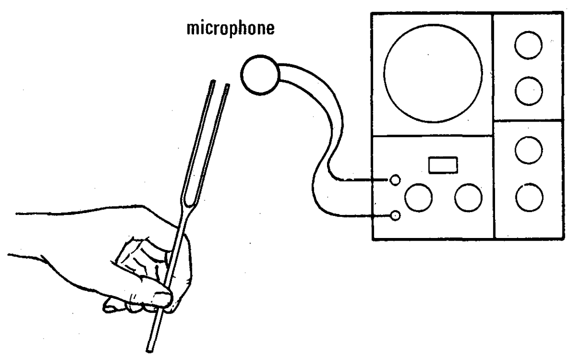
Experiment 39
Wave form of the mains voltage, plotted electronically

An oscilloscope can show you the graph of alternating voltage from the mains plotted against time – as the spot is driven across at constant speed by a repeated electronic time base. What can you say about it?



Experiment 40
Wave form of your voice and other musical instruments, shown electronically

Sing to a microphone. The microphone generates a tiny voltage which follows the pattern of the sound waves from your voice. Let the microphone's voltage drive the spot up and down on an oscilloscope. If you sing softly and very smoothly, you can make the air vibrate with motion which is S.H.M.

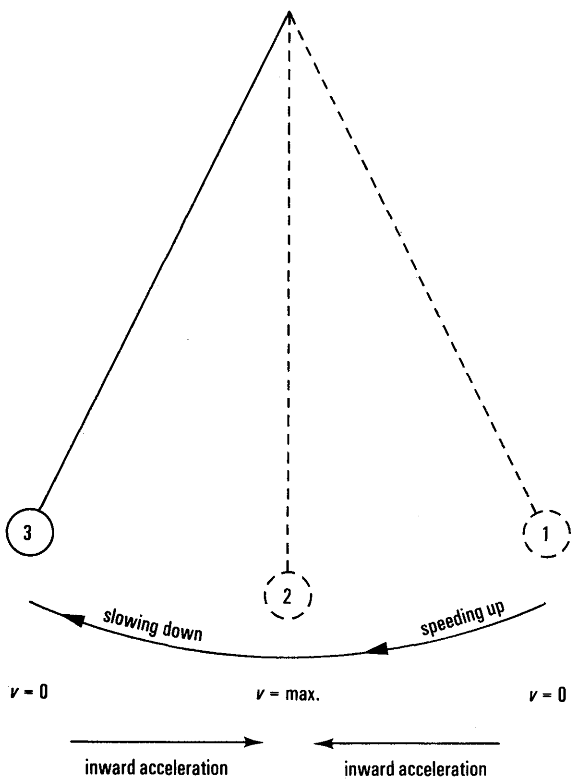


Try a tuning fork, after hitting it gently with a rubber hammer – never on the bench top: that might damage it and would certainly excite some extra vibrations. What does the wave form look like? Does it agree with the wave form you saw in another experiment?

If you like, try other musical instruments. Try singing a steady vowel sound; you may find it seems to be a compound of two simple harmonic motions, one belonging to the note you are singing, the other a higher frequency characteristic of the vowel sound.

Thinking carefully about S.H.M. So far we have not described S.H.M. still less defined it. We have only shown examples. Now watch a long pendulum swinging to-and-fro and think about its motion. Does it move with constant acceleration? Discuss that with your teacher.

Where is the bob moving *fastest*? If it is moving fastest at a certain place, can it move any faster just beyond that place? Can it be accelerating just where it is moving fastest? If it is accelerating there it must soon be moving fast*er*, and then it could not have been moving *fastest*! Already, by thinking about it you have discovered something about acceleration.



Out near the end of the swing, you can see it moving slower and slower. It has an inward acceleration slowing its outward motion down. As it starts to return, it goes faster and faster. Now that inward acceleration speeds it up.

Think about the forces at the end of the swing. There is the pull of gravity down on the bob and the slanting pull of the string. These are the only two forces acting on the bob which can change its motion. They cannot balance to make zero force: they must make some resultant force towards the centre of the swing. So the bob is accelerating, inward, at the end of the swing.

A scientific question What determines the period of a pendulum – its time of swing to-and-fro? You know that the period '*T*' of a pendulum is somehow related to its length – a long pendulum takes a longer time to swing to-and-fro than a short one. How is *T* related to other things that you could change and measure? Make some guesses and discuss them with your teacher. Try **Experiment 41**.

You should plan to make careful measurements with a good stopwatch or clock and investigate the effects of as many factors as you can.

Experiment 41
Look for rules for pendulums

Scientific planning often begins with questions. Here you may ask: 'How does the period, *T*, of a pendulum's oscillation depend on the mass, *M*, of its bob? And how is *T* related to the length of its thread, *L*?'

This is an investigation, like a project, to be shared with some other pupils.

Since there are two things that may affect the period, MASS and LENGTH, you need to keep one of those constant while you investigate the effect of the other.

[You did that when you investigated the behaviour of air in Year 4. The volume of a sample of air can be changed by changing the temperature, or by changing the pressure, or by changing both temperature and pressure. If you change both of those at the same time, you will find it difficult to discover simple laws. It is better science to keep the pressure constant while you investigate the effect of changing the temperature. Then you could do a second experiment: keep the temperature constant while you change the pressure. Then you could extract two rules: Charles' Law and Boyle's Law.]

Perhaps there is a third thing that may affect the period. Look at a pendulum swinging to and fro and think what else you can change as well as MASS OF BOB and LENGTH OF THREAD. Try out any guesses you make on your teacher.

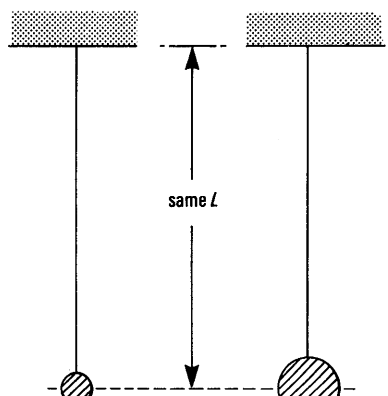
a. *Investigate the relationship between T and M* Work with one partner. Set up a pendulum with a thread a metre or more long. Make sure the thread is firmly clamped between jaws at the top. Practise measuring the time of swing. Pull the bob aside a small distance so that the pendulum makes an angle of 10° at most with the vertical. Let the bob go and count swings as the bob passes through the LOWEST point.

Why is it better, for accurate measurements, to choose the lowest point as your standard position for counting and timing swings? How much doubt have you about the exact instant when it swings past the LOWEST point? How much doubt do you have about the exact instant when it reaches the HIGHEST point, at the end of a swing?

The period is the time of a complete cycle, one 'swing-swang'; so you must time it from the instant when the pendulum swings through its lowest point one way (say, *to the right*) to the instant when it swings through the lowest point, the *same* way (again to the right).

Timing a single oscillation is not likely to be very accurate. (There are two kinds of error that might easily arise. What are they?) Time a batch of swings, say 50, counting 0-1-2-. . .48-49-50. It is safer to count out aloud. Beware of starting like this 1-2-. . .49-50. (How many swings would you time in that case?)

After timing such a batch, exchange jobs with your partner. If the results disagree with each other seriously, what should you do?



Now replace the bob by a much more massive one, taking great care to keep the length of the pendulum the same. Measure from the jaws at the top to the *centre* of the first bob. Make sure you have the same distance from the jaws to the centre of the second bob.

Then time a batch of swings.

What conclusion do you arrive at? Discuss with your teacher.

b. *Investigate the relation between T and L* Your teacher can give each pair a different rough length to use. Then there will be enough measurements to make a communal graph. For example you and your partner might be asked to use 'a length between 100 and 110 cm' and another pair might be asked to use 'a length between 30 and 35 cm'.

Measure the length of your pendulum, from the jaws at the top to the *centre* of the bob. Your partner should also measure it. Record the length, L.

Time a batch of swings very carefully. Then let your partner time an equal batch.

Calculate the time, T, of one complete swing.

Take your measurements of L and T to your teacher to be plotted on a communal graph of T versus L.

Does the graph look like a simple straight line through the origin? If so, you have found a simple law, 'T is proportional to L' (the same as $T \propto L$ or T/L is constant). If not look at the sets of measurements to see whether you could obtain a straight line by plotting something else against L. Try $1/T$, $\sqrt{T}$, T^2. Discuss this investigation with your teacher.

c. *Another factor?* All this time you have been taking something for granted: the effect of that 'third thing' you were invited to guess. Discuss that with your teacher; then make a quick test.

. . . .

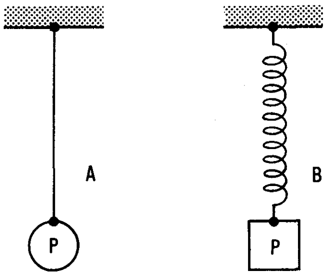
Progress Questions

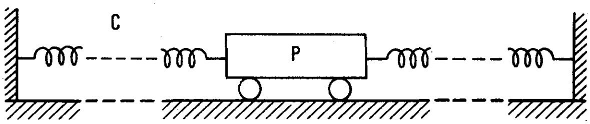
1. P is a load on a string (A), on the end of a spring (B), and a trolley fixed between two stretched springs (C). In each of the examples, P can be made to oscillate.

a. For each one

(i) say what you must do to make it oscillate and say in which direction it oscillates.

(ii) Write down all the things you noticed when you saw it oscillating.



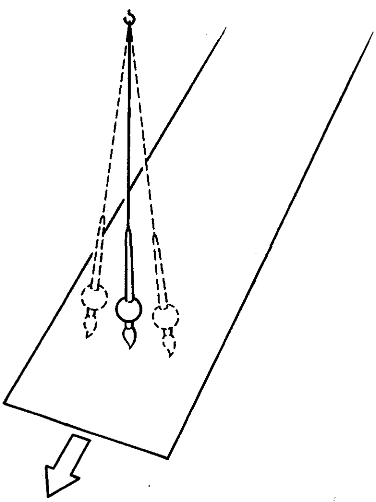


b. In what ways are the oscillations alike?
c. In what ways are the oscillations different?

Here are some changes you can make in the cases sketched above:
(i) You add more mass to P in each one.
You go back to the first mass but:
(ii) in A you make the string longer;
(iii) in B you make the spring stronger;
(iv) in C you make both springs stronger.
d. Now say whether each of the changes makes the motion faster or slower or leaves it the same.

2a. Explain how you can measure the time of one complete swing of a simple pendulum.
b. Does this time period get smaller or longer when the pendulum is made longer?

3. A swinging pendulum has an inked brush attached to it. This brush touches a long sheet of paper on the floor below it. The pendulum is set swinging, and the paper is pulled steadily along.



a. Draw the shape of the ink mark you will see on the paper.
b. Explain how the ink mark fits in with what you see when you watch the pendulum. (Label special points on the ink mark if you like.)

4. You hold a piece of chalk against the blackboard, and move your hand up and down. You will get a line on the board. Now you walk along beside the board, still moving the chalk up and down. Draw the pattern you expect to get on the board.

5. Here are the results of an experiment in which the time period of a simple pendulum and the corresponding lengths of the pendulum were measured:

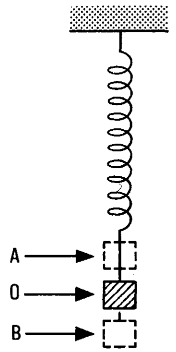
Length in metres	0.1	0.2	0.3	0.4	0.5	0.8	1.0
Period in seconds	0.6	0.9	1.1	1.3	1.4	1.8	2.0

a. Plot a graph of these results with the length of the pendulum along the x axis.
b. What is the period of a pendulum of length
(i) 1 metre?
(ii) 0.7 m?
(iii) 25 cm?
c. Describe carefully how you would measure the period of a simple pendulum reliably.
d. It is never possible to make a 'perfect' measurement. What stops you making a 'perfect' measurement in this experiment? That is, what errors are there?
e. Which of the periods given in (b) would it be hardest to measure reliably? Explain why.

Questions

Things moving backwards and forwards

6. Look at some kind of to-and-fro motion that is smooth and not jerky; a load hung on a vertical spring for example. Let O be the rest position of the motion. Let A and B be the positions where the distance of the load from its rest position is greatest.

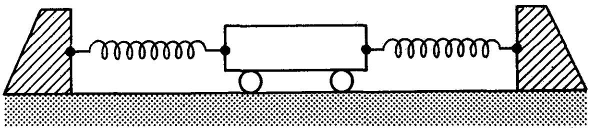


a. Copy and complete the following table.

position	*distance from O*	*velocity*	*acceleration*
A	maximum upwards	zero	maximum downwards
O	..?..	maximum up or down	..?..
B	..?..	zero	..?..

b. Say why there are *two* answers for velocity at O.

7. The sketch shows a trolley attached to two springs stretched horizontally. The mass of the trolley can be increased by loading it with pieces of



anything suitable or even a second similar trolley placed upside down on top of it, thus doubling the mass. (Anything placed on the trolley must be firmly attached so that it does not slide about when the trolley moves.) The 'stiffness', or 'spring factor' may be altered by using stronger springs (or by using four similar springs – two side-by-side pairs instead of two single ones), thus doubling the 'spring factor'.

a. What kind of motion do you see when you displace the trolley and then release it?

b. Why does it do this; that is, why doesn't it simply come back to the rest position and stay there?

c. If loads are placed on the trolley, what do you expect to happen to the trolley's 'time of oscillation'?

d. Why does this happen?

e. If four springs are used instead of two, what do you expect to happen to the time of oscillation?

f. Why does that happen?

g. What experiment would you do to find out whether doubling the *mass* factor has the same effect on the time of oscillation as halving the 'spring factor'? (*Hint*. As well as the straightforward obvious tests, there is an ingenious one. Can you think of it?)

Describe your experiment.

8. An experiment was carried out in which the period of a spring oscillating vertically was measured for several different attached loads. The results are given in the table:

Mass of load in grams (m)	100	200	400	600	800
Period in seconds (T)	0.57	0.80	1.13	1.38	1.60

a. Plot a graph with load m along the x-axis.

b. *(i)* What masses give periods of 0.6 and 1.2 s?

(ii) How do 0.6 and 1.2 s compare with one another?

(iii) How do the corresponding masses compare?

(iv) Can you see a pattern in the numbers for T and m? If so, what is it?

c. Choose another pair of times – say 0.8 s and 1.6 s. Does the same pattern apply?

9a. How would you show, to your own satisfaction, that objects that are making a sound are vibrating?

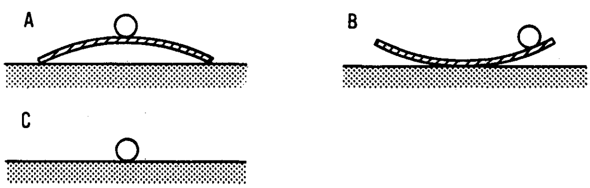
b. What is meant by 'frequency' of vibration? What connection is there between frequency of vibration and the musical pitch of the note produced?

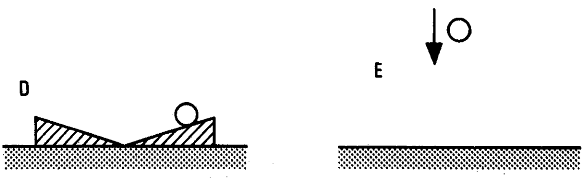
Simple harmonic motion

10a. (*Advanced*) If the acceleration of an object towards a fixed point – the 'rest position' – is proportional to its distance out from that point, then the object moves with simple harmonic motion (S.H.M.). It follows that the *force* pulling the object back to the rest position must be proportional to its distance out: why does this follow?

b. A load hung on a spring, when displaced and released, bounces up and down with S.H.M. if the spring 'obeys Hooke's Law'. Why is this?

11. Diagrams A to E show a small steel ball which can move on any of five different surfaces. In A and C the ball is given a small push sideways. In the others the ball is held out at one side and then released.



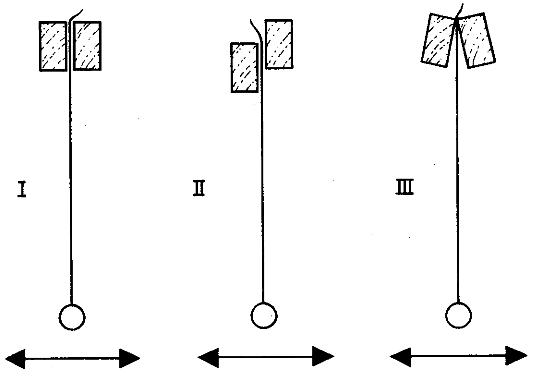


(i) In some of the cases the ball will not oscillate to-and-fro at all. Which?
(ii) In one or more of these cases the ball will oscillate, but not with S.H.M. Which ones?
(iii) In one case the ball may very well oscillate with S.H.M. Which one?
(iv) What can be said about case E?

Pendulum

12a. What experiment(s) would you do to find whether the period of a pendulum depends on its amplitude? What result would you expect?
b. What experiments would you do in order to find whether the period of a pendulum depends on the mass of the bob? What result would you expect?

13. (*Advanced*) In order to find how the period of a pendulum depends on its length, you 'timed' the pendulum for various lengths, and then, by dividing by the number of swings you counted, you found the period T for each length, L. You then plotted T against L and then T^2 against L.
a. Why is it more useful to plot T^2 against L?
b. Sketch I shows a pendulum with the top end of its string clamped between two pieces of wood.



Copy the sketch and show on it exactly what length you would measure in order to find L, the length of the pendulum.
c. Sketch II shows a badly fastened pendulum. Does this pendulum oscillate in S.H.M.? Explain.
d. Sketch III shows another badly fastened pendulum. What would it do?
e. A pendulum of length 1.0 m has a period of 2.0 s. What is the period of a pendulum of length *(i)* 2.0 m, *(ii)* 4.0 m, *(iii)* 0.5 m?

14a. (*Advanced*) Suppose the trolley and springs (see question 7) is taken from the Earth to the Moon. A friend thinks that its period of oscillation would be found to be the same as on the Earth. Do you agree with him? Give a reason for your answer.
b. A spring with a load hung on it is taken from the Earth to the Moon. It is found that:
(i) when the spring is held vertically in the usual way, it stretches less than it does on Earth;
(ii) when the load is allowed to oscillate up and down, the period of oscillation is the same as on the Earth.

How do you explain these two results?
c. A pendulum is taken from the Earth to the Moon. Its period is found to be greater than on the Earth. How do you explain this?

CHAPTER 7
Alternating currents

Simple dynamo When you use a model electric motor as a dynamo, it produces a direct voltage and drives a direct current. It is direct because the commutator reverses the connections from the coil every half turn. But it is d.c. of a rather bumpy wave form.

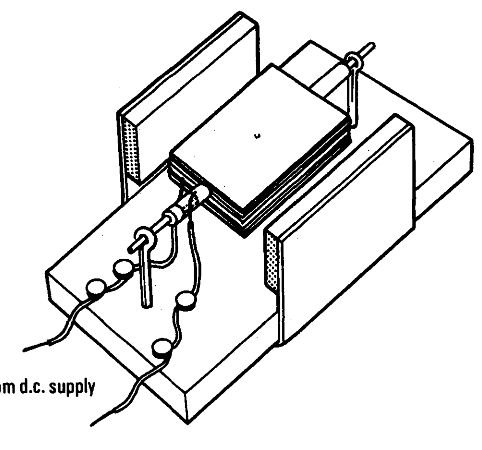
If you replace the commutator by a pair of slip rings with the brushes rubbing on them, you have a model a.c. dynamo.

The bicycle dynamo produces a.c. and is nearer to the form of the generators in power stations. Its field magnet is kept spinning (the rotor) and that induces an alternating voltage in the stationary coils (stator) arranged round the outside. In power station machines, the field magnet is an electromagnet, run by d.c. from a small generator on the same shaft as the big alternator.

EXPERIMENTS FOR REMEMBERING AND CATCHING UP

In Year 3 you made your own model electric motor. After that you used the motor as a dynamo and saw it producing a rather bumpy d.c. voltage.

Then you changed from a commutator to slip rings and had an a.c. dynamo. If you missed that work with dynamos, or if you are uncertain of it



now, you should make a model motor again – quickly – and try the following experiments. But hurry, or you may get left behind!

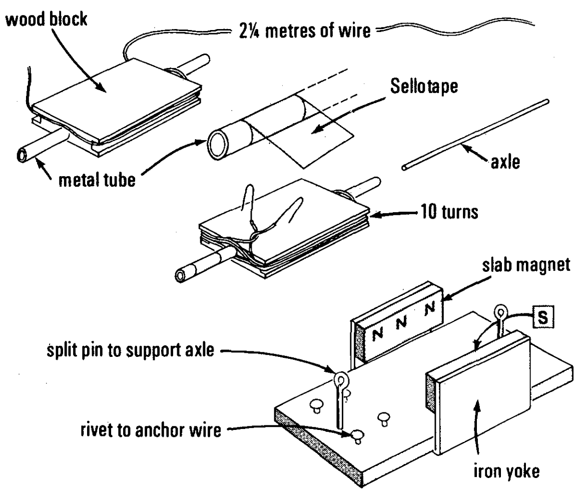
†Experiment 42
Simple a.c. and d.c. generators

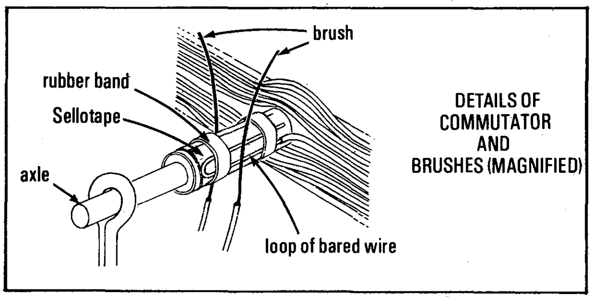
a. *Make an electric motor*
A motor has a coil built on an axle so that it can revolve freely. That coil, with its supporting core, is called the 'armature'. A magnet provides a magnetic field which exerts catapult forces on the coil.

The sketches show you what to do to make a model motor.

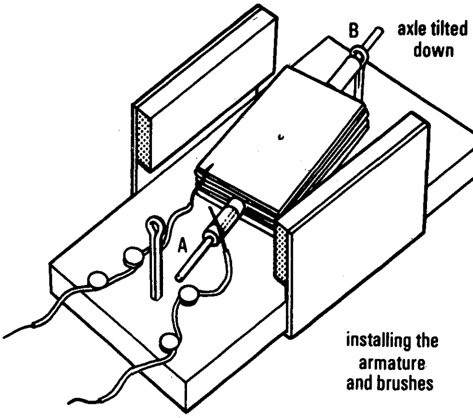
b. *Use the motor as a dynamo*
When you have made your motor run, remove the power supply and connect the brushes to a galvanometer or milliammeter. Spin the axle by hand and see what happens. Then connect the brushes to the input of an oscilloscope and spin the armature fast. Wrap a thread round the axle and saw the thread to and fro to do this.

CONSTRUCTION OF MODEL MOTOR





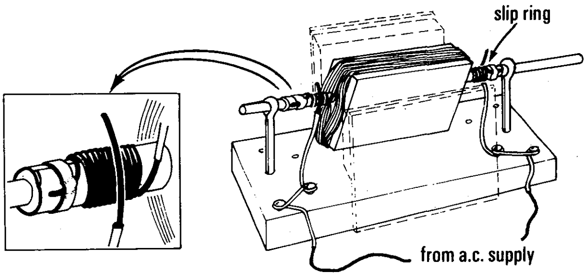
† denotes revision of the work of an earlier year.



c. *An a.c. generator*

Change from a commutator to two 'slip rings', one at each end of the axle.

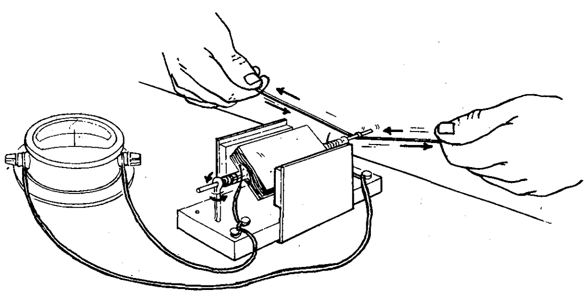
Bring out the two ends of the coil's wire to opposite ends of the metal tube that carries the coil. Near each end of the tube put a wrapping of



Sellotape as insulation. Wind a *bare* end of the coil's wire round the Sellotape at each end of the tube.

Move one of the brushes to the other end so that you have a brush at each end.

Then connect the brushes to a galvanometer. Try spinning the coil slowly.



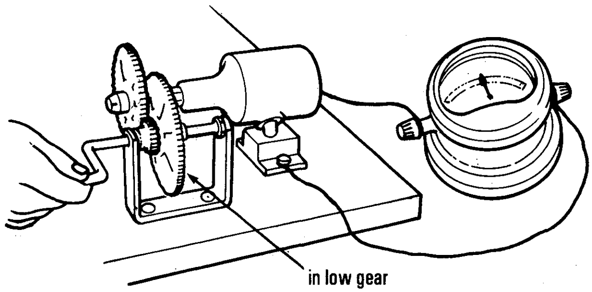
driving the a.c. dynamo fast

Connect the brushes to the input of an oscilloscope, set to maximum gain. Spin the armature faster and faster.

You have a model alternator – an a.c. generator.

†Demonstration 43
Bicycle dynamo

You may see the output of a bicycle dynamo shown on a milliammeter, then, as the dynamo is driven faster, on an oscilloscope.



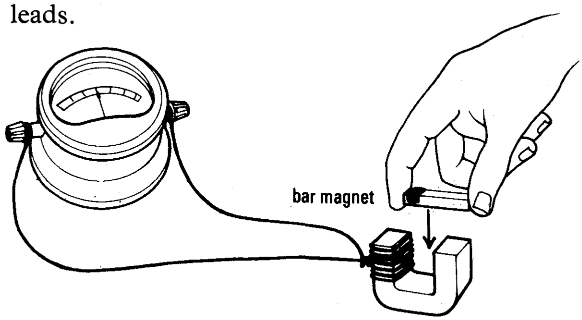
ELECTROMAGNETIC INDUCTION

In Year 3 there were experiments to show the basic effect which underlies the working of all dynamos: a voltage is induced in a wire in a magnetic field which moves or changes.

You may want to repeat some of those experiments.

†Experiment 44
Dynamo effect: magnet and coil wound on an iron core

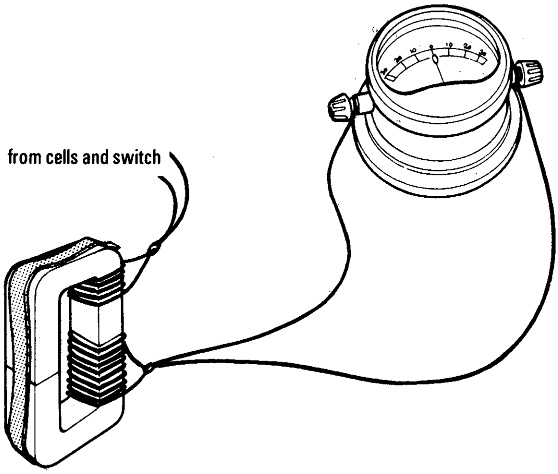
Wind a coil of about 20 turns on one arm of the C-core and connect the coil to a galvanometer by long leads.



Place a magnet across the ends of the core and watch the effect. Then remove the magnet and watch the effect.

†Experiment 45
Simple transformer with d.c. supply and switch

Take the C-core used in Experiment 44 to form the secondary of a transformer, keeping it connected to the galvanometer.



Wind 10 turns of wire round another C-core to form the primary.

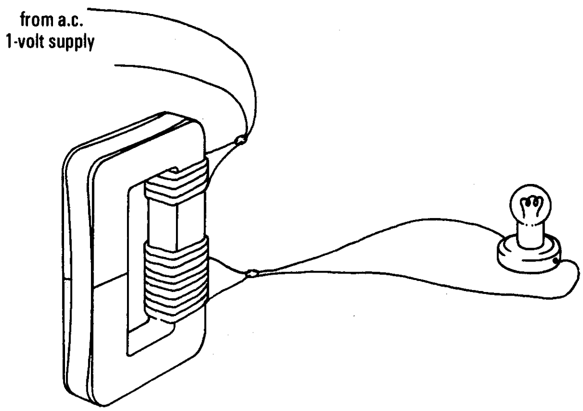
Clip the two C-cores together.

Touch the two ends of the primary coil on to the terminals of a dry cell. Watch what happens. When does it happen?

Be careful not to leave the dry cell on too long.

Experiment 46
Simple transformer with a.c. supply

Use the same arrangement as in the previous experiment, but replace the dry cell by an a.c. supply. Connect the ends of the secondary coil (25 turns) to a lampholder with a 2.5 V lamp in it. Connect the primary (10 turns) to a 1 V a.c. supply.



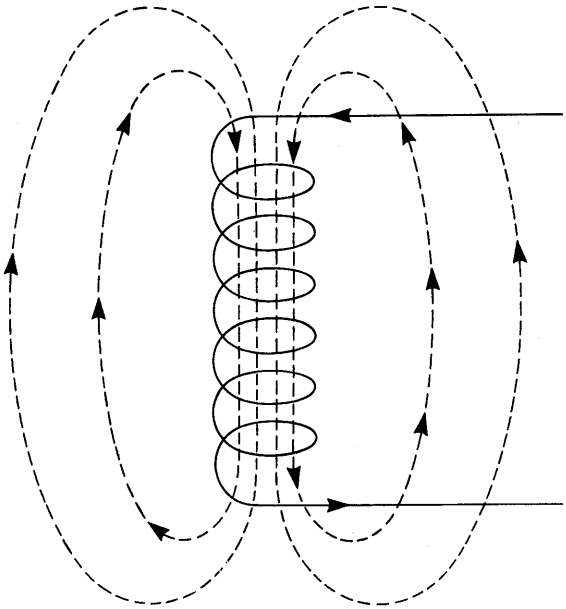
If you like, see how well a lamp will light without the help of this 25:10 'step-up' transformer. You need not disconnect your lamp; just connect another, equal, lamp straight across the low voltage a.c. supply. Does that second lamp glow as brightly? To show that this is not due to some difference between the two lamps, interchange them.

MAGNETIC FIELDS

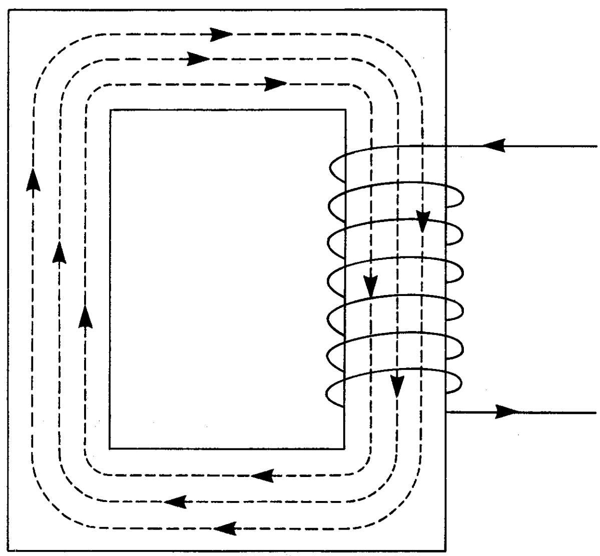
Field of a coil Send an electric current through a long hollow coil of wire. As long as the current flows there is a strong magnetic field inside the coil, and a weaker field outside.

The lines of the magnetic field pattern run through the coil; spread out from the end; go round outside and in at the other end.

field inside and outside a coil



much stronger field inside an iron core



These are not real lines, like the ones you draw with a pencil. They are lines that we imagine, as in a sketch, to show the pattern of the magnetic field, the directions along which a sample of iron would be magnetized by the field.

Where the field is strongest, the lines are most closely crowded.

With a steel bar magnet, the lines seem to sprout out at one end and run round and in again at the other end. Sometimes we like to imagine there are 'poles' at or near the ends, but cutting a magnet to find a pole always fails to catch a single pole – they always come in pairs, N and S.

With a hollow coil the lines form complete rings. If there is an iron core in the coil, it becomes magnetized and seems to make the field much stronger – while the current is on.

INDUCED VOLTAGES: DYNAMO EFFECT

In general there is an induced voltage while a magnet is moving towards a coil or away from it, when a coil or any other wire moves across a magnetic field, or when the magnetic field in the region of a coil is growing stronger or weaker. It is *motion* or changes of a magnetic field relative to a wire, that induce voltages in the wire. This was Faraday's discovery that led to the development of dynamos and power stations, when before there had been only batteries.

TRANSFORMERS

When we make a transformer, we call the coil that carries current round the *iron core* the *primary* winding. Then we wind another coil round the same core and call that the *secondary*.

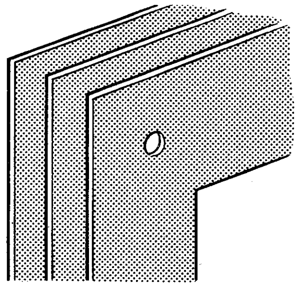
When there is a steady, constant, current in the primary there is no effect in the secondary. But there *is* an effect in the secondary *when the primary current is changing*.

A changing primary current induces an e.m.f. in the secondary; and if the secondary is joined in a complete electric circuit that voltage drives an induced current in it.

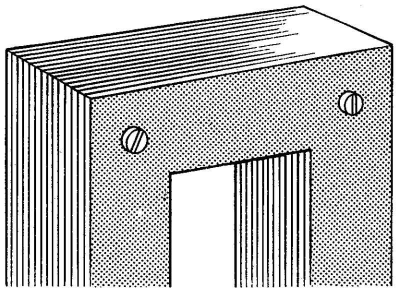
Transformer cores The iron core is usually a complete ring – the shape, round or square, does not matter. The magnetization due to a current in the primary coil runs all the way round the ring. The basic magnets of the iron line up tail-to-head, as they did in the small ring you tested in Year 3.

Then the primary and secondary coils can be wound anywhere on the ring – because the iron carries the changes in magnetization from one coil to the other.

The iron core is itself a crude secondary (like a coil of one turn) and changes of primary current induce little circular voltages in the core. Iron is a conductor, though not such a good one as copper, and, if the iron core were solid, the induced voltages would drive wasteful secondary currents in it. So the core is made of many thin sheets clamped together, with the face of each sheet coated to make it a very poor conductor. Look at your transformer cores and see the edges of those sheets.



thin plates like this (coated with poorly conducting tarnish)

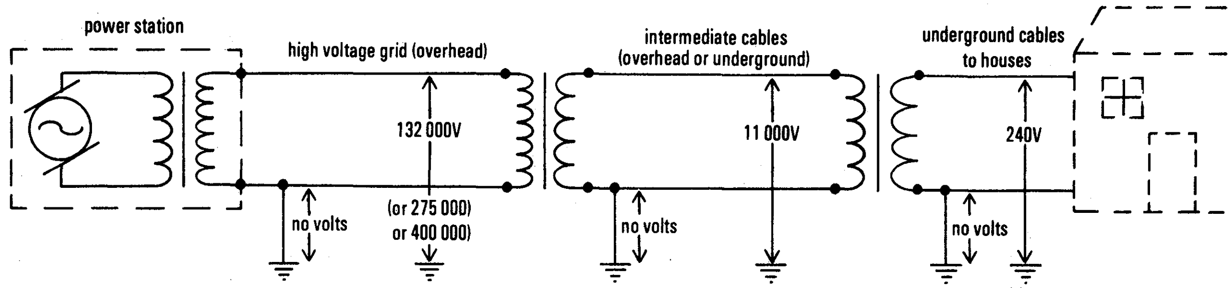


plates are clamped together like this to form the core

CORE OF A TRANSFORMER

A changing primary current is needed In your experiments you saw the effect with d.c. – nothing happened in the secondary except when current in the primary was switched on or off. With a.c. in the primary there was a continual series of changes in primary current, and the secondary showed a continual series of effects.

Number of turns When the primary current *changes*, a voltage is induced in each turn of the secondary coil. Watch the effect of winding a secondary coil on a core. As it is wound, turn after turn, more voltage is induced, 'volt after volt' so to speak.

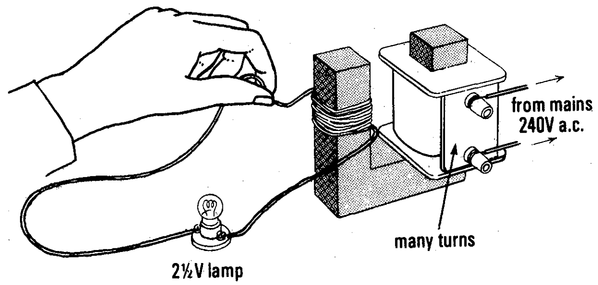


Once you have chosen the primary coil and sent an alternating current through it, you can change the secondary voltage by winding more turns, or fewer, on the core.

If the primary has 1000 turns and is fed from a 200 V a.c. supply, you may expect a secondary coil of 1000 turns to give almost 200 V a.c. Or a secondary of 100 turns will give 20 V. Or a secondary of 10 turns, easily wound by hand, will give about 2 V a.c. and run a small lamp.

If you start with no secondary and then wind on a secondary coil, turn after turn, you gain 2/10 V for every turn, because the changing magnetic field cuts through every turn. As you wind on 1 turn, then 2 turns, then 3, 4, . . . 10 turns you have successively 0.2 V, then 0.4 V, 0.6 V, 0.8 V, . . . 2.0 V across the secondary.

Demonstration 47
Winding a transformer turn by turn
The sketch shows the arrangement. The primary is fed by the mains 240 V a.c. supply (instead of 200 V which was chosen above for an easy example).



Watch the lamp while turn after turn of wire is added to the secondary winding.

What happens when the magnetic ring is completed by a bar 'yoke) across the U-shaped core?

Automatic voltage changers Thus you can have a *step-down* transformer from 200 V across a primary of 2000 turns to 2 V across a secondary of 20 turns; or a *step-up* transformer with 1000 turns of primary fed by 200 V a.c. and a secondary of ten times as many turns, 10 000. What voltage would that secondary give?

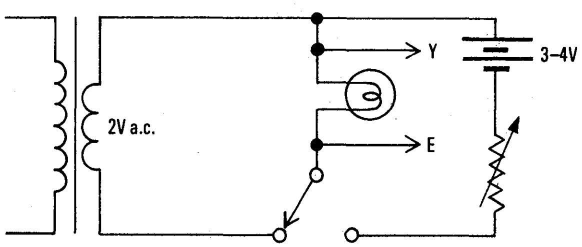
Efficiency Transformers are very efficient (the little power they waste appears as heat) and they run by themselves, needing no supervision.

Transmission or power lines Step-up and step-down transformers are used for the transmission or power lines of the grid. You have already seen in earlier years how a small voltage between the wires of a model power line makes it very inefficient. With a larger voltage, it can be very much more efficient – but also dangerous.

So step-up transformers are used to take the generated voltage (25 000 V) at the power station to high voltage (132 000 or even 400 000 V) on the transmission lines. At the consumer's end, step-down transformers change the supply to a safer voltage (240 V for house lighting, etc.). (See above.)

Mains a.c. If you have not seen the wave form of mains a.c., you should try **Experiment 39** (see page 100) now.

Demonstration 48
Comparison of r.m.s. value and peak value
Connect a 2 V a.c. supply to a small lamp. Attach a crocodile clip to one lead, to act as a home-made two-way switch.



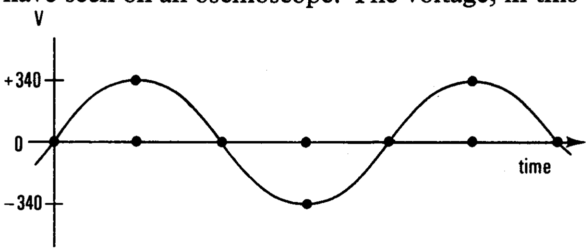
Also connect the two dry cells and a rheostat to the lamp. The two-way switch gives a choice between the two supplies. With that d.c. supply, adjust the rheostat so that the lamp glows with the *same* brightness as with the a.c. supply.

Take leads also from the lamp to the vertical input of the C.R.O. with the time base running.

Switch to and fro between the two supplies, to make the comparison. With d.c. you will see the trace deflected upward (or down); with a.c. you will see the wave form. Are the peaks higher than the d.c. deflection?

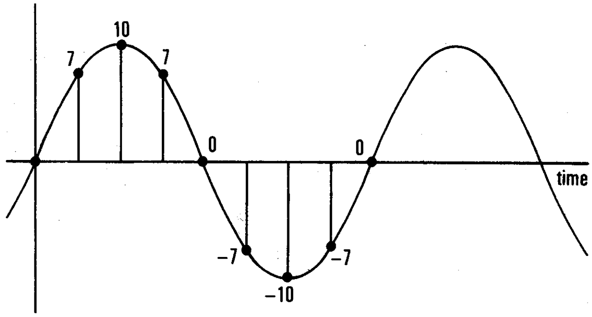
CHARACTERISTICS OF ALTERNATING VOLTAGE AND CURRENT

Look at the sketch. It shows the pattern you may have seen on an oscilloscope. The voltage, in this example the voltage of the a.c. mains, swings from zero to a maximum to zero to a maximum the opposite way; to zero . . . and so on. The maximum value is called the *peak*. *Why is the peak labelled 340 V in the sketch, when you know the mains voltage is 240 V?*



Average value What is the average value? Since the voltage is as often one way or the other, equally often + and −, so to speak, the plain average is zero.

Another average? An electric current heats a wire whichever way it is flowing. An alternating current must heat a wire – and it does – in every part of its cycle. (Remember that heating by current I through resistance R is proportional to I^2R; and I^2 is positive whether I is positive or negative.) Heating effects must follow the average of (I^2), and so do some other effects. So we use a special average, the *root-mean-square* average (r.m.s.). Take the current (or the voltage) at each instant in turn, square it, add up all the squares (all positive) and divide by the number of samples, to find the *average square* or *mean square*. Take the square root of that.



Here is an example:
Suppose the time samples are

0 7 10 7 0 −7 −10 −7 etc.

Square them:

0 49 100 49 0 49 100 49.

Add them and divide by the number of samples, 8: (TOTAL 396)/8.
The average is almost 400/8 or 50.
Take the square root – almost 7.
With proper, careful algebra, for a wave trace of S.H.M. the r.m.s. average turns out to be

$$\frac{\text{(peak value)}}{\sqrt{2}} \quad \text{or} \quad \frac{\text{(peak value)}}{1.41}$$

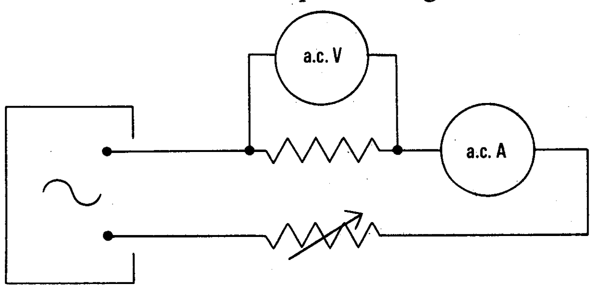
$$\text{or (peak value)} \times 0.707$$

METERS FOR ALTERNATING CURRENTS AND VOLTAGES

There are ammeters and voltmeters designed to measure root-mean-square average values. Nowadays they are usually d.c. meters with a built-in rectifier. Since the one-way bumps of rectified current have to be shown as a steady average on the dial, the scale on the dial must be specially numbered to read r.m.s. values.

Demonstration 49
Ohm's Law with a.c.?

See a quick test made with ammeter and voltmeter that take the root-mean-square averages.

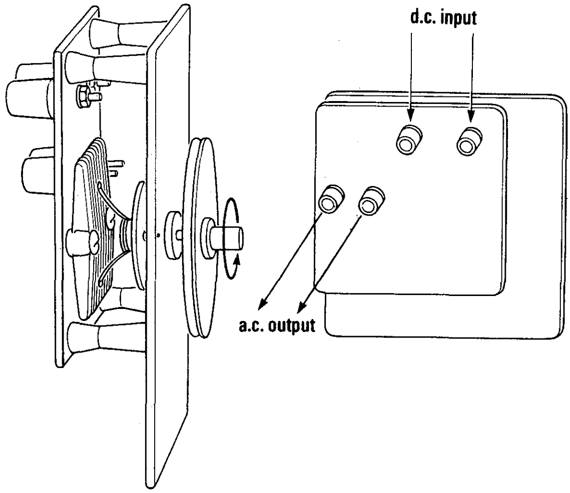


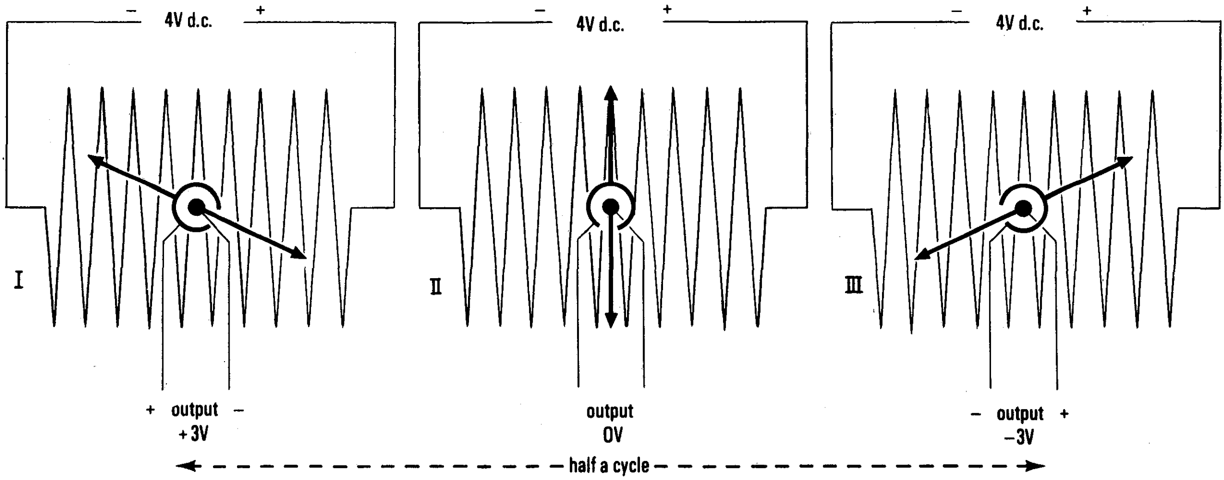
SLOWLY ALTERNATING CURRENT

To learn more about alternating currents, do some experimenting with very low frequency a.c. Try some of the following experiments, and perhaps see some others as demonstrations.

The special generator Instead of the mains, whose voltage alternates with frequency 50 Hz, use the generator sketched. It takes an input of 2 or 4 volts d.c. and produces an output that swings from maximum (2 or 4 V) to zero to maximum the opposite way to zero . . . and so on, as slowly as you turn the handle.

Look at the diagram, and look inside the generator. Can you see how it works?





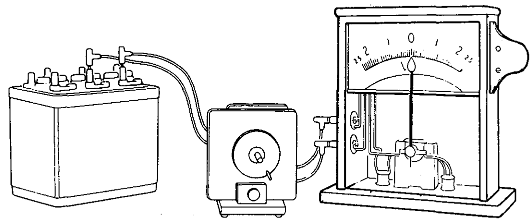
Experiment 50
Slowly alternating current and voltage

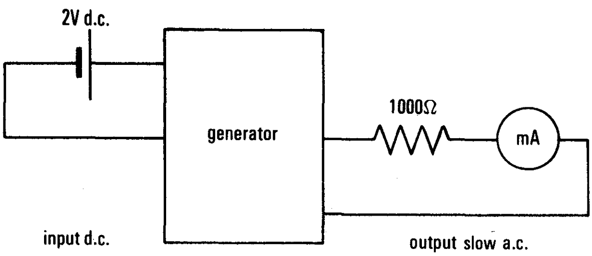
a. *An alternating current* Try the output of the generator on a milliammeter (galvanometer). Connect the output terminals to the milliammeter with a 1000-ohm resistor in series to pass a suitable current. Turn the handle slowly.

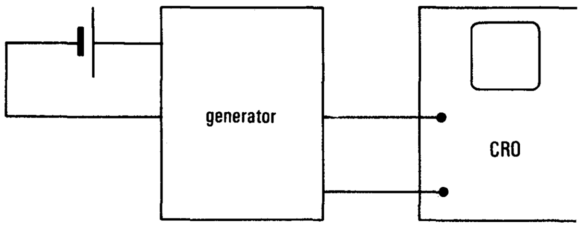
b. *An alternating voltage* Set the a.c.-d.c. switch on the oscilloscope to d.c.: turn off the time base and set the Y-gain to about 1.

Connect the output of the generator to the input of the oscilloscope. (It does not matter whether you keep the resistor in or not.)

Turn the generator handle slowly and watch the oscilloscope. Then switch the time base to its lowest speed on range 1 as you turn the generator handle.







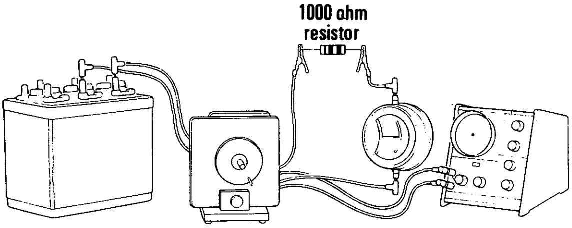
Increase the time-base speed and turn the generator faster.

Ohm's Law? What happens when a slowly alternating voltage drives a current through a resistor? Try the next experiment and see whether you can decide from it.

Experiment 51
Slow a.c. and a resistor

Connect 2 V d.c. to the input of the generator.

Connect its output to the input terminals of the class oscilloscope which serves as a voltmeter. Connect the output terminals also to a 1000-ohm resistor in series with a centre-zero galvanometer.



Keep the brilliance control of the oscilloscope as low as possible, and keep the spot out of focus, to avoid damaging the screen.

Start with the time base of the oscilloscope switched off and the a.c./d.c. switch in the d.c. position. Set the gain to 5 divisions per volt. Adjust the Y-shift so that the spot is in the centre of the screen when the galvanometer reads zero.

Turn the generator by hand at speeds of $\frac{1}{2}$ to 1 rev./second.

Watch and decide whether current and voltage (p.d.) are in phase (that is swing to and fro in step).

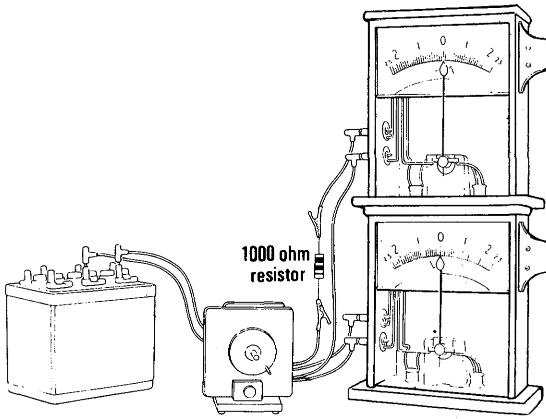
It is easier to compare phases if you hold the galvanometer with its face side by side with the oscilloscope screen and turn it so that the needle moves up and down like the spot.

If you have time, ask for a rectifier (from the circuit board kit) and insert it in one of the leads from the generator to the resistor.

You may also see a demonstration of that with a large ammeter and a large voltmeter.

Demonstration 52
Slow a.c. and a resistor

Watch the two meters. Do their pointers swing to and fro in step (in phase)?

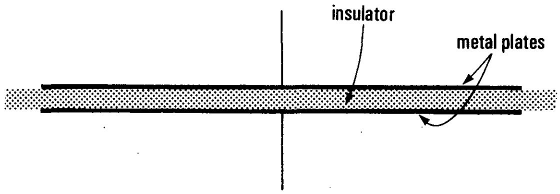


Experiment 53
Slow a.c. and a capacitor

This experiment is just like the last one except that you replace the resistor with a capacitor.

The capacitor consists of two metal plates separated by a thin slab of insulator. (That 'sandwich' is rolled up and put inside a case to protect it, but the two plates are still separated by the insulator.)

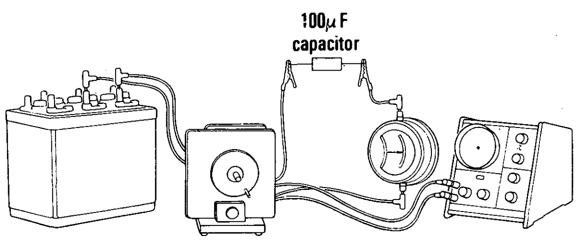
You should follow the same instructions as for **Experiment 51**.

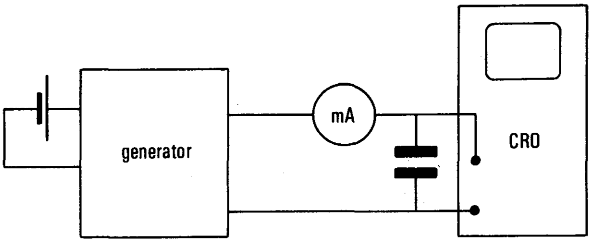


STRUCTURE OF A CAPACITOR (UNROLLED)

As you turn the generator by hand, at about 1 rev./second, watch the galvanometer. The pointer will move, but not very far. For greater motion you would need more voltage or a larger capacitor – one with a larger area of plates. Consult your teacher about using a larger d.c. voltage on the generator.

Now compare voltage and current as you did for the resistor. This is easier if you hold the galvanometer on its side. Both voltage (on the





oscilloscope) and current (on the galvanometer) change as the generator produces the slowly alternating voltage. But do they keep in step? Are they in phase? Does the current reach maximum at the same instant as the voltage?

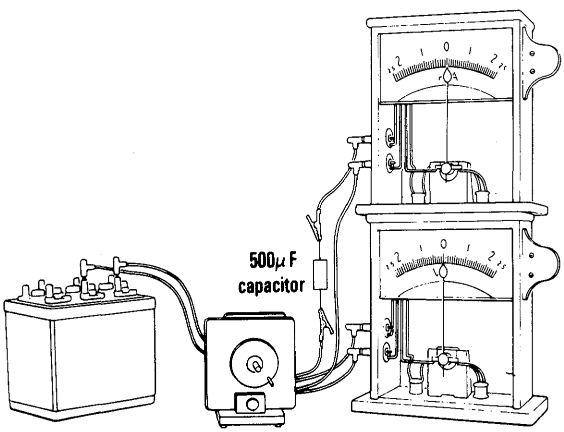
Discuss that behaviour of current and voltage with your teacher.

Can the current shown by the milliammeter really run *through* the capacitor? A current consists of moving electric charges. Can charges run on and off the capacitor's plates? If they did, could the milliammeter show a current as charges run through it, to or from the plates?

When an alternating voltage is applied to a capacitor, a current *seems* to pass through it. In fact, charges swing on and off the plates of the capacitor. Energy surges into the capacitor and is stored in the electric field between the plates. But then it surges out again, back into the supply. And as charges then flow in to the plates the opposite way round, energy surges in again.

Demonstration 54
Slow a.c. and a capacitor

You may also see a demonstration of this. Again watch the meters. Do current and voltage reach their peak at the same instant, or does one lag behind the other?

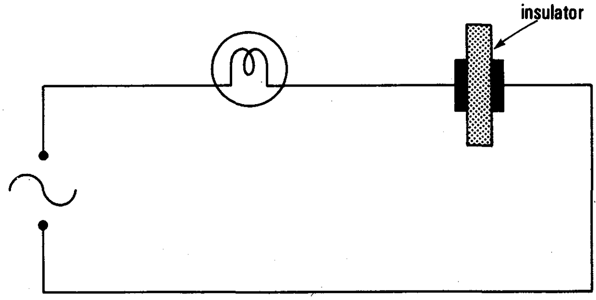


ALTERNATING CURRENT GOES THROUGH A CAPACITOR

A lamp and a capacitor with a.c. The current that runs in and out of a capacitor when an alternating voltage is applied can light a lamp on its way to and from a plate of a capacitor.

Demonstration 55
Capacitor on a.c. with a lamp

See the demonstration sketched. There is still no ordinary electric current through the insulator between the plates of the capacitor, yet the lamp lights.



POWER TRANSMISSION

Now return to the model power line which you tried earlier with d.c. (Years 3 and 4), but this time with a.c. After trying a 12 V a.c. supply as the 'power station' ask your teacher to start with the same low voltage (12 V a.c.) and use step-up and step-down transformers.

What will be the voltage between your model power-line wires? Why must that part of the experiment be done as a demonstration by your teacher?

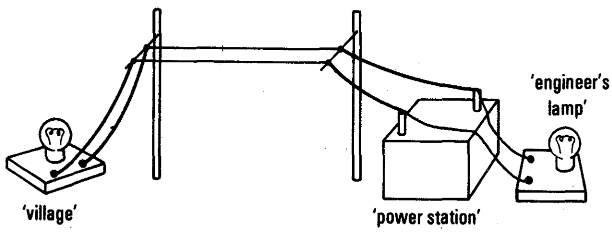
Experiment 56
Power or transmission lines

a. *Low-voltage d.c. power or transmission line (revision)* Set up the experiment sketched. Use a 12 V battery (or similar power supply) as your 'power station'. Run wires from the 'power station' to the terminals on a pylon nearby.

Run two thin wires from the pylon to a second pylon at a 'village' far away. Those wires are your model power line.

At the 'village', connect a 12 V lamp to the power line.

Switch on. How well is the 'village' lit?



b. *Low-voltage a.c. transmission line* Keep the same arrangement as in **a** but use the 12 V a.c. terminals of your transformer for the 'power station' instead of the 12 V battery. How well is the village lit? (You will not need to use an ammeter or voltmeter.)

c. *High-voltage a.c. transmission line* See this demonstration with step-up and step-down transformers. *The lamp at the 'village' is still the same low voltage one as before.*

Discuss the benefits – and the troubles – of alternating current for national and international supplies of electric power.

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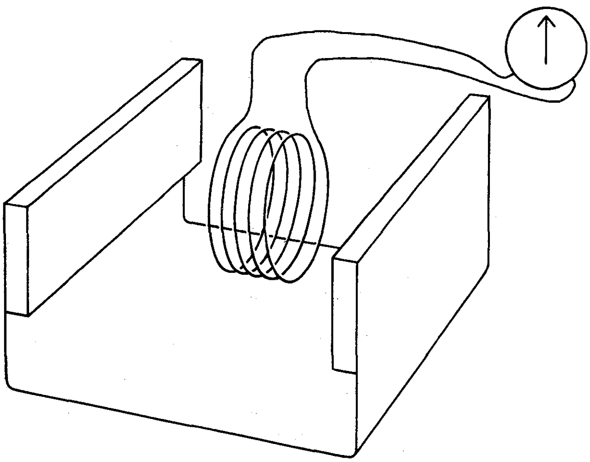
Progress Questions

Revision: dynamos

1. Suppose you wind some wire round your fingers to make a coil and join the ends to a galvanometer. Then hang the coil in a magnetic

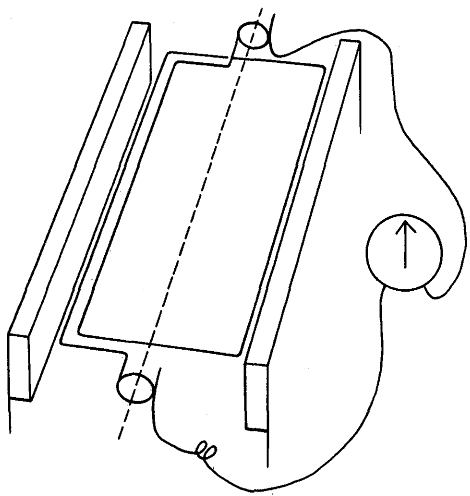


field. Now turn the coil round smartly. (The wires will tangle a bit, but try to keep the coil between the magnets.)

(*i*) What happens to the galvanometer pointer?

(*ii*) Does the pointer always move to the same side, or does it move towards each side in turn?

(*iii*) Try turning the coil a half-turn and then stopping; and then the next half-turn, and so on. What does the galvanometer needle do?



2. The sketch shows a model a.c. dynamo or generator, with only one turn of the coil, for simplicity.

a. Copy the sketch and label the *slip rings* and the *brushes*.

b. What happens if the coil is spun sharply?

c. What is the purpose of the slip rings? Why not just join the brush straight to one end of the wire which forms the coil?

3. The bicycle dynamo in your lab. can be turned by hand to transform energy to electrical energy.

a. The output is connected to a small lamp, and the handle is turned fast. What do you see happen?

b. The lamp is removed, and the output connected to a milliammeter. What does the needle of the meter do when you turn the handle:

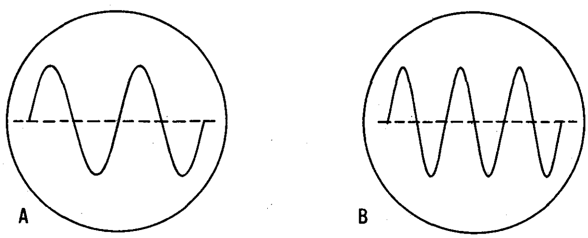
(*i*) very slowly?

(*ii*) faster and faster?

c. The traces shown in the sketches were obtained on an oscilloscope with a bicycle dynamo connected to the input terminals.

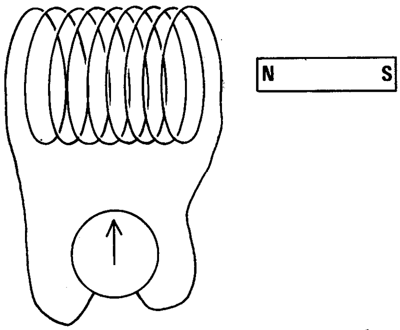
(*i*) In which of these two (A or B) was the dynamo handle being turned the faster?

(*ii*) Explain how you decide.



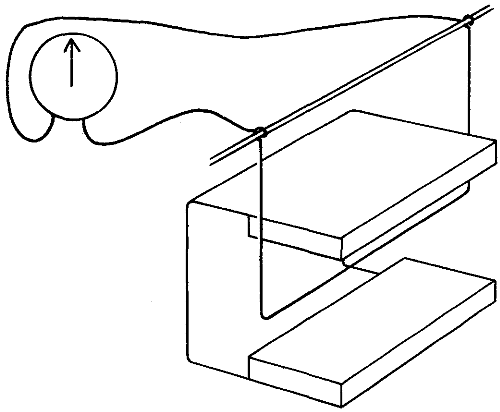
Revision: electromagnetic induction

4. Suppose you connect a coil to a galvanometer and hold a magnet nearby.



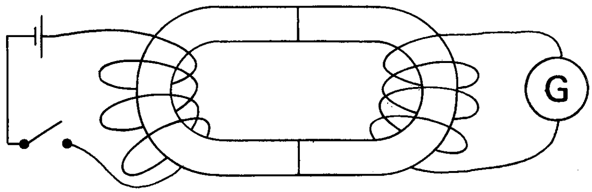
a. Say what happens as you move the magnet sharply towards the coil.
b. How could you produce the opposite result? (There are two ways.)
c. There is another way of producing the result seen in (a). What is it?
d. What happens if you leave the magnet stationary inside the coil?

5. Instead of a coil, used in the last question, you simplify the apparatus and use a straight wire



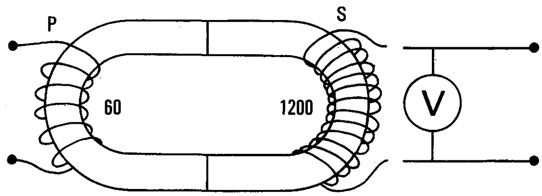
instead. You make your wire into a swing, and hang it in a magnetic field with the ends of the wire connected to a galvanometer.
(i) You move the bottom of the swing smartly to the right, then to the left. What does the galvanometer needle do?
(ii) You also try moving the wire straight up and straight down. What does the galvanometer needle do then? Does it do anything at all?

6. Look at the sketch.
a. How can you use the electromagnet to make a current flow through G?
b. How long does the current through G last?
c. How could you get a current lasting for several minutes?
d. What sort of current would it be?



Transformers

7a. If the voltage put in across the primary coil P of the transformer shown in the sketch is 12 V, what is the voltage across the secondary coil S?
b. Here you find energy in one circuit P transferred to energy in a second circuit S. Could there be more energy in S than in P, or not? Explain your answer.

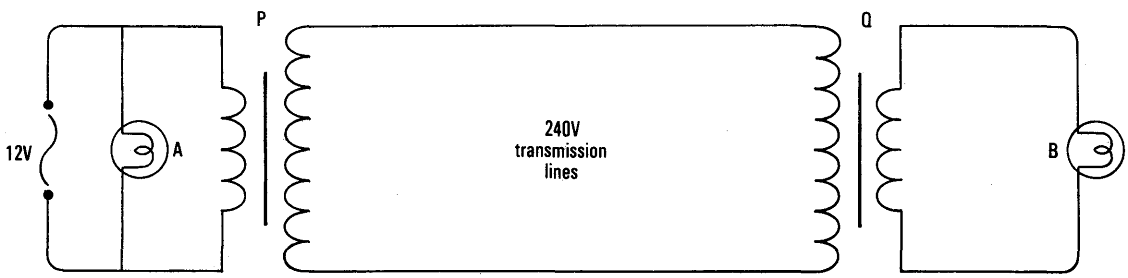


8. A transformer which takes in energy at low voltage and sends energy out at a higher voltage is called a 'step-up' transformer. One that takes in energy at a high voltage and sends energy out at a lower voltage is called a 'step-down' transformer.

Suppose the mains voltage is 240 V. Do you need a step-up or a step-down transformer to run:
a. an electric toy train which requires 30 V to drive it?
b. an X-ray set needing 10 000 V to work it?
c. an electric door-bell needing 6 V?

Power line

9. In the arrangement shown both the lamps are marked 12 V, 12 W. Transformer P turns 12 V to 240 V. Transformer Q turns 240 V to 12 V.

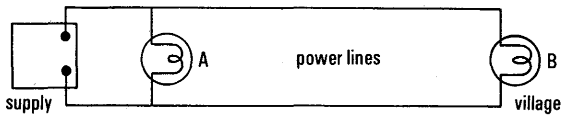


a. Copy the diagram and label the *step-up* transformer, the *step-down* transformer, the *high-voltage* part of the circuit, and the *low-voltage* part.
b. What do the markings on the lamps tell you?
c. Copy and complete:
Lamp B is [a lot dimmer than/about the same brightness as/a lot brighter than] lamp A.
Electrical energy is carried through the long thin wire at [high/low] voltage and delivered to lamp B at [high/low] voltage.
The current in the long thin wire will be [lower/higher] than the current in the lamp B.

10. The diagram below shows how electrical energy is carried from the power station to a house. Transformer L turns 240 V into 11 000 V and transformer M turns 11 000 V into 240 V.
a. Copy the diagram and label the *step-up* transformer, the *step-down* transformer, the *high-voltage* part of the circuit, and the *low-voltage* part.
b. Copy and complete:
The voltage between the power lines is much [higher/lower] than the voltage at the power station and at the houses.
The current in the power line is much [bigger/smaller] than the current supplied by the generator in the power station and the current in the village.
c. Explain as carefully as you can why all those transformers are necessary.

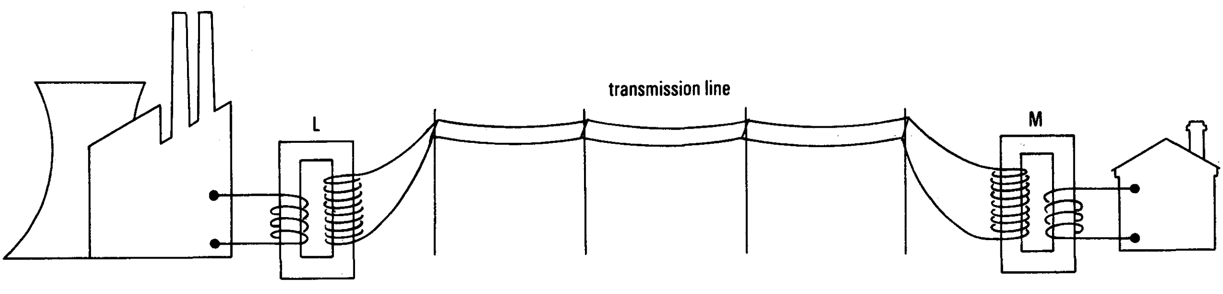
11. You have seen a model which shows how electrical energy is transmitted across country so that as little energy as possible is wasted in the transmission (or power) lines.
a. Why is it a good idea to use electricity at a reasonably low voltage like 240 V?
b. Why does the Electricity Board put transmission lines high up on pylons, out of reach?
c. The pylons are made of steel. How is it that electric charges at the very high voltage of 132 000 volts don't travel straight down the pylons to earth? Look carefully at the places where the wires are attached to the pylon.
d. What might happen to a bird which was large enough to land with each foot on a different wire?

12a. In North America the supply voltage in houses is 117 V. What might happen if a tourist from North America used an electric hair dryer marked 117 V on a 240 V supply?
b. Could you use an electric shaver marked 240 V on a 200-V supply? What difference might this make?



13. The sketch shows a model power line. It is used first with d.c. and then with a.c. Copy and complete each of the following:
a. When the supply voltage is 12 V d.c., and both lamps are marked 12 V, 24 W, lamp B is a [lot dimmer than/about as bright as/a lot brighter than] lamp A.
b. When the supply voltage is 240 V d.c., and both lamps are marked 240 V, 24 W, lamp B is [a lot dimmer than/about as bright as/a lot brighter than] lamp A.
c. When the supply voltage is 12 V a.c. and both lamps are marked 12 V, 24 W, lamp B is [a lot dimmer than/about as bright as/a lot brighter than] lamp A.

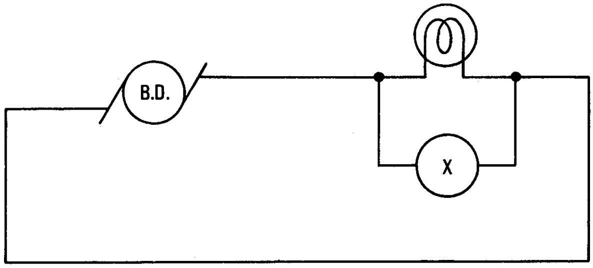
A general question
14. When you made an electric motor, you were using the discovery that with *electric current* and *magnetic field* it is possible to get *motion energy*.
a. Have you been able to show that *motion energy* with a *magnetic field* gives electrical energy?
b. Describe one way of showing this.
c. Does it make any difference whether the motion is given to the field or to the wire?



Questions

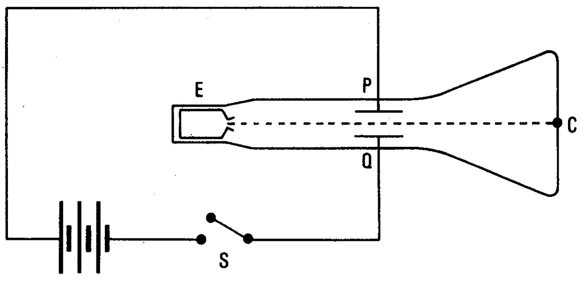
Alternating currents

15. The diagram shows a generator, such as a bicycle dynamo (B.D. in the diagram) connected to a small lamp, with a meter X across the lamp. Say what you expect to notice in each of the cases **a, b, c** below.



a. The dynamo is turned very slowly and X is a milliammeter (possibly with a resistor in series to keep the pointer deflections on the scale).
b. X is a voltmeter designed to work with direct current generators or batteries, and the dynamo is turned rapidly enough to light the lamp.
c. The dynamo lights the lamp, and X is a voltmeter intended for use with alternating current generators.

16. A narrow beam of electrons from an electron gun E (in the sketch) travels along an oscilloscope tube, past the plates P and Q, and makes a spot C at the centre of the screen.



a. Draw a sketch of the tube showing what happens when the switch S is closed.
b. Draw a second sketch showing what happens when the switch is closed after the battery has been reversed, + for −.
c. The secondary of a transformer is now used instead of the battery shown. This transformer, when joined to a 6 V lamp, lights it with the same brightness as the battery does. Draw the appearance on the screen at the end of the tube: (*i*) with the battery; (*ii*) with the transformer.

17. A time base is now applied to the oscilloscope in the sketch of Question 16. This moves the spot across the screen from left to right at a steady speed. The spot then travels back from right to left in almost no time at all.

Five experiments were done, in which the plates P and Q were either joined together or joined to a battery or to an a.c. supply.

Experiment A, P and Q joined together, no battery or a.c. supply.

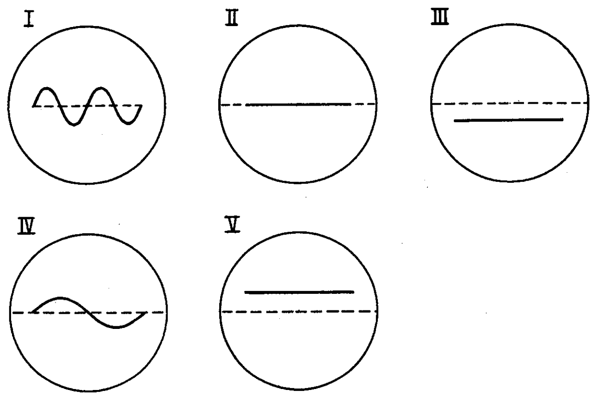
Experiment B, battery with P joined to + and Q to −.

Experiment C, battery with P joined to − and Q to +.

Experiment D, 50 Hz a.c. supply across P and Q.

Experiment E, 100 Hz a.c. supply across P and Q.

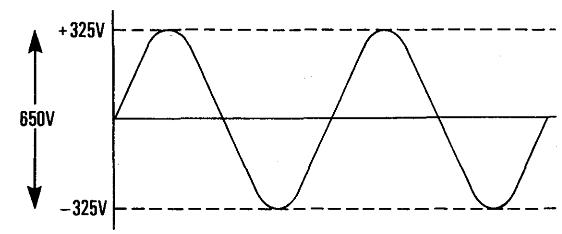
In each case a sketch of the trace was drawn (figs I to V) showing what was seen on the screen, but the sketches were not labelled with the appropriate letters.



a. Say which sketch is A, which is B, and so on.
b. What was the period of the time base; that is, how long did the spot take to cross the screen and return to start again?
c. Give the reason for your answer to (b).

Peak value, average value

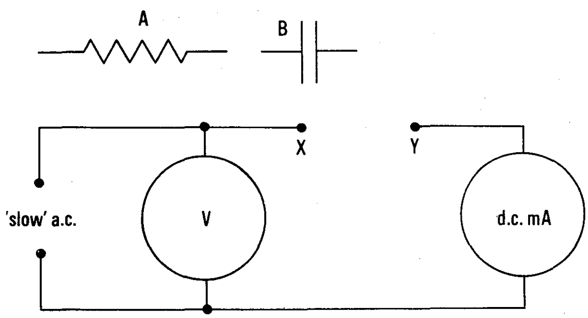
18. The electricity supply in a certain town is stated to be '230 volts a.c.'. When this supply is applied, in a suitable manner, to a cathode ray oscilloscope, the voltage is seen to swing from +325 V to −325 V as in the sketch.
a. Is the Board wrong in calling this '230 volts a.c.'?



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? What is the *average* voltage?
d. What is the r.m.s. (root-mean-square) average voltage? Choose from the three values, 0 V, 230 V, 325 V.

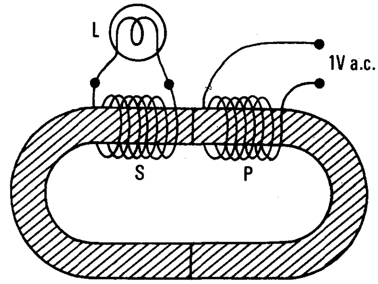
19. Look back to Question 16. Note that the 6 V battery and the a.c. transformer both light the lamp with the same brightness.
a. What is the peak voltage of the a.c.?
b. If the spot on the oscilloscope screen is displaced 1.5 cm when the battery is applied, what is the vertical range of the trace seen on the screen when the a.c. is applied?
Note: r.m.s. voltage or current is $1/\sqrt{2}$ of the peak value.

Phase differences
20. A d.c. voltmeter is connected across the output of a 'very slow a.c.' supply. A 'load' consisting of either a resistor (A) or a capacitor (B) is connected between X and Y. The current through the load is measured on a d.c. milliammeter. (Assume that the supply, the load and the meters are correctly matched so that easily observable readings can be obtained.)



a. Say for each case what you would expect to notice about the readings of the two meters.
b. If a rectifier were joined in series with the milliammeter, what would then be your answer for the resistor A?

Transformers
21. P is a primary coil of 20 turns, joined to a 1 V a.c. supply. S is a secondary of 50 turns joined to a



small lamp. The lamp lights with 'normal brightness' when 2.5 V are applied. These facts are expressed in the top line of the following table.

Number of turns on primary, P	Number of turns on secondary, S	Brightness of lamp	Secondary volts
20	50	N	2·5
50	20		
20	30		
40	100		
20	80		

Use the knowledge you have gained in experiments with a similar transformer to fill in the remaining spaces in the table. In the third column, write N if the lamp is normally bright, D for dim or not alight, and B for brighter than normal (or even 'burnt out').

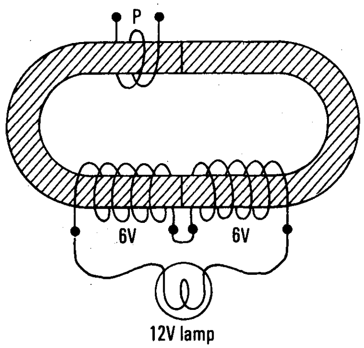
22a. Suppose your experiments show (as in Question 21) that you can get 2.5 V from the secondary of a certain transformer by applying 1 V to the primary. However this does not contradict the law of 'conservation of energy'. Why not?
b. In fact, you cannot get quite as much energy out from the secondary as you put into the primary. Suggest one *or two* ways in which energy may be wasted in the transformer, by being converted into heat.

23. A transformer has three similar secondary coils placed on the same core, with one primary. If each secondary is connected to a lamp, all three lamps light normally.
a. How do you explain this result?
b. How would you expect the primary current in this case to compare with the primary current when there is one secondary with one lamp?

24. If a transformer, like the ones you have used, has loose parts, e.g. if the clip is removed, then a hum is heard. If you start to pull the halves of the core apart, then there is a loud 'chatter'.
a. How do you explain this noise?

b. Why is the hum worse if the transformer is in contact with the bench?

25. A transformer has two secondaries, each of which is used to light a 6 V, 12 W lamp.
a. How would you use this transformer to light one 12 V, 24 W lamp?
b. In an attempt to light the 12 V lamp, a boy joined the transformer coils, wound in the manner



shown in the diagram. The lamp did not light at all. Why not?
c. Re-draw the sketch, showing the connections he should have made.

Safety?
26. A new laboratory is to be equipped with a low voltage d.c. supply and a higher voltage a.c. supply. The mains input to the laboratory is at 240 V a.c. but it was decided that this was dangerously high for a bench supply, and that 100 V would be better. A large step-down transformer was used, and the design was such that its primary required four turns of wire in its coil for each volt input.
a. How many turns were required on the primary?
b. How many on the secondary?
c. The secondary had a centre tapping, 'which' said the physics teacher, 'we will "earth" on to a metal water pipe for the sake of safety'. Why is it safer to earth the centre tapping, rather than one end or the other of the secondary coil?

Transmission or power lines
27. What is the chief advantage of alternating current over direct current for the purpose of supplying current by overhead cables across country? Suppose alternating current is generated at a power station with a voltage of about 10 000 V:
a. Why is this voltage stepped down to 240 V for use in houses?
b. Why is the 10 000 V sometimes stepped up at the power station to 132 000 V for transmission over long distances?

CHAPTER 8

Waves and theories of light

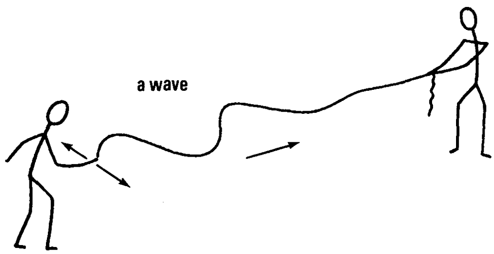
This chapter starts with some well-known waves, then asks questions about the behaviour of light. You may find that it seems to answer the questions 'What is light?', 'Is light a stream of bullets or a stream of waves?', but you will find further discoveries ahead, so you should read this chapter with an open mind.

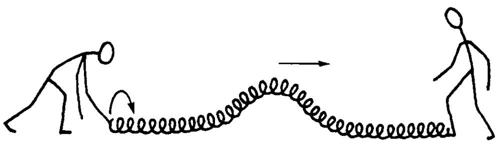
EXPERIMENTS FOR CATCHING UP

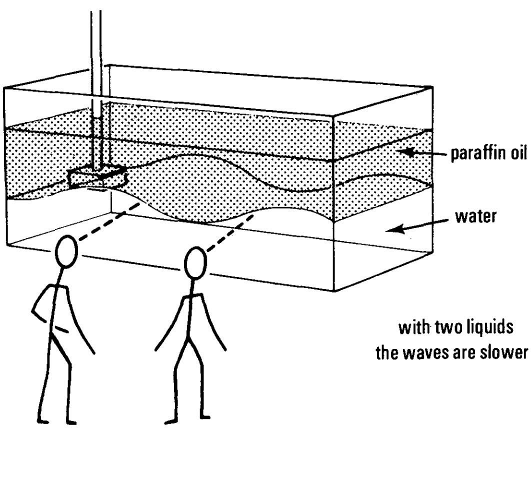
If you missed demonstrations of waves in earlier Years you may see some now.

Demonstration 57
Examples of wave motion

Waves on a rope; waves on a slinky; waves on water.



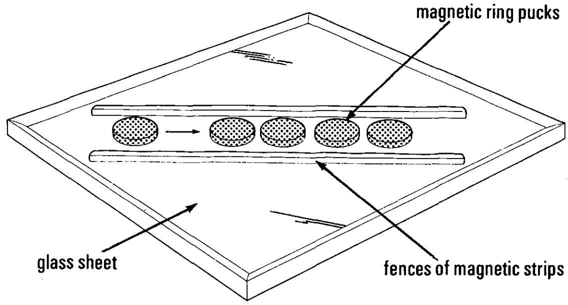


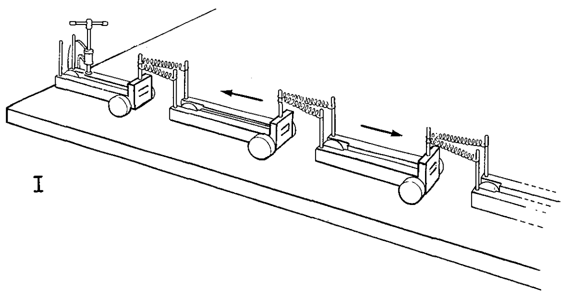


with two liquids
the waves are slower

Demonstration 58
New examples of wave motion

See waves in a line of pucks and waves in trolleys connected by springs.





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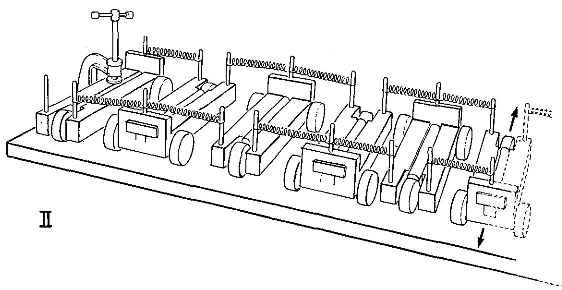


II

WAVES AND ATOM MODELS

Modern atom models are difficult to think about. Atoms and their details are far too small for us ever to draw pictures of them as if we could see them. Instead, we invent models which help us to talk about atoms, and even to make some calculations about their behaviour. These models are the way we describe and remember and use our present knowledge; and they do enable us to make predictions.

Modern 'thinking models' of atoms are described by wave patterns. We certainly do not believe the waves are really there inside an atom; but we do find that thinking with wave patterns in mind helps us to understand the behaviour of atoms as we find it in experiments.

Some of the wave patterns that we use in 'thinking models' are not waves that travel along but 'standing-wave' patterns which do not travel but have strong vibrations at some places, with quiet places in between.

You can see such standing waves if you waggle a rope at the right frequency.

STANDING WAVES

It is easy to build up a motion that *looks* like a wave but does not travel along. Then you have a vibration pattern which we call a standing wave. See some examples.

Demonstration 59
Standing waves

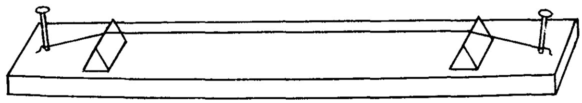
Anchor a taut tope at each end. Near one end use a hand to move the rope up and down. That will start waves along the rope, but if you continue to make waves and move your hand faster and faster, you will suddenly find the rope settling into a standing wave pattern. Then the pattern follows the stages shown in the sketch.

'Loops' and 'nodes' There are loops where there is much motion, and there are places of no motion, which we call nodes.

Other examples: also see standing waves on a slinky and in water in a tank.

Demonstration 60
Music from standing waves: vibrating string

Stretch a taut wire over a wooden sounding board. Pluck it near one end and you will hear a mixture of musical notes. You will see the wire vibrating with a standing wave of one loop, the middle moving up and down a lot while the ends are fixed.

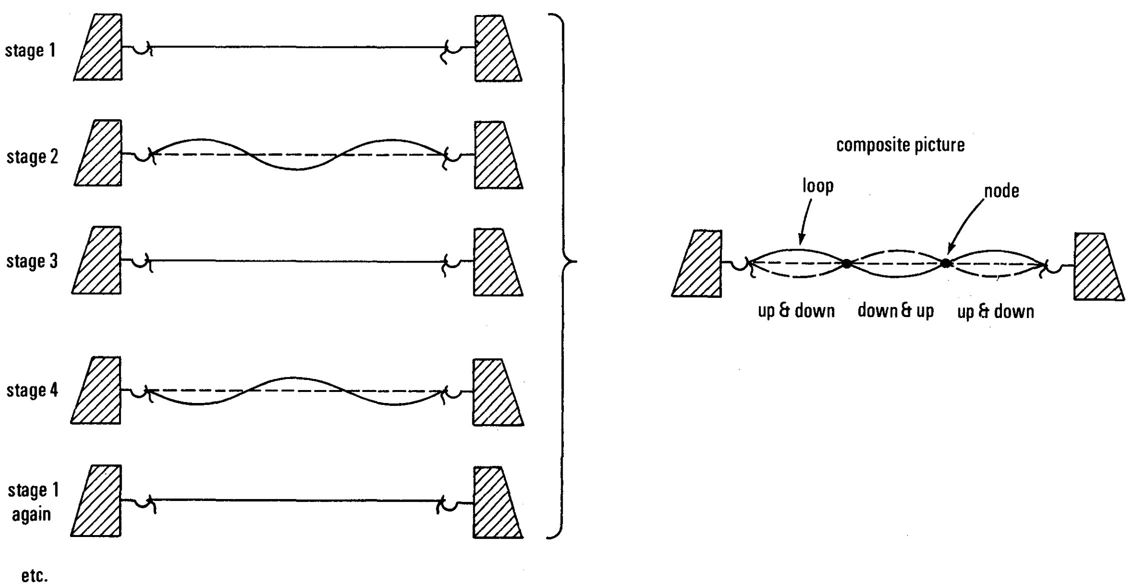


Just when you pluck the wire, also touch its mid point very gently with a finger. That will encourage it to vibrate in two loops, one loop moving up and down rapidly while the other loop moves down and up. What musical note do you now hear?

How could you encourage the wire to vibrate in three loops? Four loops?

In that way you could make higher musical notes, each of them produced by a standing wave pattern of several loops – these are called *harmonics*.

STANDING WAVES ON A STRING



Such a series of definite 'modes of vibration' plays an important part in our ideas concerning electrons in modern 'thinking models' for atoms.

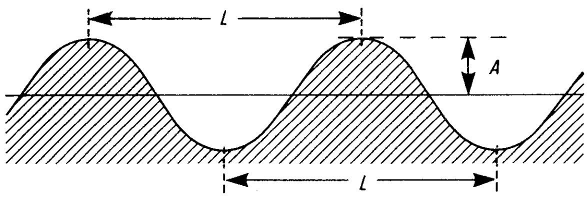
MEASUREMENTS OF WAVES

A wave is a moving pattern, often carrying momentum and energy without carrying the material or medium bodily along with it.

Think of a hump travelling along a taut rope.

Think of a continuous wave of humps and troughs following each other across a ripple tank or sweeping into a bay at the seaside.

Here is a snapshot of a continuous wave, such as you might take with a camera and flash gun.



The pattern repeats (it is a continuous wave) and we call the repeat-distance the *wavelength*.

The WAVELENGTH (which we shall call L in this book) is the distance from one crest to the next crest or from one trough to the next trough of the wave.

The AMPLITUDE is the maximum distance up or down (or out or in) from the calm position. It is the distance A in the sketch.

The FREQUENCY is an important property. In a ripple tank, how many times a second does the vibrating bar dip in the water? How many complete wavelengths does it send out in each second? Both of these are the frequency, f, of the wave. For waves on rope or water, any piece of material makes f complete oscillations (both up and down) in each second as the wave goes by. FREQUENCY is measured in *hertz* (Hz).

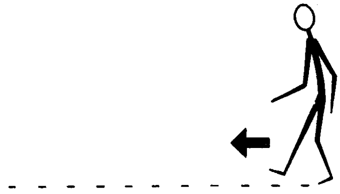
WAVE SPEED or VELOCITY is the speed at which the pattern travels along; it is the speed of a crest or a trough.

There is a relationship between WAVE SPEED, v, and WAVELENGTH, L, and FREQUENCY, f. It is $v = f \times L$.

You can arrive at that by arguing about the progress of a wave.

The 'wave formula'

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



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

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

His speed = [no. of strides per minute] × [stride]
or $v = fL$

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

WAVE SPEED = [NO. OF WAVELENGTHS TURNED OUT PER SECOND] × [WAVELENGTH]
WAVE SPEED = [FREQUENCY] × [WAVELENGTH]
$v = fL$

Some common frequencies

The mains alternating voltage has a frequency of 50 Hz.

The notes of the piano range from about 20 Hz to about 4000 Hz.

Many stopwatches tick at 2.5 Hz.

BBC broadcasts range from thousands of hertz (kilohertz) to millions of hertz (megahertz).

The frequency of green light is about 600 000 000 000 000 Hz (6×10^{14} Hz).

Standing waves Look at the pattern of loops and nodes that you saw demonstrated. Although the pattern does not travel along, a snapshot of it would show a wavy shape (at most stages of the motion). So we speak of the WAVELENGTH of a standing wave, each loop being half a wavelength. Each loop is also half a wavelength of a *travelling wave*. If you measure the frequency of a standing wave pattern and measure the length of a loop from node to node, you can calculate the speed of the travelling waves – without seeing them! In this case v = frequency × (twice the length of a loop).

THEORIES OF LIGHT

Two thinking models of light have been argued about for many years. Three hundred years ago Isaac Newton favoured the idea that light is a stream of small bullets. Some other scientists agreed with him but some put a different view: that light is a stream of waves, like ripples in a ripple tank (but the stuff that moves to and fro cannot be seen or touched like water).

Which view or model is preferable?

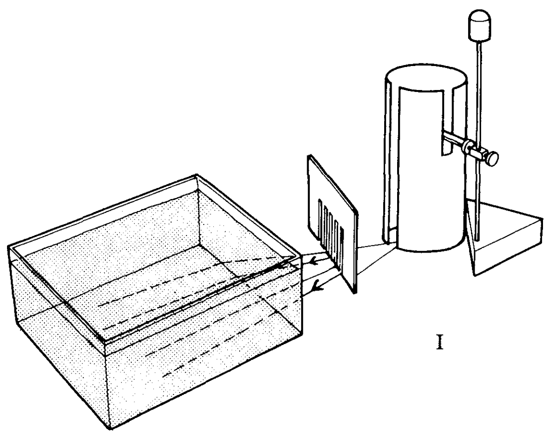
Bullets? Light travels in *straight lines* and (seems to) cast sharp shadows. Do very fast bullets travel (almost) straight?

Rays of light are *reflected*, with a simple rule of angles. Do bullets 'obey' that rule?

Experiment 61
'Reflection' of a particle

Does a ball thrown at the wall bounce with angles that fit the reflection rule? Try some experiments.

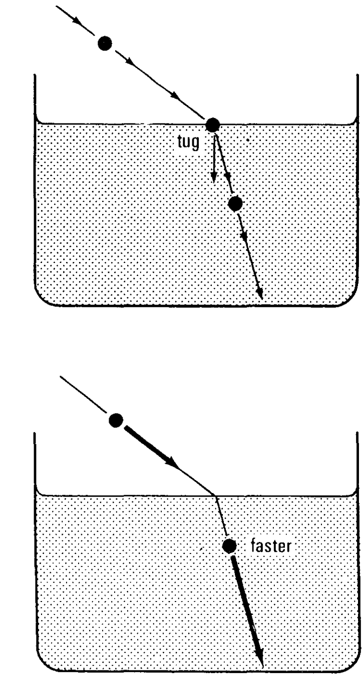
Bullets? Rays of light are *refracted* (bent) when they enter water or glass from air. If light is a stream of bullets, what must happen to a bullet of light when it enters water from air, and its path is bent? Diagram I shows a Year 3 experiment.



I

In diagram II the ray is bent *downward* as it enters water. The light-bullet must be pulled downward by some force as it enters water – just a sudden tug made by the water. But what *must* happen to the bullet's speed if it is tugged like that? (A real bullet fired into water would go straight on.

II

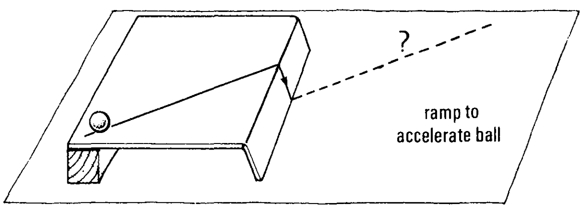


Also it would begin to slow down at once and finally come to a stop. A light-bullet would have to behave differently.)

Try a model with a rolling ball, with gravity allowed to give it a successful tug.

Experiment 62
Particle model of refraction

Set up a small level plate to represent 'air', with a short downhill slope to the table. Gravity will make its successful tug on that slope. Arrange a launching ramp for the ball on the upper plate. Let the ball roll along a slanting path. Watch what happens to its path, and its speed.

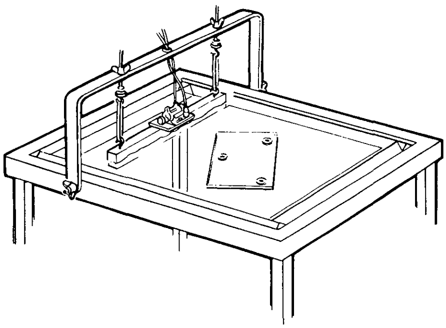


This model suggests that light bullets (*if* that is what light is) must move faster in water (or glass) than in air.

Waves? Suppose, instead, light is a stream of waves. Did you see water ripples being 'refracted' when they travel from deep water to much shallower water, with a change of speed at the boundary? If not, you should try it now.

Experiment 63
Refraction of ripples

Ripples travel at a different speed in shallower water. But they also die away soon, because their energy is taken away by water friction. However, if you level your tank and adjust things very carefully you should be able to see what happens.



To make a patch of shallow water, put a sheet of glass in the tank. (Put some small bits of metal under the glass so that you can take it out again easily.) Pour in water until it *just* covers the glass. Then take out a little water, leaving a *very* shallow layer of water above the glass. (The tank must be very carefully levelled for this.)

Lower the vibrating bar until it just touches the water. Run the motor *very* slowly.

(i) Arrange the glass sheet so that the ripples meet its edge head-on. *What happens to their speed? What happens to their wavelength (distance from crest to crest)?*

(ii) Turn the glass so that the waves will meet it in a slanting direction. Now watch carefully what happens to them.

Make a sketch of what you see, showing how the *direction* of the waves changes when they meet the shallower water – and, as you know from *(i)*, they travel slower. Add to your sketch a 'ray' perpendicular to the waves, to show their *directions of travel.*

What happens to the speed of the ripples at the boundary between deep and shallow water?

What happens to the direction of the guiding rays when ripples strike the boundary at a slant?

By watching real ripples, decide whether light, *if it is a stream of waves*, must travel faster in water (or glass) than in air, or slower.

Decision? *Can you think of a 'crucial experiment' which would help you to make a decision between these two 'thinking models' for light?* Such an experiment has been done. Ask your teacher about it.

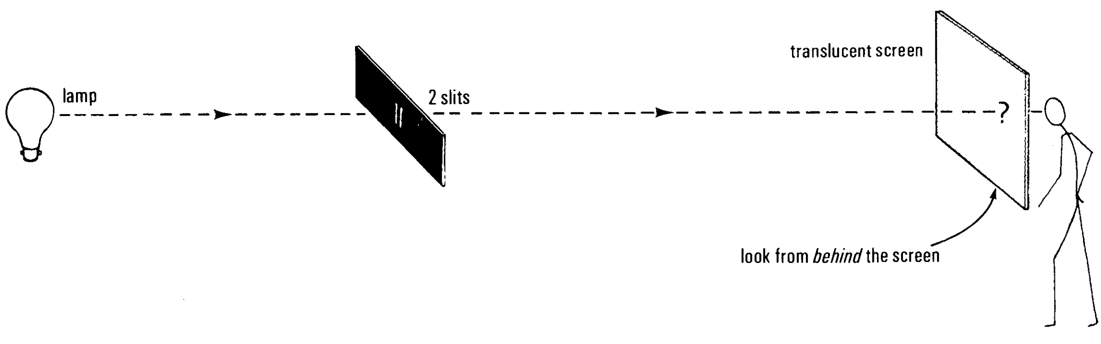
Experiment 64
Light from a pair of slits: Young's fringes

The clearest witness to give evidence in the dispute about light is this experiment.

Let light pass through two narrow slits and go on to a screen far away. (This is rather like the ripple-tank experiment with two sources.) The experiment is for you to find out what you can see on the screen.

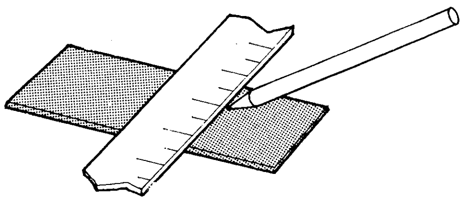
Use a lamp with a straight filament as the source of light, near one end of the room. Make sure its filament is vertical.

Ask for a small sheet of glass coated with black paint. You can scratch two slits in the paint very close together. Then, if light shines on the black sheet, two lots of light will get through the slits and make two patches of illumination on a screen at the

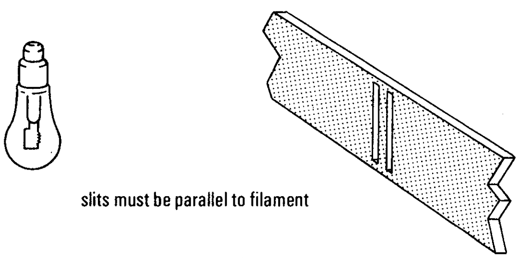


other end of the room. If the slits are thin and close together the light from each slit will spread and the two patches will overlap. What will you see there?

To make the slits, hold a ruler across the glass sheet and scratch the black paint away by dragging a blunt pin or a fine ball point pen along the ruler.



To make the second slit, hold the ruler there, but tilt the pin or pen and drag it along again. The slits need to be *very* close, about $\frac{1}{2}$ millimetre apart, or even closer. Make several pairs of slits on one sheet of glass. Then ask your teacher to look at them and choose a pair that will behave well.



Place the slits in a clip, one or two metres from your lamp. Make sure the slits are vertical, parallel to the lamp filament.

When the room is dark, hold a piece of paper just beyond your pair of slits and see the light that comes streaming through and spreading out a little.

Then go as far away as possible – it must be several metres – and hold a translucent screen of greaseproof paper there. Place the paper to catch the light that comes through the pair of slits.

Go round *BEHIND* the screen and look at the bright patch where the two lots of light overlap.

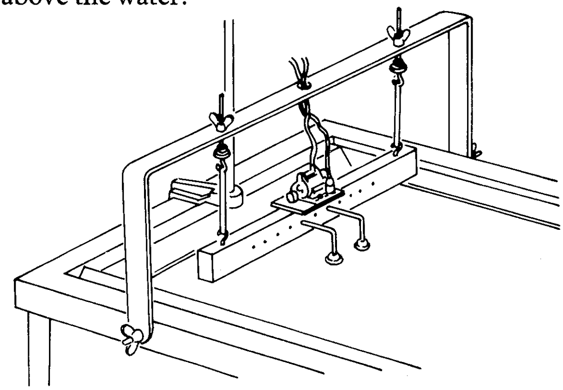
What do you see? What do you think that tells you about light?

Could two streams of bullets make such a pattern where they arrive and mix?

Could two streams of waves make such a pattern? You can answer this question by an experiment with water ripples.

Experiment 65
Ripples from a pair of sources: Young's fringes

Set up your ripple tank with the vibrating bar just above the water.



Install two dippers about 3 cm apart on the vibrating bar. Run the motor as slowly as possible (about 10 revs/second). Look at the pattern in the shadow of the tank. Can you see some curved lines where there seems to be no motion, and other lines where there is much motion? All those lines are due to two lots of ripples adding their effects.

Make the motor run faster and use a hand stroboscope to make the pattern visible all the way out across the tank.

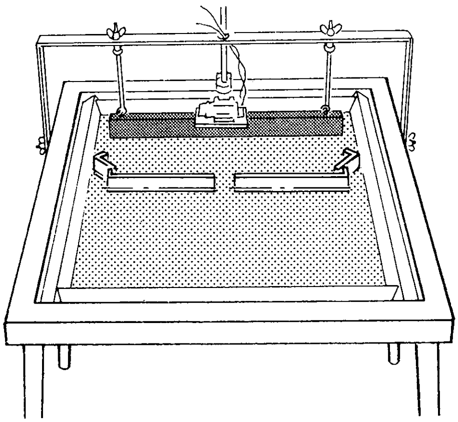
If you like, try changing the distance between the dippers.

At *all* places the two lots of waves *add* their effects. But, where a crest of one wave arrives just when a trough of the other wave arrives, the two heights add to zero or 'sea-level'. And where crest and crest arrive at the same instant, they add to double crest. This has long ago been given the very poor name 'interference of waves'. Waves do *not* upset each other or frighten each other! They just add. But the name is well established so we shall use it. Its meaning is a little clearer when we speak of *constructive interference* and *destructive interference*.

While ripple tanks are in use, you should also look at ripples passing through a gap in a barrier.

Experiment 66
Straight ripples pass through a gap: diffraction

Set up your ripple tank. Adjust the vibrating bar so that it is just in the water. Then it will make straight waves.



Build a wall of barriers about 5 cm from the beam. Leave a 10 cm gap for waves to pass through. Run the motor slowly and watch the waves that go through.

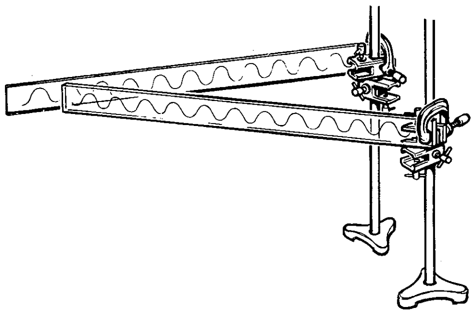
Run the motor fast and look at the pattern with a stroboscope.

Then narrow the gap to about 1 cm. What do the waves beyond the barrier look like now?

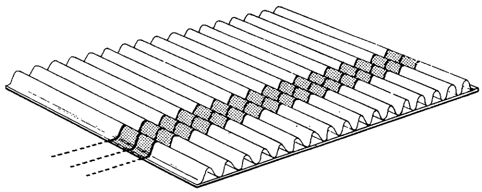
Try a still narrower gap.

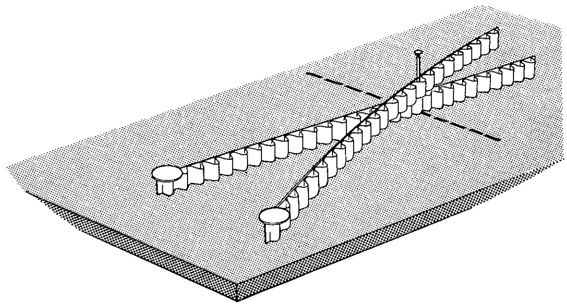
Demonstration 67
Plastic wave model for interference

You may see the demonstration sketched, a teaching-model made of two strips of plastic with a wavy pattern on each. These represent two



streams of waves. When you have seen that, try making your own model with strips cut from corrugated cardboard.





Straight rays of light? If light always travels in straight lines (in air), shadows cast by a tiny source of light must be sharp. Are they always sharp? Take turns in looking at an important test.

Class viewing 68
Sharp shadows

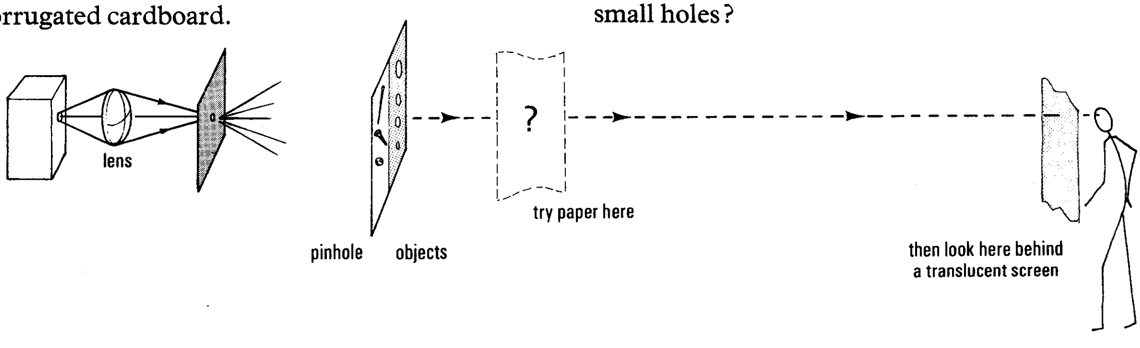
See the shadows of a plate with holes in it and of various other objects, cast by light from a very small bright source. If light is a stream of bullets, the plate with holes should cast a dark shadow with round patches of light for the holes. With a tiny point as the source of light the edges of all shadows should be sharp, if light travels in straight lines.

Look closely at the metal plate with holes and any other objects held beside it in the light. Hold a sheet of paper *just beyond* the objects and see the sharp shadows.

Then go *much* further away and catch the shadow on paper.

The pattern is probably too faint to see clearly on a wall at that distance. Therefore, let it fall on a screen of *translucent* paper and *look at that from behind.*

What has the light done that passed through small holes?



See the strangest sight of all; the shadow of a small ball or disk. Could bullets pass by a ball, or bounce off it, and make what you see here?

For comparison with the ripples passing through a gap in a barrier, see what the light does when it passes through a slit in a plate; first a narrow slit, then a very narrow slit, then an extremely narrow slit.

Note that there are no lenses in the arrangement – except the lens of your eye. You are seeing the unaided behaviour of light.

Light bends round corners You have seen light bending to make shadows which are not sharp. Water ripples bend round the edges of a barrier when they pass through a gap. They bend a lot if the gap is narrower than a wavelength. But light seems to bend less easily, on a much smaller scale. In fact, at first sight shadows are often quite sharp. What does that suggest about light?

Young's fringes You have seen two beams of light (from the same source) overlap and add their effects.

LIGHT + LIGHT = LIGHT in some places
LIGHT + LIGHT = darkness in some places

What does that suggest about light?

Even though the two slits are close together the fringes are crowded into a small pattern. What does that suggest about light?

However, you can never be quite sure of a conclusion that you get from indirect evidence. But you can say, '*It seems very likely that light . . .*', and then you can certainly say '*IF* light . . ., then its wavelength must be very small*'. With that *if* just at the edge of your mind, estimate the wavelength of light by measuring Young's fringes.

Experiment 69
Young's fringes: estimate of wavelength

Obtain a good clear set of Young's fringes as you did before. (If you kept a good pair of slits from your previous experiment, use them again. Otherwise make several new pairs and choose the best – you will find that it is a much quicker job in this second attempt.)

Measure the spacing of the fringes on your translucent screen. Go round behind the screen with a scrap of paper. Hold the paper against the screen and make pencil marks on it at each bright fringe. Then carry the paper out into daylight, and measure the distance between extreme marks. Divide to find the distance from one fringe to the next.

If you like, compare your estimate with the estimates of your partners and take an average.

Measure the distance from your pair of slits to your translucent screen. Since your fringe measurement is likely to be fairly rough, it would be unscientific to measure the large distance very accurately – measuring to the nearest few centimetres is good enough.

Measure the distance between your two slits, centre to centre. This is the most difficult measurement of all. But remember that you are going to arrive at something far smaller still, the wavelength of light. So any rough measurement is still very valuable.

You may be able to compare your double slit with a millimetre scale under a magnifying glass or even under a microscope. Or you may be able to hold it in a slide projector beside a transparent scale. Measure it *somehow* even if you are partly measuring, partly guessing.

The calculation

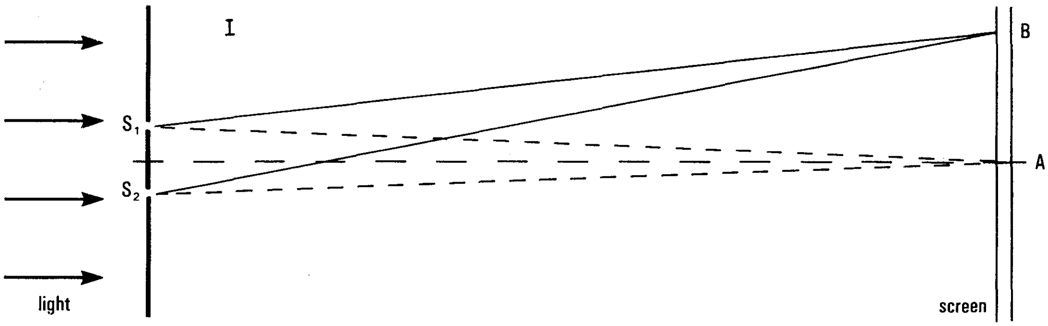
Look at sketch I. This shows the arrangement but it is greatly distorted: it makes the distance between the slits much too large compared with their distance from the screen. For the central bright fringe at A, the wave contributions from the slits S_1 and S_2 arrive in step. The paths are equal. So $S_1A = S_2A$.

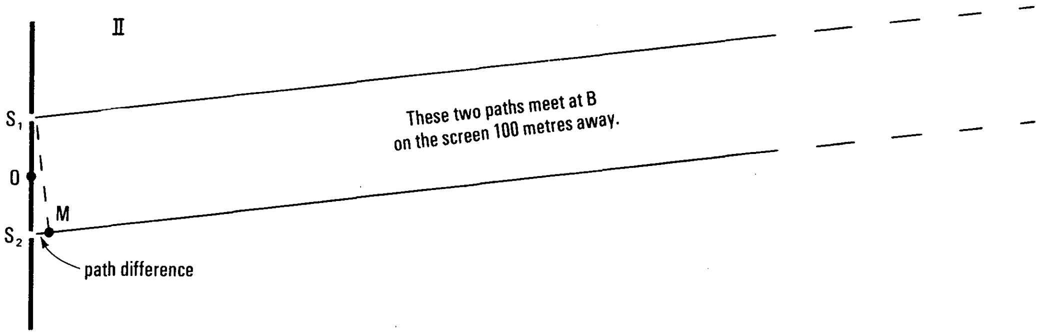
For the next bright fringe at B the wave contributions again arrive in step, but one path is a whole wavelength greater than the other: $S_2B = S_1B + L$ or $S_2B - S_1B = L$, one wavelength.

Now look at sketch II which is *greatly magnified* but *not distorted*. Imagine the two wave paths continuing out to the screen and meeting there at B. (For a $\frac{1}{2}$ mm distance between slits magnified to 1.5 cm in sketch II, *the screen would have to be shown 100 metres or more away!* Can you see from that how very near to parallel the wave paths must be?)

On sketch II S_1M cuts off the extra path from S_2. We have drawn S_1M practically perpendicular

* 'If' is a very important word in science because it tells us what is being taken for granted, whether it is a wild hunch or almost a certainty.

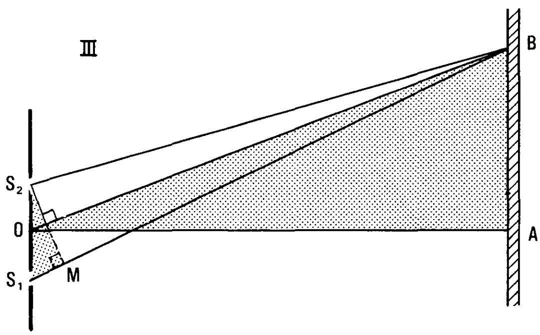




to both wave paths since there is so little to choose between their directions.

Then S_2M is the extra wave path for the light from S_2. For the first bright fringe out from the central one, that extra path must be one wavelength. $\therefore S_2M = L$.

Sketch III attempts the impossible, to maintain the magnification and yet show the screen on the paper! In sketch III, the triangles S_1MS_2 and OAB are practically the same shape ('similar') because OB from the mid-point between the slits is drawn accurately perpendicular to S_1M, and therefore the angle S_2MS_1 is *almost* 90°. In the large triangle OAB the angle OAB is of course *exactly* 90°.



Use y for the fringe spacing, AB.
Use d for the distance between the slits.
Use D for the distance OB from slits to screen.

Then, in those two triangles:

$$\frac{L}{d} = \frac{\text{short side, } y}{\text{longest side, } D}$$

$$\therefore \text{wavelength } L = \frac{y}{D} \times d$$

Draw your own sketch and label your measurements on it. Then calculate the wavelength of light.

Your result will be an average for the many colours of white light, but since there is plenty of green light in it, and green is the colour to which your eyes are most sensitive, you might call it the value for green light. (If you prefer, start again, using a green filter; then indeed you will be measuring the wavelength of green light.)

This is not a precise measurement. It is a case of 'desperate measures in desperate circumstances', where even a rough estimate is very valuable because it tells you which county you are in. It tells you how very small the wavelength of light is.

Quite apart from your own success, this measurement is a remarkable achievement – to find the tiny wavelength of light by measuring much larger distances. Even the distance between the two slits is enormously bigger than the wavelength, as you now see.

That is something we have to do with tiny atoms: try to weigh and measure them by making larger measurements and using ingenious arguments.

In modern astronomy it is the other way round; we estimate huge distances and sizes by small measurements, again with ingenious arguments.

Interference patterns made by thin films

Instead of using streams of light from two slits, you can use streams of light reflected by two mirrors very close together, one behind the other.

The light comes from one original source. Reflection by a mirror makes the reflected light seem to come from the image of that source. The two mirrors make two images, close together, which serve as (virtual) sources.

The mirrors must not be silvered ones like an ordinary looking glass, because then no light would get through to the second one to be reflected. The mirrors are the front and back surfaces of a piece of soap bubble, or of a piece of very thin glass sheet, or of two glass plates holding an air sandwich.

With the help of the model, you saw how the bands of bright and dark (Young's fringes) are made by differences of *path length* from the slits to the screen. In this case they are made by differences of *film thickness* which lead to differences of path length.

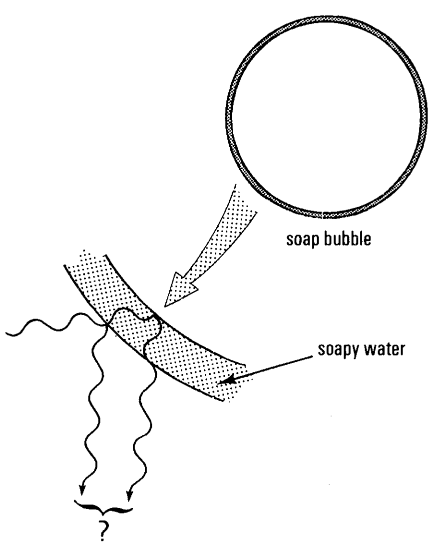
The light has to travel further for the reflection at the back of the film. Since it travels through the film and back, its extra path is twice the thickness of the film. So you see the bands of dark and light or bands of different colours according to the thickness of the film.

Demonstration 70
Soap film

If you blow a soap bubble you see a fine display of colours as it drains to a thinner film of soapy water. It becomes thinner and thinner at the top and remains thick at the bottom.

It is easier to see the bands of colour if you make a *flat* soap bubble by dipping a ring of wire in soapy water. A vertical flat film drains to a wedge shape in thickness.

Why are there colours? Look at a soap bubble (or flat film) through a red filter then a green one in quick succession. *What do you guess from that?*

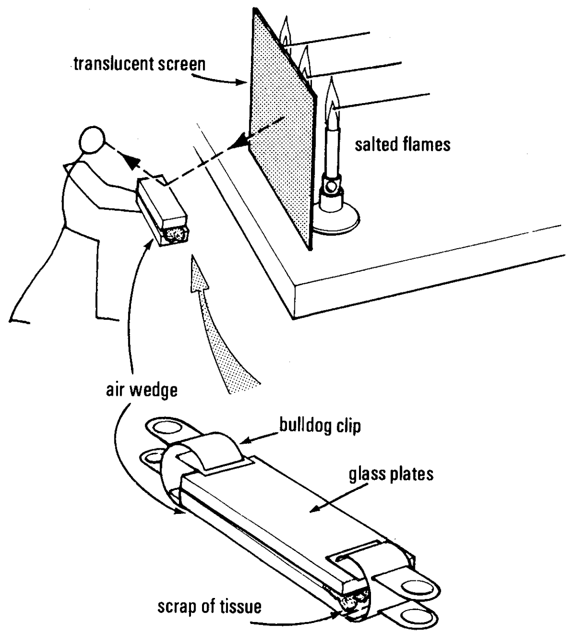


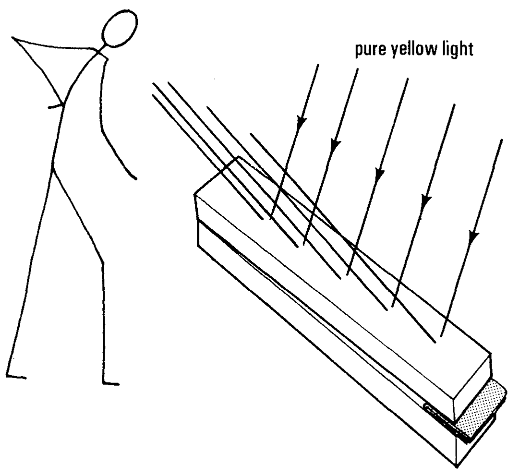
Experiment 71
A thin film of air

Make a sandwich of two plates of glass with a very thin layer of air between them. That layer of air can take the place of a soap film.

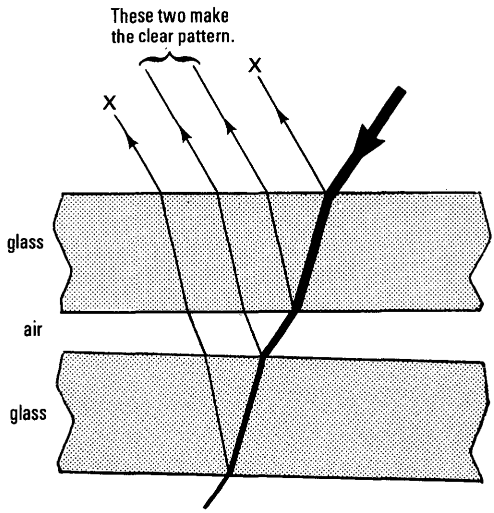
Make the layer of air wedge-shaped by propping the plates apart at one end with a scrap of thin tissue. Clamp the plates together with a bulldog clip at each end, so that the thickness of the air layer is zero at one end and one tissue thickness at the other end.

Hold the sandwich in front of a wide source of pure yellow light; and look at the source's image reflected by the sandwich.





There are four streams of reflected light: two from the inner faces of the sandwich, where glass meets the thin wedge of air; and two from the outer surfaces of the glass plates. The two streams from the inner surfaces have a small path difference (about twice the thickness of the air wedge at each place); and you will see interference bands of bright yellow and black.



(The streams reflected from the outer surfaces of the glass plates have too great a path difference to show an interference pattern noticeably.)

Suppose you counted the stripes all the way from one end of the sandwich to the other. If you knew the wavelength of yellow light (about 600×10^{-9} m), what could you then estimate?

In fact, counting interference fringes like these is the basis of the modern way of specifying the international standard metre.

Home Experiment 72
Air wedge

If you live near a street with sodium lamps, try looking at a sandwich made with any small, flat plates of glass.

The fringes may be far from straight, but they will be visible by reflection if the plates are held firmly together with thumbs and fingers.

Other examples

When you receive radio on VHF, the aerial may pick up two signals, one direct from the broadcasting station, the other a little late after reflection by some wall near by. These may combine to produce a strong radio signal ('bright fringe') which will in turn make a loud sound, or a weak radio signal ('dark fringe') and a soft sound. Move your radio to a different place in the room and you may move from 'dark' to 'bright' or vice versa.

If you are watching television on a receiver with an indoor aerial which stands on top of the set, you may find that the picture suffers from interference which can be caused by you moving about near the receiver. The effect is similar to the brightening and darkening seen in Young's fringes.

When an aircraft flies overhead, waves reflected from it may 'interfere' with direct waves from a broadcasting station and you may see this effect spoiling your TV picture.

Radar A radar picture is different. A short pulse of radio waves, of very small wavelength, is sent out from the ground. An aircraft far away reflects a little of that pulse, but the reflected waves arrive back at the ground after the original pulse has ended so there is no interference pattern. But it makes a very useful signal: a blip on an oscilloscope screen.

Depth sounders on ships use sound waves in much the same way as radar uses electromagnetic pulses.

Moving interference patterns In the examples mentioned so far, fringes are made by two streams of waves of the same frequency, the same wavelength – the same pitch if they are sound waves, the same colour if they are light.

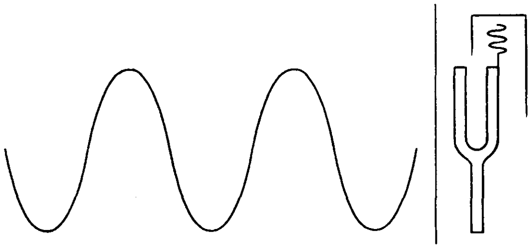
If one stream has slightly different frequency and wavelength from the other, the fringe pattern will move; it will sweep across the observer. That is how you hear 'beats' when two musical instruments play notes that are almost, but not quite, the same.

....

Progress Questions

A wave shape

1. The shape of the trace shown in the sketch is produced by drawing a prong of a vibrating tuning fork across a smoky glass plate. This shape is called a 'sine wave'. Mention several other ways you have seen of producing a trace like this.



Ripples

2. Imagine you have set up a ripple tank. A small motor makes a small dipper bob up and down in the water.

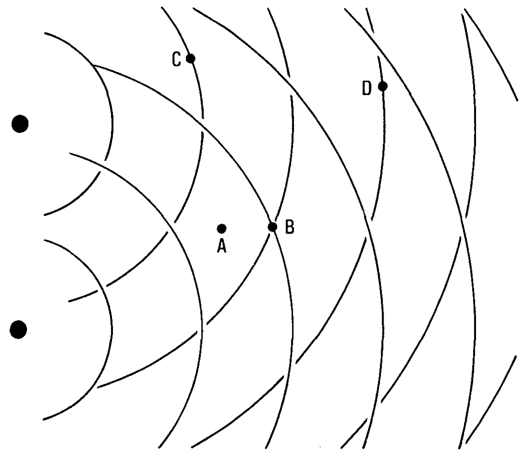
a. Sketch the wave you see when the motor is set going.

b. The dipper is set vibrating faster – that is higher frequency. Sketch the new wave pattern you see.

c. Say, in words, how your sketch for (b) differs from your sketch for (a).

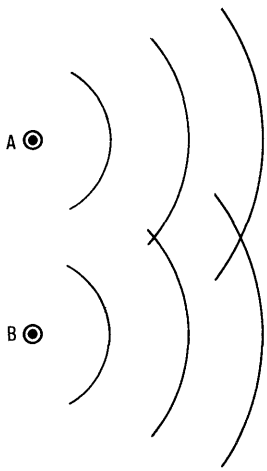
Ripples meeting

3. Suppose the vibrating bar is arranged with two dippers touching the water. The sketch shows successive crests.



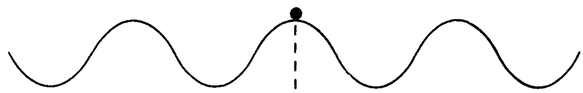
a. What shape of wave does each dipper make?

b. Say what is happening at each of the places A, B, C, D.



Adding two waves together

4. A wave in a ripple tank makes a scrap of floating sawdust go up and down as the wave goes past.



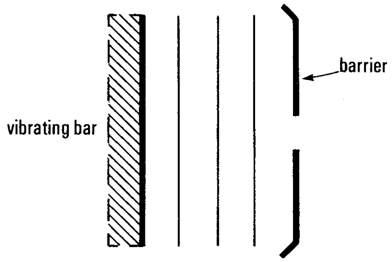
Suppose there are two waves in the ripple tank, starting perhaps from two dippers, or two narrow gaps in a wall. Will the sawdust go up and down higher and lower than before? What else could happen to it?

5. Two dippers, A and B, are both making circular ripples of wavelength 1 cm.

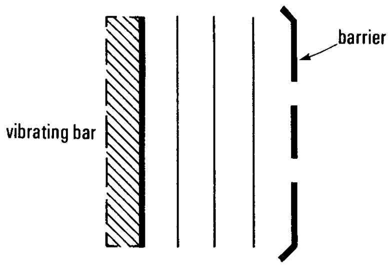
a. Measure from A to B and from B to P, and also from A to P. When the waves meet at P, will they both make the water go up and down *together* or will one wave go down when the other goes up?

b. Also measure from A to Q and from B to Q. Will both waves go up together at Q, or will one go up when the other goes down?
c. Copy the diagram and mark in another place where the same thing happens as at Q.
d. Now think again about P. Will you get extra big waves at P, or will the water be calm there?
e. What about Q?

Diffraction and interference
6. Waves are made in a ripple tank with a straight vibrating bar. In front of the bar is a barrier with an open gap in it. Copy the sketch and draw in the waves to the right of the barrier.



7. The vibrating bar is the same as in Question 6, but the barrier has *two* small gaps in it.



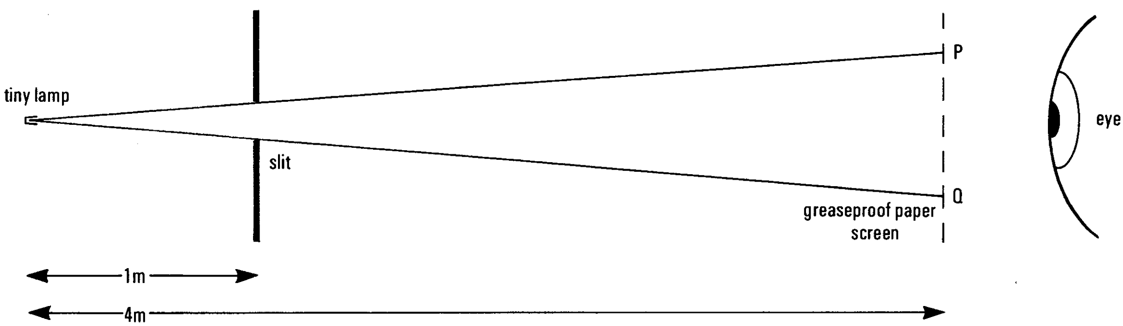
a. Sketch the pattern beyond the barrier.
b. Label some of the interesting places in your drawing and explain what is happening at each one.

Behaviour of light
8a. When the slit shown is $\frac{1}{4}$ mm wide, PQ is 1 mm. When the slit is 1 cm wide, what will straight rays make PQ? (Simple geometry here!)

When the lamp is on, you get a patch of light on the screen. For a 1 cm slit, the patch is 4 cm wide. For a $\frac{3}{4}$ mm slit, the patch is a little wider than 1 mm. What does that suggest?
b. For each slit, copy the diagram below, and mark in the size of the patch of light. (Think about whether it is bigger or smaller or the same as PQ.) You could try marking in the path of the light between slit and screen, too.
c. In which case does the light stream straight through the slit in straight lines?
d. In which case does the light spread out after it goes through the slit?
e. Look back at Question 6. When do water waves spread out most – when they go through a narrow slit, or when they go through a wide one?
f. Copy and complete:
Water waves spread out a lot more than you might expect when they go through a [wide/narrow] slit. Water waves go straight through a [wide/narrow] slit, without spreading much. Light spreads out when it goes through a [wide/narrow] slit. Light goes straight through a [wide/narrow] slit without noticeable spreading.

9. Both light and water waves spread out when they reach a narrow gap. (That is, a slit which is narrow compared with the wavelength of the waves.)
a. What is the effect on water ripples of making the slit narrower still? Do the waves spread out more or less?
b. Which leads to the greater spreading of light outside straight line behaviour, $\frac{1}{4}$ mm slit or a wider slit?

Theories for light
10. Where two water waves meet and go up and down together, in step, you get extra big waves.



But where two water waves meet out of step, so that one goes up when the other goes down, you get *no* wave, and the water is still. Now think about the *wave* model for light.

a. Suppose two light waves meet in step. What would you see – extra bright light, or darkness?

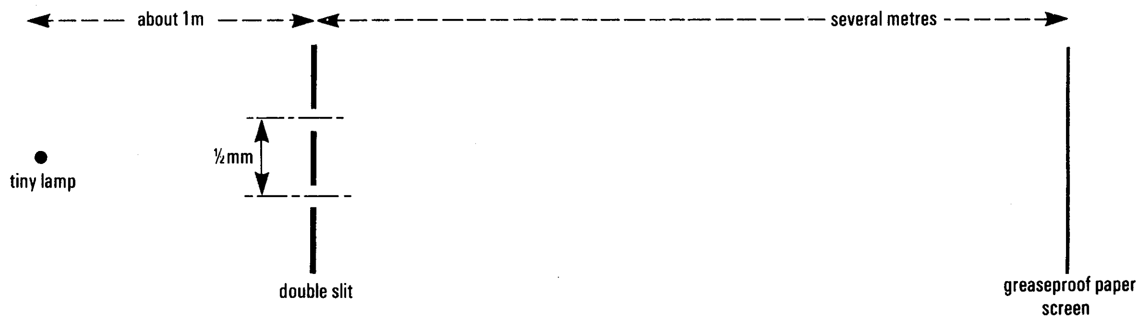
b. Suppose two light waves meet out of step. What would you see where they meet – extra bright light, or darkness?

Interference: Young's fringes

11. Two slits each about $\frac{1}{4}$ mm wide and $\frac{1}{2}$ mm apart are scratched on a smoky glass slide. They are set up as shown in the sketch. The slits are parallel to the filament of a lamp.

a. What kind of pattern do you see on the screen? Draw it.

b. You have to make the room very dark to see the pattern. Why?



c. Use the wave model for light to explain why you get the pattern on the screen.

d. Try to use the bullet model to explain the pattern.

e. Which model do you think is better for this experiment?

Light waves? A test

12. How can we test whether light travels as waves or not? You can get a clue from the behaviour of the waves in a ripple tank when there are two sources. To make this test we need two sources very close together.

a. How can you make a 'barrier' with two openings close together for light to get through?

b. If light *does* travel as waves, it should in some places add up to brightness, and in some places cancel out to darkness, when there are two sources. Where did you look for this effect? Describe what you saw.

Questions

Remembering Year 3 work on waves

13. One example (A) of wave motion is given below, together with the way in which it is started, and what it is that oscillates, and whether it oscillates at right-angles to the direction of motion, or along the direction of motion. Copy this, and add two more examples, B and C, of your own choosing.

	Example A	Example B	Example C
WAVE:	stretched string		
HOW SET UP:	plucked sideways		
WHAT OSCILLATES:	particles of string		
OSCILLATION DIRECTION:	at right angles to wave travel		

14. A *pulse* is a wave of very short duration, a *short piece* of wave, one or two wavelengths at most. For example, you slam the door and the window curtains flutter, or a vase falls off the mantelpiece.

a. How could the driver of a shunting engine demonstrate a pulse along a train of goods wagons?

b. How could you demonstrate a pulse, given a flat table and a number of pennies?

c. How would you demonstrate a pulse in which the wave movement is *at right-angles* to the direction the pulse travels?

(In each case, say what is done and what happens.)

15. How would you show that two waves can cross each other, or pass through each other, unharmed:

a. for water waves or ripples?

b. in a stretched spring (such as a 'slinky' – you may assume that another person is available to hold the other end)?

c. Compare what happens in (b) with what happens when two balls are rolled in opposite directions along a grooved plank so that they meet head-on.

16. You hold one end of a 'slinky' spring, and the other end is fixed in a rigid support. You send a pulse down the spring; what happens when the pulse reaches the fixed end, and afterwards?

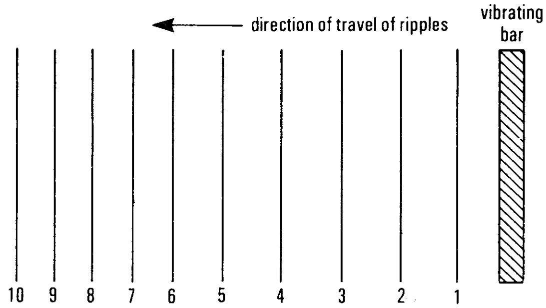
17. A stone is dropped in water. Ripples spread further and further, get smaller and smaller in height, and finally vanish. Why do they get smaller (two reasons)?

18a. What has wave motion to do with simple harmonic motion? Answer by considering what happens in:
(i) a stretched cord, when one end is continuously moved up and down with a simple harmonic motion;
(ii) a stretched elastic string, or a 'slinky' spring, when one end is continuously moved in and out along the line of the string or spring, with a simple harmonic motion.
b. Do all particles of the cord, string, or spring move with:
(i) approximately the same amplitude?
(ii) the same frequency?
(iii) Do they move all together at the same time, that is, are they 'in phase'? Write a sentence or two of explanation.
Note: You should imagine that the end of the cord or spring not held in the hand is loose along the floor, or immersed in treacle, so that you do not get the complication of waves reflected at the end of the cord.

Speed, frequency, and wavelength for ripples
19a. Write out the two sentences below, filling in the blanks.
The distance between the crests of two neighbouring ripples or waves (or between the troughs) is the ..?..
The number of ripples passing a given point in unit time is the ..?..
b. If we use a centimetre rule and a watch measuring seconds, in what units would each of these quantities be measured?

20. Show that $v = fL$ where f is the frequency of a wave motion, L is its wavelength, and v is its speed.

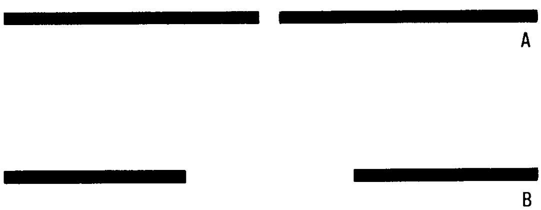
21. The sketch represents a set of straight ripples in a tank. The ripples come from a vibrating bar on the right of the diagram. They appear in the positions shown when a stroboscope is used to



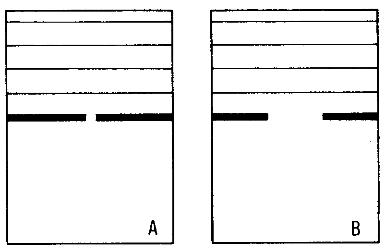
make the ripples appear to be stationary. A flat glass plate rests on the bottom of the tank and makes the water above the plate shallower; the ripples are parallel to the edge of the plate.
a. Where is the edge of the plate situated? (Is it between positions 2 and 3, or 8 and 9, or where?)
b. Is the plate on the right or the left side of the diagram?
c. What can you say about the frequency of the ripples on the right and on the left? (Remember that the stroboscope holds *all* the ripples apparently stationary at *the same time*.)
d. What is the wavelength on the right? (Measure on the diagram.)
e. What is the wavelength on the left? (Measure on the diagram.)
f. If the velocity of the ripples is 21 cm/second on the right, what is the velocity on the left?

Diffraction of ripples
22. Diagram I (one-third actual size) represents two barriers A and B placed, each in turn, in a ripple tank. In each case, a series of straight ripples arrives head on at the barrier in the manner shown in diagram II.

I



II



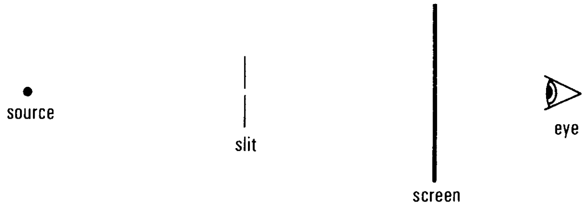
A shows a barrier with a single small gap.

B shows a barrier with a gap 6 cm wide.

Copy diagram IA three times the size shown. Show on your copy the shape of a ripple that has travelled 3 cm beyond the barrier. Do the same for IB.

Diffraction of light

23. You have seen ripples passing through various sizes of openings in a barrier. The sketch shows a similar arrangement using light instead of water ripples. The slit is very narrow, about $\frac{1}{4}$ mm wide.



a. How can you make a single narrow slit like that shown without any special apparatus?

b. The source may be a 'straight' filament lamp. Should the direction of the slit, for best viewing, be at right-angles to the filament, or parallel to it, or at some other angle?

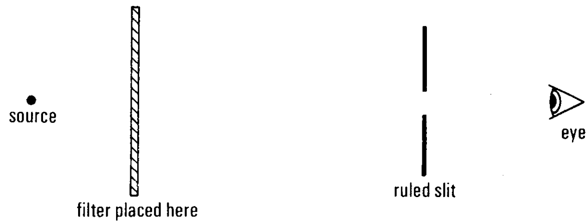
c. Suppose the slit is just $\frac{1}{4}$ mm wide and vertical and the source is a thin vertical line. Suppose the distance between screen and slit is roughly equal to the distance between source and slit, each about 2 m. If light always travelled accurately in straight lines, how wide would the bright patch on the screen be?

d. In fact the bright patch would be much wider than your answer for (c). What conclusion about the nature of light can you draw from this?

e. However, although the bright band is wider than the simple geometry of straight-line rays would lead us to expect, it is still quite narrow, and does not spread all round the screen. What does this suggest about the wavelength of light (*if* light is a wave motion) compared with the width ($\frac{1}{4}$ mm) of the slit? (Remember the ripple experiments.)

24. Hold a narrow slit close to one eye and look through it at a straight filament lamp a few metres away. You see a pattern similar to that which you saw when you tried **Experiment 68**. It is the diffraction pattern of white light. Now put a piece of green filter between the lamp and the slit.

a. The filter makes the pattern green, and rather dimmer than before. What other differences does it make?



b. Next use a red filter. Hold the green and red filters side by side, so that you can shift quickly from one to the other. What change of spacing of the bands do you notice? What conclusions about the wavelengths of red light and green light can be drawn from this? Why?

25. The experiments you have done or seen so far suggest that:

(*i*) Light is a wave motion.

(*ii*) Its wavelength is very small compared with that of water ripples.

(*iii*) The wavelength of green light is less than the wavelength of red light.

Describe briefly an observation that leads to conclusion (*i*), one that leads to (*ii*), and one that leads to (*iii*).

Interference of ripples

26. Two dippers in a ripple tank are 5 cm apart. Each produces circular ripples in the usual way. They are in phase (that is, they bounce up and down together).

a. Describe briefly (adding a diagram) the pattern produced.

b. What difference would it make to the appearance of the pattern if the dippers were (*i*) closer than 5 cm; (*ii*) further apart than 5 cm?

c. What difference would it make if, instead of being in phase, the two dippers were exactly out of phase, one moving up as the other moves down?

Interference of light

27. Look at the diagram of Question 24. Suppose that, instead of a very narrow single slit, you have two very narrow slits, ruled on the same piece of blackened glass and about $\frac{1}{2}$ mm apart.

a. What difference is there between the pattern obtained with the double slit and that obtained with the single slit?

b. Suppose you insert a green filter in the position of the shaded line in the diagram. What difference is there between the double slit white-light pattern and the double slit green-light pattern?

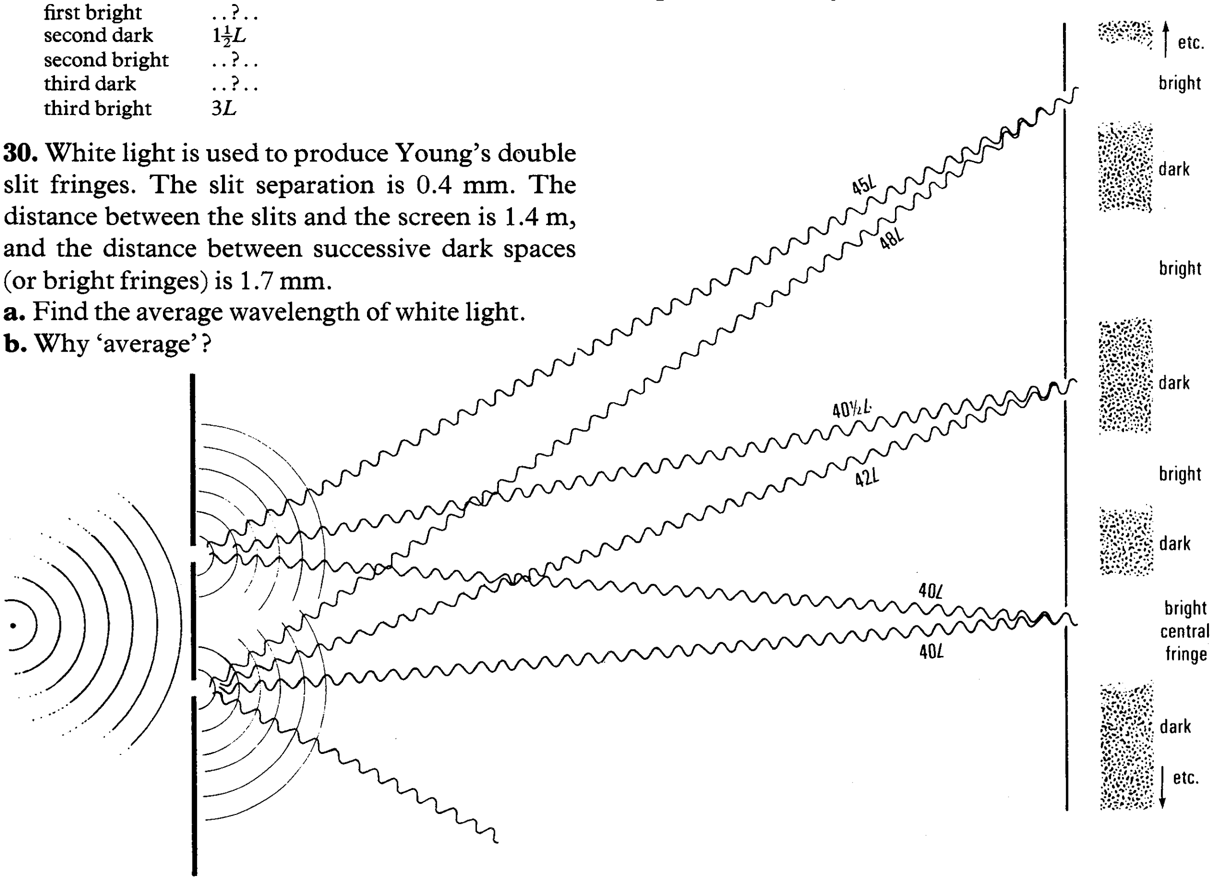
c. You then try a red filter; what difference is there in the 'spacing of the fringes' with red light and with green light?
d. What difference would it make to the 'white-light' pattern if the slits were, say, 0.75 mm apart instead of 0.5 mm?

28a. Given 'Young's fringes' apparatus, including a lamp with a straight filament and a 'double slit', how would you set them up in order to make a measurement of the wavelength of light? Give a diagram.
b. How would you measure the distance between one bright fringe and the next?
c. How would you measure the distance between the double slit and the place where you observe the fringes?
d. How would you measure the distance apart of the two slits which form the double slit?

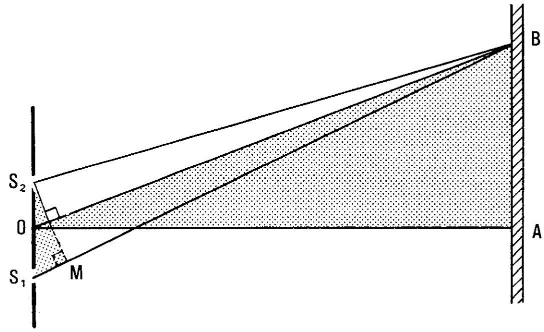
29a. Explain what the diagram is meant to show.
b. Copy and complete the following table by filling in path differences for 'first dark', 'first bright', etc.

Fringe	*Path difference*
central bright	0
first dark	..?..
first bright	..?..
second dark	$1\frac{1}{2}L$
second bright	..?..
third dark	..?..
third bright	$3L$

30. White light is used to produce Young's double slit fringes. The slit separation is 0.4 mm. The distance between the slits and the screen is 1.4 m, and the distance between successive dark spaces (or bright fringes) is 1.7 mm.
a. Find the average wavelength of white light.
b. Why 'average'?



31. In the diagram, S_1 and S_2 are the two 'double slit' sources, A is the position of the *central* bright fringe; B is the position of the *first* bright fringe beyond P, and T is the mid-point of S_1 and S_2.



a. Why is $(S_1B - S_2B)$ equal to L, one wavelength of the light producing the fringes?
b. *Assume* that the two shaded triangles are similar. Explain how we arrive at:

$$L = \frac{(\text{distance between slits}) \times (\text{distance between fringes})}{\text{distance from slits to fringes}}$$

32. (*Advanced*) 'If it were not for diffraction, Young's double slit interference fringes could not be produced.' Why not?

33. Light illuminates a pair of slits. Each slit of a pair acts as an independent light source and interference is produced. A neighbour says, 'Why not use two straight filament bulbs placed next to each other?' You say, 'Well, for one reason, the filaments would still be so far apart that the interference fringes would be much too close together to see.' 'All right,' says your neighbour, 'get someone to put two filaments very close together in the same bulb.' 'That still wouldn't work,' you say. Why wouldn't it?

Supplement: Some questions from Year 3

These questions were optional in Year 3 but they now apply to topics in this chapter.

34a. A friend says, 'I've never thought about it before, but I suppose the idea of light being particles, rather like bullets, does explain some things. It explains why light travels in straight lines so that an electric-light bulb *is* where I see it, and not somewhere round a corner. But what else does it explain?'

Write a few sentences telling your friend, in *your own words*, how the particle theory explains: (a) reflection, and (b) refraction, of light.

b. Your friend then says, 'We can have a very bright light or a very dim light, and anything in between. How do particles explain *that*?' What is your answer?

35. A photographer's light-meter measures the 'strength' or 'intensity' of light falling on it.

A light-meter is placed first 1 metre from a small light source and then 2 metres. At the 2-metres distance the strength of the light is only one-quarter of what it is at 1 metre. Explain how this is explained by a 'bullet' theory of light.

Young's fringes

36. Imagine you are asked to set up the apparatus to show the fringes to two or three members of your class who were absent before. You have an electric lamp with a straight filament, a 'double slit', and a sheet of oiled paper (with, of course, the means of supporting them).

a. Where would you place the lamp, the double slits, and the oiled paper? And where would you place the pupils to see the fringes? (This is best answered by a sketch with labels.)

b. Suggest suitable distances between these items, or mark them on your sketch.

c. Would you start by placing the double slits so that they are parallel to the filament? Or at right angles? Or at some other angle?

d. What would you suggest for the spacing between the slits? 0.15 cm? 0.5 mm? 0.05 mm? 0.005 mm?

e. If you drew the slits too far apart, making the spacing too great, how would that affect the appearance of the fringes?

f. Suppose you show the 'white light' fringes; then put a green filter in front of the lamp. Someone then asks, 'Why is it I can now see *more* fringes than before?' What would you say to that? How would you use a red filter to support your explanation?

g. You would point out to your 'pupils' that here we have 'light + light = no light'. You ask them what other experiment they have seen in which (something) + (something) could give nothing. What do you hope they will reply? Describe briefly the experiment you would then like them to repeat.

CHAPTER 9
Diffraction gratings; spectra; electromagnetic spectrum

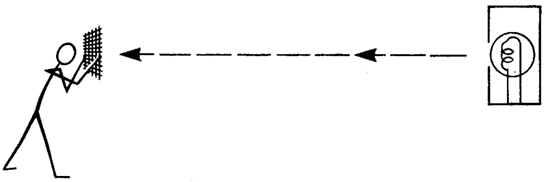
Now we make use of interference to spread light into a wide spectrum of colours, or, in fact, several spectra at the same time. A spectrum is not only beautiful to look at but it can also give information about atomic structure.

LIGHT PASSING THROUGH A VERY FINE GRATING

Instead of the two slits for Young's fringes, we can rule thousands of slits side by side to make a grating. Then we can spread out the colours of the spectrum and make very useful measurements.

Experiment 73
A quick look

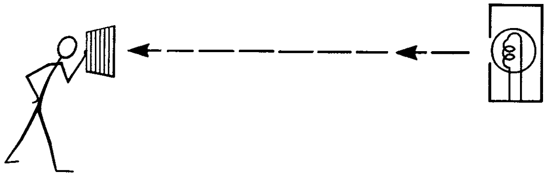
Hold a piece of finely woven cloth in front of your eye. Look through it at a small bright lamp far away. What do you see?



(You can do a similar experiment on your own, using an opened umbrella for the fabric and a distant street lamp.)

Try a professionally ruled grating A diamond is used to rule thousands of furrows, equally spaced – like the furrows in a ploughed field – on a flat piece of metal or glass. Then plastic copies are made by casting from it. We call it a *diffraction* grating, because each furrow is so narrow that light passing through it spreads out and overlaps the light spreading from other furrows.

With so many slits you can get a pattern like Young's fringes but with a lot more light. However, you do need a lens to coordinate the light. You can arrange a lens to form an image of a small lamp on a screen far away; then place the grating just beyond the lens. But it is easier to use the lens of your eye. Let your eye remain slack – focused for looking at something far away – and hold the grating just in front of your eye. Your retina will receive the pattern.



Experiment 74
Coarse and fine diffraction gratings

Try **Experiment 73** again but this time use a piece of thin plastic sheet ruled with furrows about $\frac{1}{1000}$ cm apart, making a thousand slits side by side in every centimetre across.

The fringes do not look as close together as in your experiment with two slits. *Why not?*

Try placing colour filters between the grating and your eye, first red, then green. *What does that tell you about those colours?*

Then try a fine grating and use it to analyse various samples of light.

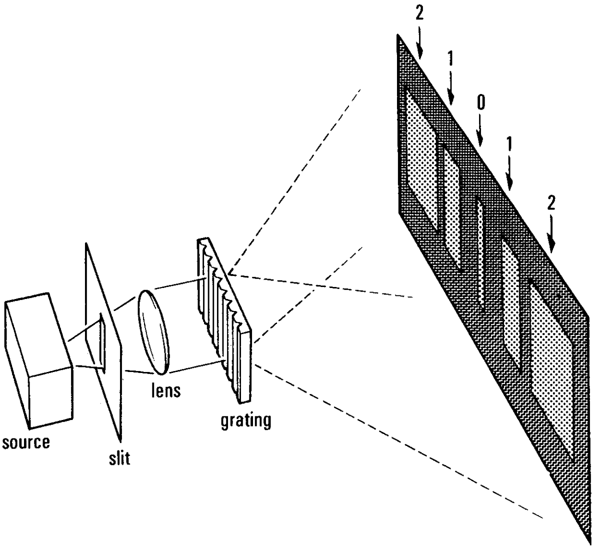
Fine gratings have furrows ruled very close together – anything from 2000 to the centimetre to 20 000 or more.

Demonstration 75
Spectra projected on a screen

Light from a small source falls on a fine grating. Just before the grating, the light meets a lens which forms an image of the source on a white screen far away. There you see a central white image of the source and the spectra formed by the grating.

First see this with a coarse grating which will make several spectra each side of the central image, then see it with a fine grating.

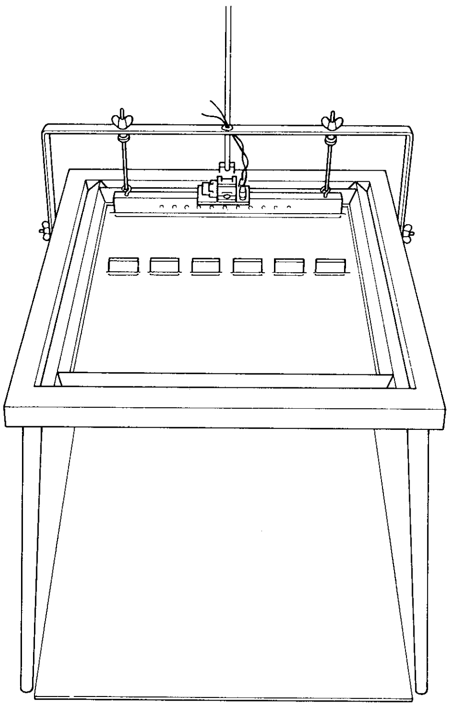
Remember that each spectrum is a series of overlapping images of the source, in the whole range of rainbow colours.



Demonstration 76
Ripple tank with a 'grating' of slits

The vibrating bar makes straight waves which meet a barrier with many narrow gaps or slits. Can you see semicircular ripples emerging from the slits? Further out, can you see waves moving out in slanting directions, as well as a wave moving straight ahead?

Try changing the speed of the motor, to make different wavelengths.



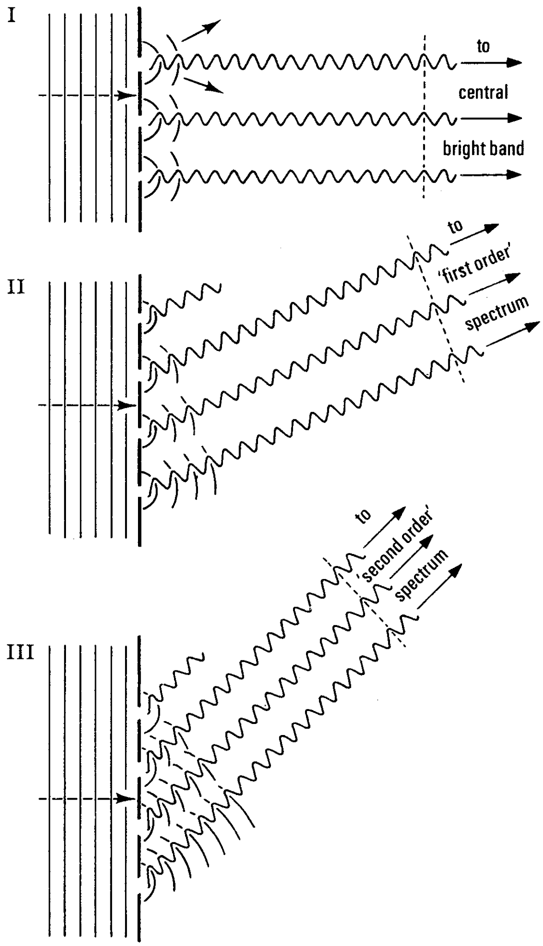
Try watching through a hand stroboscope.

You may see a motor-driven stroboscope in action.

How does the collection of contributions from many slits add up? *If* a beam of white light *is* a stream of waves, a wavelet must emerge from every illuminated slit of the grating. Since the slits *must* be very narrow – because there are so many crowded together in the small grating – those wavelets must almost be semicircles. Look at them in the diagram *and* in the ripple tank.

If we let them continue out to a screen very far away, there will be places where the wavelets from all the slits arrive in step. In the central bright image all those contributions have the same path length – they arrive in step whatever their wavelength, so the central image is white (I).

In a certain direction slanted to either side of the direct image, contributions arrive in step because the path from one slit is just one



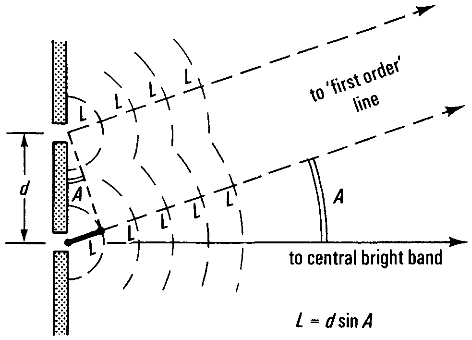
wavelength more than the path from its neighbour. See diagram II.

Do waves really make spectra like that when they pass through a grating? Look carefully at ripples passing through a row of small slits.

What is happening in diagram III?

Now look at diagram IV. Contributions from all the slits arrive in step in directions given by angle A if $d \sin A$, the extra path from one slit to the next, is one whole wavelength, L. That is for the first spectrum out from the centre. It is $2L$ for the second spectrum, etc.

IV



If we measure the angle A for any particular colour and we know the value of the distance between the slits, d, we can calculate the wavelength of that colour.

Red light is swung out most (therefore its wavelength, L, is greatest), then orange, yellow, green, blue, and violet.

HELP FROM YOUNG'S FRINGES TOWARDS UNDERSTANDING GRATING SPECTRA

For simplicity, here is a Young's fringes arrangement, with two sources. Energy flows out to each fringe.

An observer at X would find a bright fringe there. Observers further out would find waves carrying energy to bright fringes ('spectra') in the directions shown.

The next diagram shows two sources making the bright and dark Young's fringes on a screen.

The specimen wave trains to P are equal, and there is a central bright fringe there.

The specimen wave trains to Q differ by $1\frac{1}{2}$ wavelengths, and there is a dark fringe there.

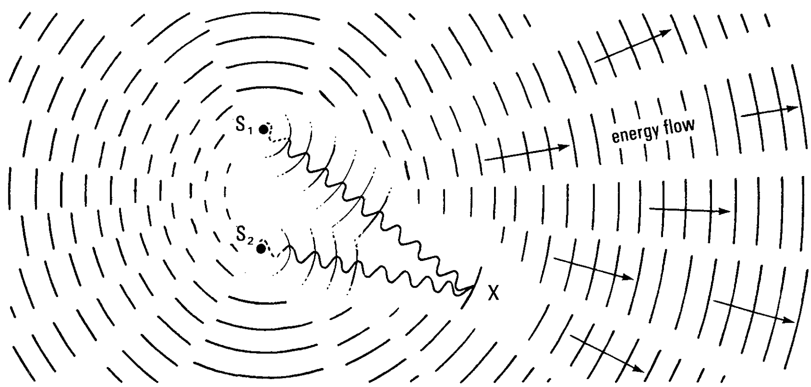
The specimen wave trains to R differ by 3 wavelengths, and there is a bright fringe there (3rd order).

Names From now on we shall call the 'slits' of a grating *rulings*, and the distance d from one ruling to the next the *grating space*.

The light that goes straight through the grating makes an image of the source that is at the same place for all colours; we call this the *zero order*.

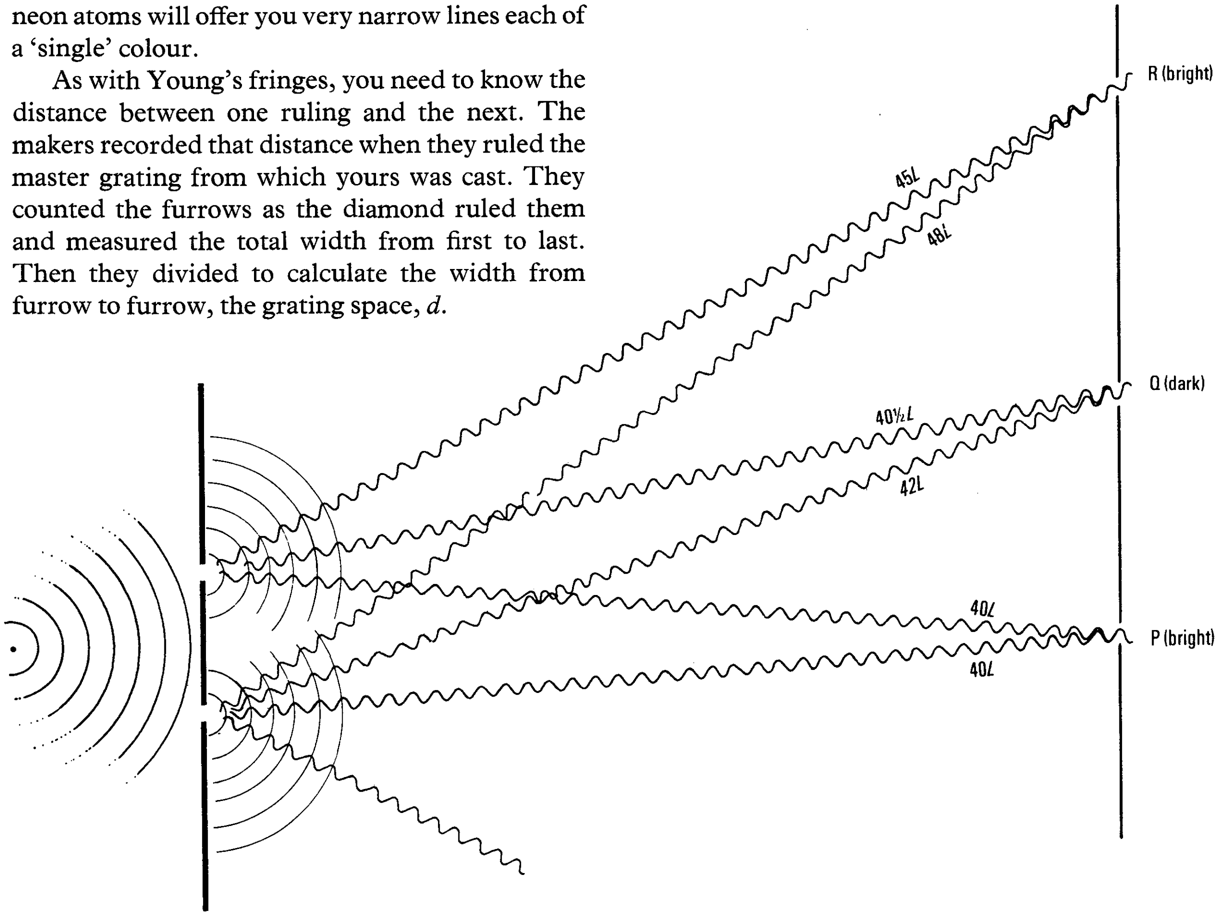
We call the first spectrum on each side of that direct image the *first order*. There, the contribution from each ruling travels one wavelength L more (or one less) than the contribution from the next ruling. In the next spectrum further out, the *second order*, contributions from adjacent rulings differ by $2L$ and again they all arrive in step for that colour.

Measuring the wavelength of light With Young's slits you could estimate an average wavelength. With a grating of thousands of slits you can measure a wavelength accurately. Your precision is limited now by the width of the part of the spectrum that you use. White light through a green filter still gives a range of wavelengths from yellowish green to bluish green. But a sodium flame or the spectrum from excited hydrogen or



neon atoms will offer you very narrow lines each of a 'single' colour.

As with Young's fringes, you need to know the distance between one ruling and the next. The makers recorded that distance when they ruled the master grating from which yours was cast. They counted the furrows as the diamond ruled them and measured the total width from first to last. Then they divided to calculate the width from furrow to furrow, the grating space, *d*.



Experiment 77
Measuring the wavelength of light

Use a fine grating for your measurement. The source should be a small lamp with a bright vertical filament.

Hold a metre rule straight out in front of you towards the lamp, with the near end of the rule at your face. Hold the diffraction grating against the near end of the metre rule and look at the lamp through it.

Ask your partner to place another metre rule, at 90° to your metre rule at its far end (see the sketch). He should hold a pencil vertically above *his* metre rule and move it along until you see it in the green region of your bright spectrum. Record the distance, x, along your partner's ruler from the pencil to the far end of *your* ruler.

When you have made your observation, record it and change places with your partner so that he can take his turn.

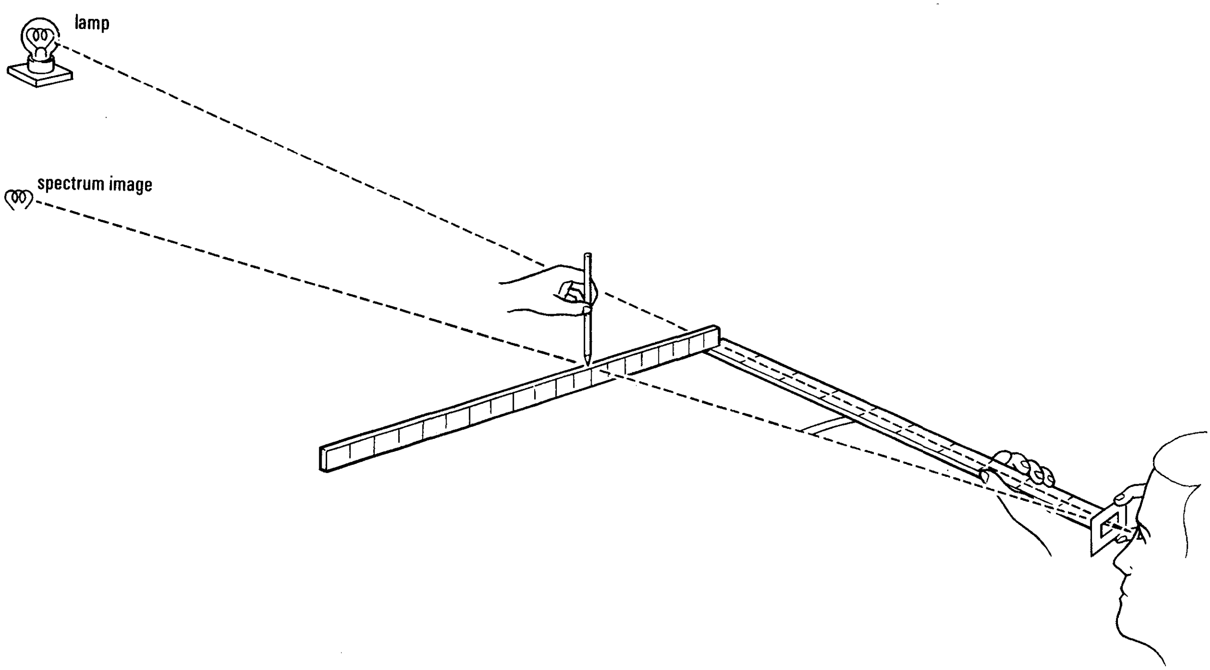
Divide your measurement x by the length of your ruler, 100 cm. This gives you $\tan A$ where A is the angle between the line of direct white light and the light to the green in the spectrum marked by the pencil.

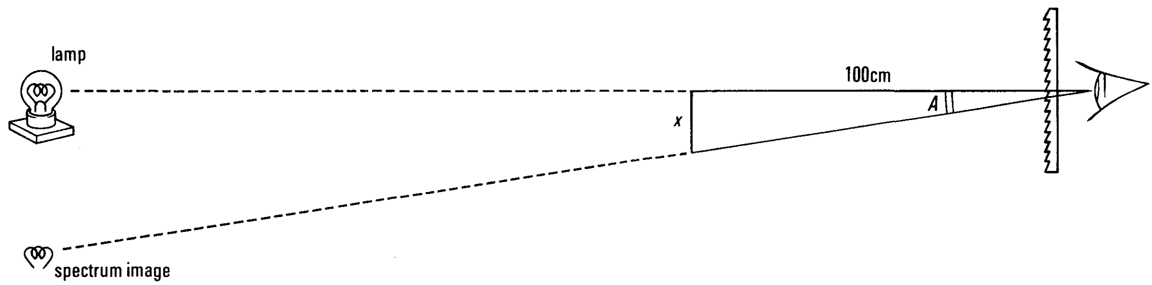
From $\tan A$ find the angle A from tables, and thence find $\sin A$ from tables.

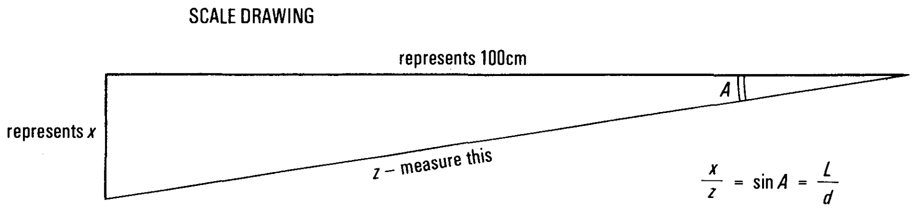
If you are not used to trig. tables, make a scale drawing instead on a large sheet of paper. Draw lines to represent the two rulers, 100 cm and x in cm long (to scale). Complete the triangle and measure the long sloping side z. Then calculate $\sin A$, which you will need for your wavelength calculation, as follows:

$$\sin A = \frac{x}{\text{slanting side } z}$$

Use the formula $d \sin A = \text{wavelength}$ to calculate the wavelength of green light. You will need the value of d, the grating space from one ruling to the next. There are usually 3000 rulings to the centimetre. If so, the grating space, from ruling to ruling, is $\frac{1}{3000}$ cm, or $\frac{1}{300\,000}$ m. Assume this, unless you are given a different value, and use it to estimate the wavelength.





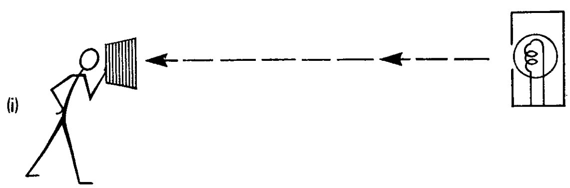


Some approximate wavelengths

BBC Radio 4		1500 m
VHF radio		3 m
Television (UHF)		0.2 m
Visible light:	red	700×10^{-9} m
	yellow	600×10^{-9} m
	green	500×10^{-9} m
	violet	400×10^{-9} m

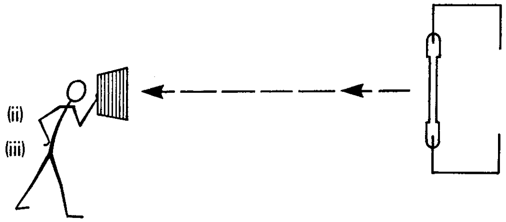
Experiment 78
Spectra

(*i*) Look at the white-hot filament of a lamp with the fine grating held close to your eye. The grating has about 3000 slits across every cm of width. You see a central white line where waves of all colours go straight through the grating. Out to each side, you see a wide bright band, which corresponds to the first bright fringe out from the centre of Young's fringes (one wavelength path difference). Since the light is white, each bright fringe is spread into a wide spectrum of colours.



Looking further out to each side, you may see a still wider, but fainter, spectrum, which corresponds to the next bright fringe out from the centre (two wavelengths' path difference).

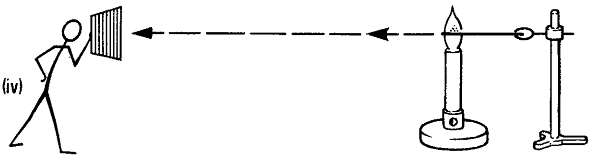
(*ii*) Look through your grating at the neon source. It is a tube containing neon atoms which are being



bombarded by electrons, etc., driven by a high voltage. The red light comes from neon atoms as they recover from that excitation.

Using your grating as a spectroscope – an instrument to spread coloured light out into a spectrum – you can see that the neon atoms do not all give out red light alone. They are not behaving like a musical instrument playing a pure musical note. They are playing like a huge well-organized orchestra.

(*iii*) Now look at the hydrogen tube. There, hydrogen atoms are being bombarded. As they recover, they give out only a few definite colours. They behave like a much simpler orchestra: so much simpler that the hydrogen spectrum was one of the first to have its vibrations decoded and so yield very important information about atomic structure.



(*iv*) Look through your grating at a yellow sodium flame – a clear flame with salt added. Do you agree that it gives out pure yellow light and not the usual mixture of red and green which we accept for 'common' yellow in colour mixing?

SPECTRA AND COLOURS

Line spectra (see p. 146)

When you sent pure yellow light from a sodium flame through a grating you saw a central yellow 'line' and an equally sharp yellow line in each first order, each second order, etc. You saw that the light from glowing neon gave many sharp 'lines' in each order. Hydrogen, when made to glow, also gives a series of lines – a red, a green-blue, a violet, obviously spaced along the spectrum according to some simple law, and the series continues in the ultra-violet. Mercury gives a pair of yellow lines, a very bright green line, a violet line, and others, but no red – hence the odd colour of light from mercury street lamps.

These are all examples of 'line spectra'.

White light

Solids and liquids emit 'white' light when they are hot enough. So do the Sun and other stars in whose interior the electrons are completely removed from the atoms. These electrons are free to radiate any assortment of colours.

Absorption

A colour filter stops some colours of white light and lets others pass through. See the spectrum when a green filter is held in a beam of white light. It does not dye the white light green! It simply absorbs red, orange, yellow, and blue light.

Absorption lines You may see another kind of absorption: not broad patches of the spectrum cut out but very narrow lines missing from white light. These are made when light from a hot source passes through cooler gas or vapour.

THE GREAT ELECTROMAGNETIC SPECTRUM

Beyond the visible spectrum Outside the visible range, there is infra-red radiation which has greater wavelength, easily measured with coarse diffraction gratings. Beyond infra-red, radio waves continue the spectrum out through microwaves (short radio waves) to long radio waves with L measured in hundreds of metres.

On the other side, ultra-violet light has shorter wavelengths than visible light, measured by fine gratings operating in a vacuum to eliminate absorption by air.

X-rays have far shorter wavelengths, usually less than 0.1×10^{-9} m in contrast with hundreds $\times$ 10^{-9} m for visible light. We could hardly rule a fine enough grating with rulings 10^{-9} m apart.

Instead we use the layers of atoms in crystals.

These radiations are all part of the great electromagnetic spectrum. You cannot see such a vast spectrum spread across a screen. Only a tiny section is visible light, to which your eyes are sensitive.

The methods of producing radiation in the various sections are different – as you can see from the sketches of sources in the picture. And the methods of detection are different. Yet *all* the radiation, throughout that spectrum, travels with the same speed in vacuum. And the radiation in each section can produce diffraction and interference effects which show that it consists of waves. Nowadays we know that these are waves in electric and magnetic fields.

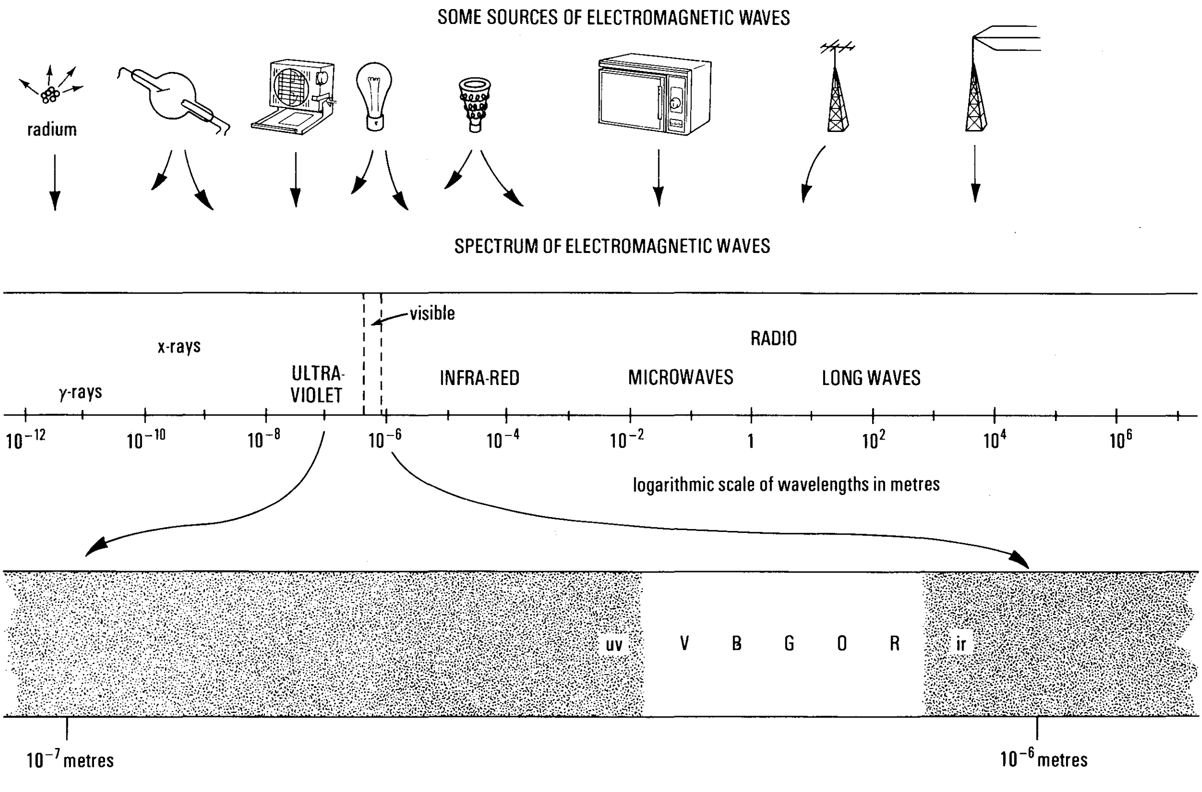
In order to fit the picture to the spectrum the wavelength scale used is one in which equal ratios of wavelengths are plotted rather than equal differences. For example, wavelengths 1 and 100 m are spaced the same distance apart as wavelengths 10^{-2} and 1 m and 10^{-6} and 10^{-4} m. This is like the scale of octaves used in music where a jump in the scale of 1 octave means the doubling of the frequency (and a halving of the wavelength). Such scales are called 'logarithmic'.

SOME USES OF SPECTRA

Analysis The atoms of each chemical element emit characteristic spectrum lines, if suitably excited. The lines are different for every element, so spectroscopes for observing spectra are useful for chemical analysis – including the analysis of the Sun and the stars.

Atomic theory The lines of an element's spectrum can be grouped in several series (like families). The wavelengths of the members of a series can be coded in a general formula. These formulae have proved of great use in atomic physics. Those for the spectra of hydrogen and helium played essential parts in building atomic models. Those for heavier elements are guides to our knowledge of complex atomic structure in physics and chemistry.

'Red shift' When we look at the spectra of stars and nebulae, we see lines which obviously come from elements which we know. But in the spectra of nebulae these lines are shifted towards the red. The red shift is greater for those nebulae which are further away (as judged by other evidence which seems trustworthy). A shift towards the red means



Line spectra for sodium, neon; hydrogen and mercury compared with the white light spectrum of a tungsten filament.
Dr. W. F. Sherman, Department of Physics, King's College, London.

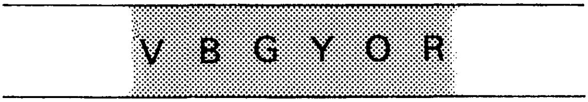
a change to a longer wavelength and also to a lower frequency. What does that mean?

When does a shift to lower frequency occur with sound waves? We often hear the sound of a car's horn, or an ambulance's siren, or an aeroplane's engine drop to a lower frequency as the source passes by and moves away from us. We guess that the red shift of the light from a nebula means that it is moving away – very fast.

What does that, in turn, suggest concerning the universe around us? You might discuss this with your teacher.

Progress Questions

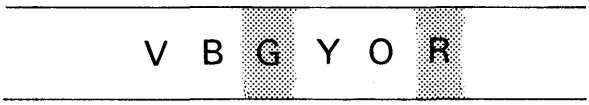
1. The sketch shows the visible spectrum of white light. The visible part that we can see is shaded



grey and the invisible regions beyond the ends have been left white.

Draw a strip like the sketch for each of the following. Use a pencil to make grey patches where you expect to see bright light of one colour or another.

a. White light is sent through a green filter. Sketch the spectrum of the light that comes through.
b. Sketch the spectrum of sodium in a salted flame.
c. A magenta filter lets through red and blue light. White light passes through a magenta filter. Sketch the spectrum of the light that comes through.
d. The sketch below shows, in the same way, the spectrum of the light that comes through a certain



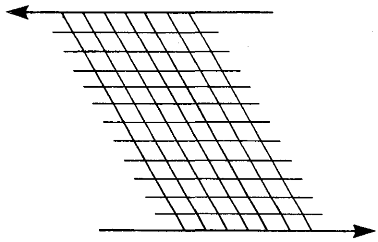
filter from a white light source. What colour will that filter show, held up against a white sky?

2. The wavelength of light is very tiny. You could get about 20 000 waves in the width of your thumbnail! Experiments show that different coloured lights have different wavelengths.
a. Which visible colour has the longest wavelength?
b. Which visible colour has the shortest wavelength?
c. Do X-rays have shorter or longer wavelengths than visible light?
d. Do infra-red rays have shorter or longer wavelengths than visible light?
e. Do ultra-violet rays have shorter or longer wavelengths than visible light?

Questions

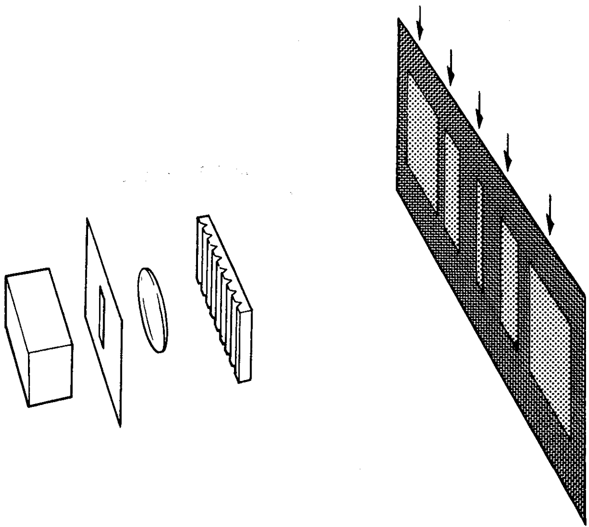
Diffraction gratings

3. Take an ordinary handkerchief, pull it reasonably taut, and look through the fabric at a lamp far enough away for it to seem like a point.
a. Draw and describe the pattern of dots you see.
b. Now take something in which the threads are more widely spaced (coarser mesh) than in a handkerchief, e.g. a linen tea towel. What difference is there in the pattern of dots? Is it what you expect? Why?



c. Now try pulling the mesh of the handkerchief diagonally as shown. Pull the mesh and release it several times, in a 'concertina' fashion. Notice how the dot pattern also 'concertinas', but with an important difference. What difference? Why?

4a. The sketch is a diagrammatic representation of a diffraction grating used to produce spectra of



light from a filament lamp on a screen. Explain as much as you can about *what is happening* (not *why* it is happening) and what is seen on the screen. (Answer by starting 'White light from a lamp passes through a narrow slit . . .').

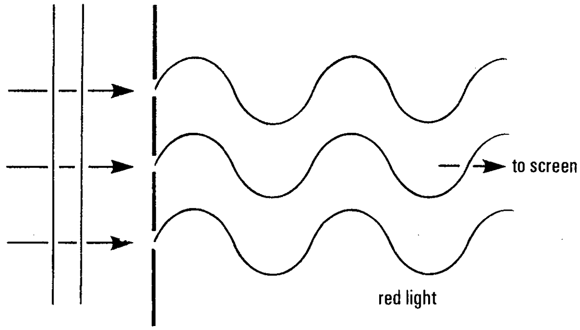
b. You can do away with the lens and the screen and simply put your eye up close to the grating; you still see the spectra. What now has taken the place of: (*i*) the lens; (*ii*) the screen?

c. What is the connection between the handkerchief experiment of Question 3 and the diffraction grating?

5a. Use sketches I, II, and III on page 140 to explain why a grating gives spectra of more than one 'order'.

b. (*Advanced*) If the grating has very narrow rulings very close together, then only the first order spectrum, and perhaps the second, are seen. When a coarse grating, like a handkerchief, is used many orders are seen very close together. Why is there this difference?

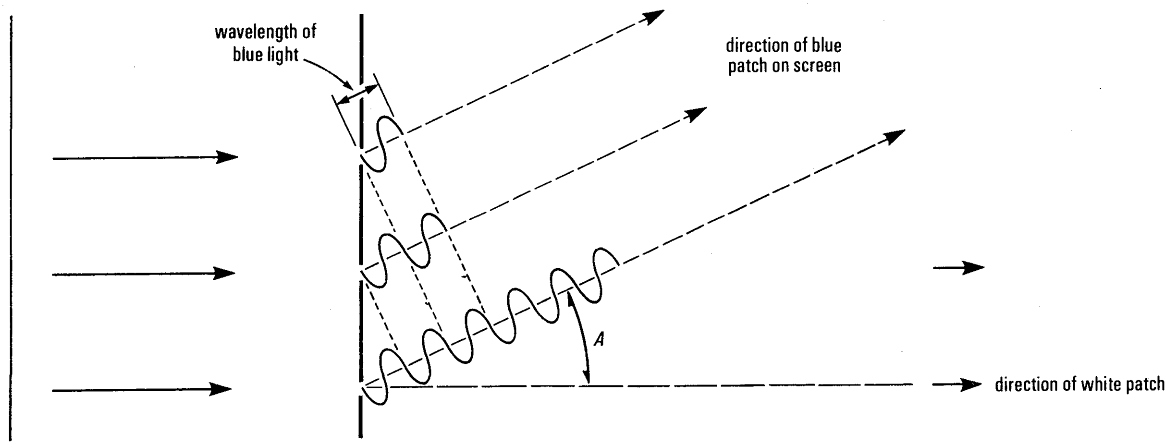
6. Use this diagram of a parallel beam of *white* light striking a grating to explain why it is reasonable to get a bright patch of light straight ahead *whatever the wavelength of the light*. (Only red light waves have been drawn beyond the grating.)



7a. Copy this diagram of a parallel beam of white light striking a grating and use it to explain why there is a patch of blue light on the screen in a direction given by angle A.

b. What do you think happens to the wavelets of light of any other colour that start off from the grating 'in step' in the same direction A?

c. Red light has a longer wavelength than blue. Would you expect to find the red patch at a larger or a smaller angle than A?



d. In some directions there are dark patches. What has happened to wavelets of all wavelengths in these directions?

Spectra

8. A grating is used to produce a number of spectra of white light on a screen.

a. What do you see on the screen if you put a red filter (for example, a piece of red glass) in the beam of light?

b. What difference does it make to the pattern on the screen if the source of white light is replaced by a sodium lamp or flame?

c. A tube of glowing hydrogen gives a different pattern. Describe this briefly.

9. In any one spectrum produced by a diffraction grating, the red colour is seen further away from the central band than the blue colour of the spectrum. What does that tell you? How do you explain it?

- -

CHAPTER 10
Radioactivity: experimental study; nuclear atom; neutrons; reactors

Radioactivity was discovered by the way some substances enable air to conduct an electric current, and the way the same substances make marks on photographic film, even through thick shields of heavy paper.

X-rays were discovered in much the same way.

These discoveries were made just before the beginning of this century. As well as developing enormous practical value for medicine and engineering, X-rays and radioactivity have helped in building the modern physics of atoms.

Several other new parts of physical science contributed to the building of atomic and nuclear physics – these were:

a. The tearing apart of atoms by electric sparks in gases at low pressure.

b. Developing from *a*, experiments with electron streams in a vacuum, and measurement of e/m.

c. Millikan's proof that all electric charges occur in basic units, all the same size; and his measurement of that electron charge e.

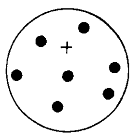
d. The development of mass spectrometers to measure e/M of the remainder of an atom that has lost an electron.

e. The 'thermionic effect': electrons boiling off hot metal filaments in a vacuum, as they do in an electron gun.

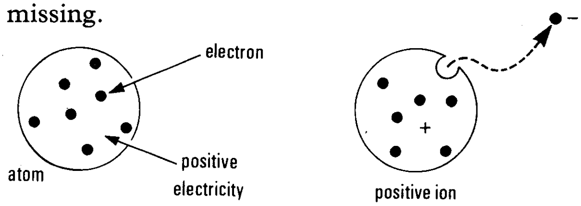
f. The photoelectric effect: light flings electrons out of metal surfaces (used in the electric eye or photo tube).

All these lines of growing knowledge joined with earlier chemical knowledge of ions in solution to build our knowledge of atoms.

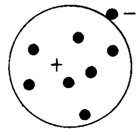
As you saw in Chapter 2, the first 'thinking model' of an atom, after electrons were discovered, was a round ball of positive electricity with negative electrons embedded in it. Then when an



electron was removed – by bombardment, by heating, by a whiplash of light, or by a chemical lending of an electron to another atom – the remainder was a 'positive ion'. We sketched it as a round ball with a + mark on it. And we might show a bite out of it where the electron was missing.

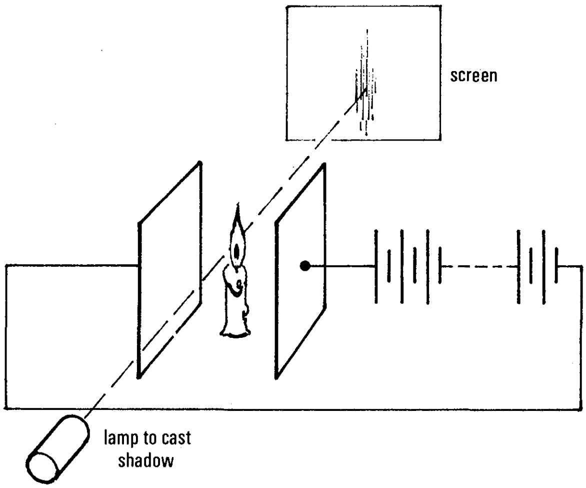


If the lost electron wanders in air, it soon attaches itself to another neutral atom or molecule. Then we have a negative ion like this:



Demonstration 79
Ions in a candle flame

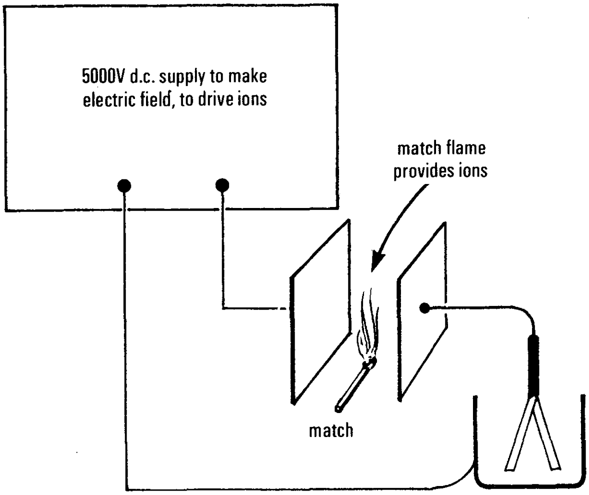
See the demonstration sketched, in which the chemical changes in the candle flame provide ions.



The electric field between the charged plates pulls the flame's ions to one side or the other according to the charge on them.

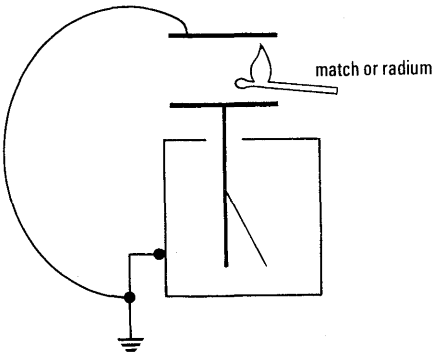
Demonstration 80
Ions carry charges to and from an electroscope

a. A match flame contributes ions which are driven across the space between the plates by the electric field there. Those ions carry charges to or from the



leaf of a charged electroscope. See the demonstration sketched.

b. We do not need the high-voltage supply to make the driving electric field. Just charge the leaf of the electroscope; then there is an electric field between the leaf and the case. Hold a plate, connected to the case, above the electroscope's top plate. Now there



is an electric field between those plates that can drive ions.

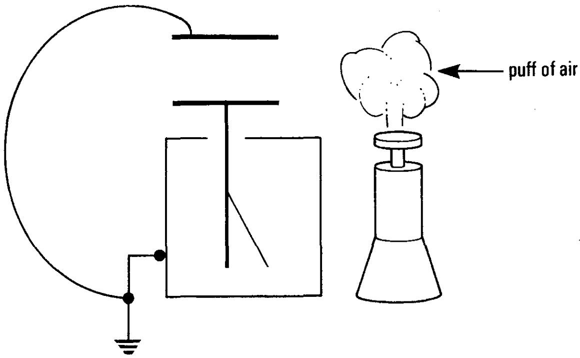
Bring a lighted match into the space between the plates and see the leaf's charge being carried away.

Demonstration 81a
Radioactive material makes ions in air

Repeat the last experiment (**80a**) with a small radioactive source instead of the match flame.

Demonstration 81b
A current of air can carry ions

Repeat the last two experiments with the charged electroscope but this time hold the source of ions out at one side, as in the sketch. Charge the electroscope and watch the leaf: it will hardly move, because ions are not getting into the space between the plates.



Then watch while some air is puffed across, above the source and into the space between the plates. Watch what happens with a match flame, then with a radioactive source.

WATCHING EXPERIMENTS

See three demonstrations which will in the end help your knowledge of nuclear physics.

Demonstration 82a, b, c
Mystery experiments I, II, III

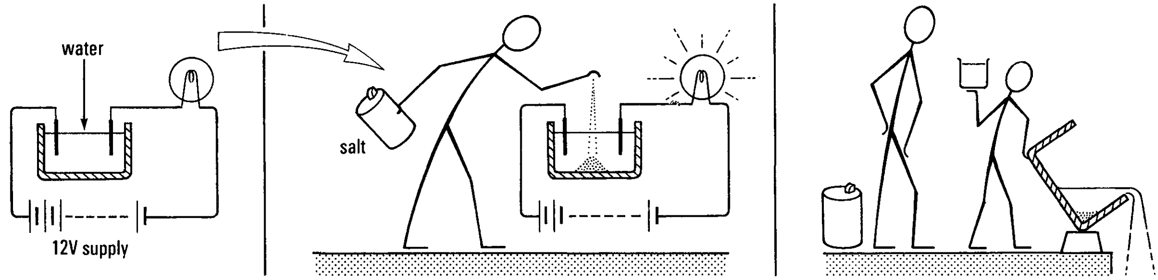
Treat them as mysteries at first, then discuss each with your teacher.

You need to remember two things about electric currents: how a current travels through liquid or gas, and what happens in a spark.

Ions in liquids Many liquids are insulators, almost perfect non-conductors. Oil is used to insulate transformer windings. Pure water conducts very poorly, but if you add to water some charged particles such as sodium ions Na^+ or chlorine ions Cl^-, those ions can be driven through the water by an electric field – and their motion *is* an electric current.

Mystery Experiment I

Connect a 12 V supply to a lamp through a bath of clean water. Add a handful of salt.



Sparks in a gas Apply a small driving voltage to a sample of a gas. Nothing happens. Air and other gases are insulators. Make a few ions by bombarding the gas with speedy electrons or some missiles from radioactive nuclei. Those ions can carry a trickle of current if they are driven by an electric field. They stagger along making harmless, elastic collisions with one neutral molecule after another.

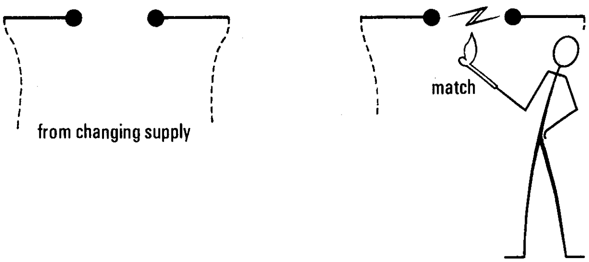
However, if we apply a very strong electric field, each ion can gain enough kinetic energy between one collision and the next to chip an electron off a neutral atom or molecule. This provides a new pair of ions, e^- and $(\text{atom})^+$, and *they* are driven by the electric field. Thus more and more ions are made in a chain reaction of collisions, and there can be an avalanche of moving charges.

If that is violent enough you see a spark – the glow of light emitted by atoms recovering an electron. You also *hear* a spark – at its largest, the thunder of a lightning flash. That comes as a sound wave from the gases expanding with the heat that is developed.

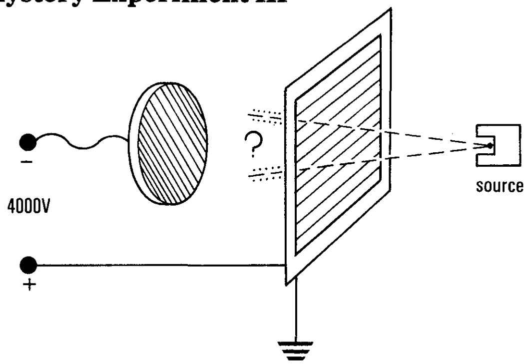
Think about the air between two plates or two metal balls, with a large voltage applied. Suppose the electric field is *almost* strong enough to start a spark. One more straw and the camel's back will break. Provide the straw by supplying a bunch of ions, and a spark will start.

How do we get the ions to throw into the gap? See two different methods in **Mystery Experiments II** and **III**.

Mystery Experiment II



Mystery Experiment III

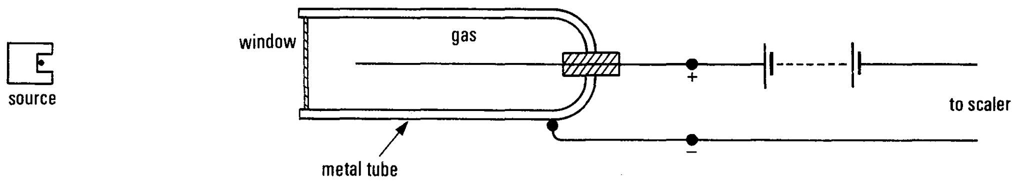


COUNTERS

In 'Mystery Experiment III', the radioactive source shoots a 'nuclear bullet' from one of its atoms. We call this nuclear chip an *alpha particle*. The alpha particle moving at very high speed through the air near the fine wires makes enough ions to 'break the camel's back' and let the electric field make more ions by collision and so start a spark. If you count the sparks, you are acting as a counter to count the explosions of radioactive atoms. You are counting nuclear events.

Instead of watching and counting you could arrange an instrument (called a scaler) to do the counting for you.

Geiger-Müller tube The scaler is usually used to count nuclear events in closed tubes rather than spark counters. In the usual form the grid of wires is replaced by a single wire inside a metal shield which takes the place of the spark counter's plate. A high voltage supply, provided inside the scaler, is applied between the wire and the shield. The scaler counts pulses of charge delivered by electron avalanches to the central wire. By filling this closed tube with a suitable gas we make sure that each spark does not last too long. When the spark is quenched, the tube and scaler are ready to count a bullet from another radioactive atom's 'explosion'.



Demonstration 83
Radiations and counters

Alpha particles Watch the spark counter while various radioactive materials are brought near it. See which of them fires alpha particles past its wires. You do not need a scaler to count the sparks.

Beta particles and gamma rays The spark counter is open to the air. A Geiger-Müller tube has a window: a closed end to keep the special gas in. Alpha particles would be stopped by any window except a specially thin one.

Tubes with a thicker window show that some other radioactive materials fling out particles that can travel through many sheets of paper, or a millimetre of metal. We need a different name for these because they have different properties so we call them *beta* particles*.

See experiments with other counter tubes and other sources, with a scaler to record the counts.

Thicker barriers, such as a centimetre of metal, will stop the beta particles from any radioactive material but there are other things which still get through. We need a third name: *gamma* rays*.

Demonstration 84
Experiments with alpha particles: range and stopping

a. Place the source 10 cm or so from the spark counter. You will see no sparks unless by accident.

Alpha particles from any ordinary radioactive source are stopped by less than 10 cm of air – they lose all their kinetic energy in minor collisions. Move the source nearer until the counter shows sparks. Make a rough estimate of the *range* of the alpha particles.

b. Try obstructing the path of those particles with a sheet of writing paper. *Can they get through?* Try thinner paper.

* We need three names for the three distinct types. We might label them A, B, C, but instead we use α, β, γ (*alpha*, *beta*, *gamma*), the first three letters of the Greek alphabet.

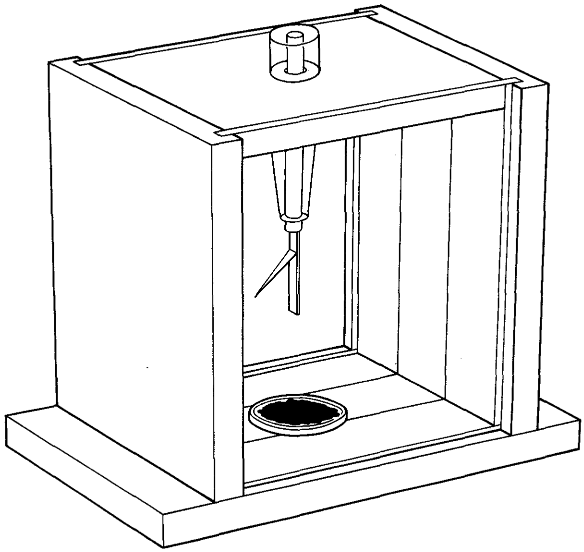
Gold leaf is probably the thinnest solid material you have in the lab. You cannot safely put gold leaf near the wires, but if you could you would find that it lets alpha particles through though they lose some energy on the way.

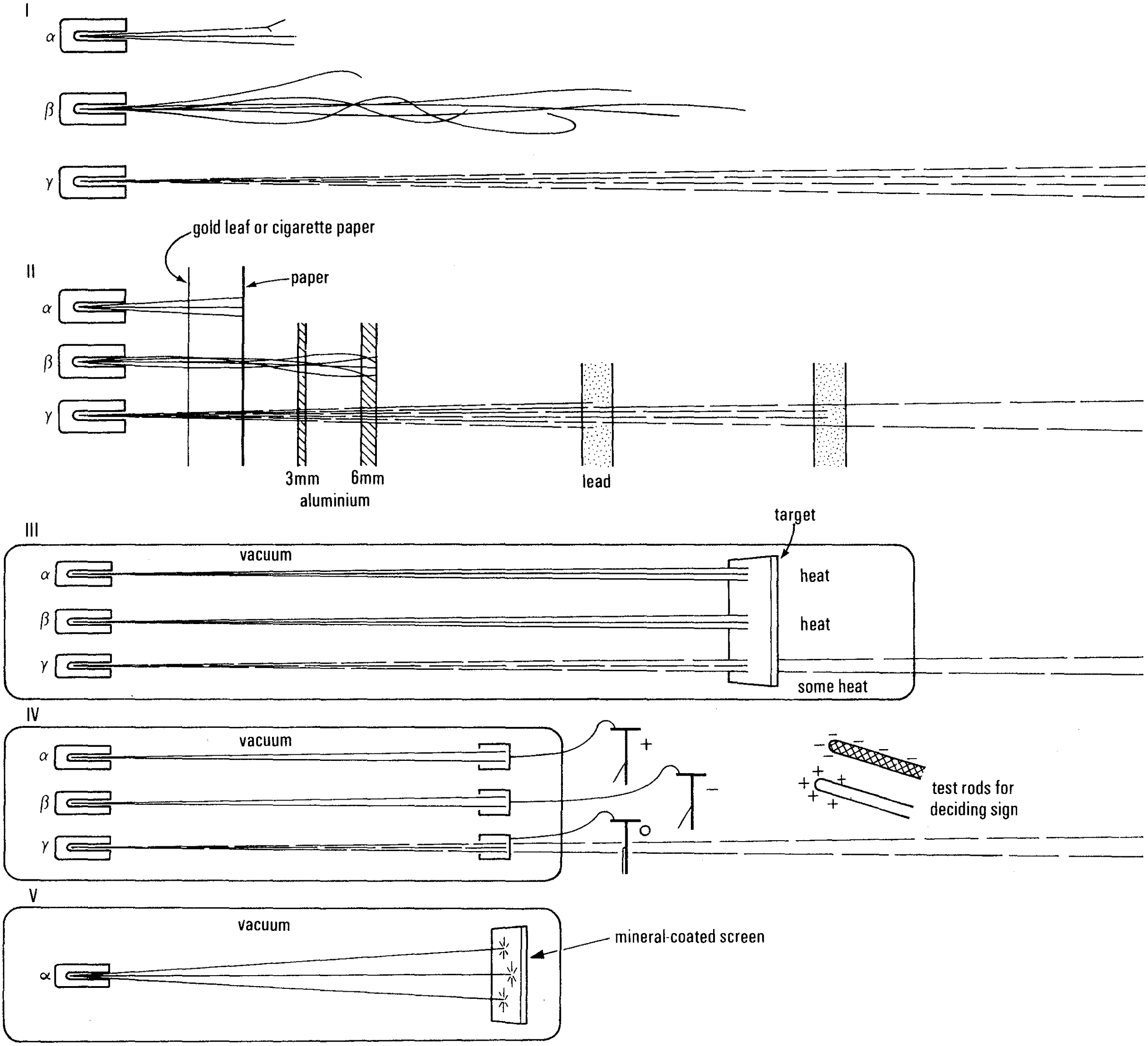
What happens to the source? Since radioactive atoms fling out projectiles you would expect the atoms remaining afterwards to be different. They *do* become different. They do not just stay permanently the same, as atoms of ordinary copper or carbon do. They are unstable and when they suddenly break up and fling out a particle such as an alpha particle, they become *atoms of a different chemical element*.

Measuring a stock of atoms Suppose you have a stockpile of radioactive atoms. By counting how many of these atoms break up in a given time, you can estimate the size of the whole stockpile. So counting with a counter is very useful.

Experiment 85
Uranium oxide source

Try a small metal tray covered with radioactive material inside your electroscope.





I Alpha, beta particles and gamma rays from radioactive sources travel through air.

II Alpha, beta particles and gamma rays are stopped by sheets of various metals.

III Alpha, beta particles and gamma rays travel straight in a vacuum and produce heat when stopped.

IV Alpha, beta particles carry charges; gamma rays carry no charge.

V Alpha particles make tiny flashes of light when they hit a suitable screen.

First charge your electroscope, as follows: attach the hook to the top of your electroscope; charge a strip of plastic (polythene) by rubbing it with a cloth. (The cloth pulls electrons off the plastic.) Scrape the charged plastic on the hook to transfer some charge to the electroscope. Then lift the hook away, using the plastic strip as an insulating handle. Without the hook your electroscope will be extra sensitive to small changes of charge on the leaf.

Watch the leaf for a minute or two. Then ask your teacher for a small tray with a thin layer of uranium oxide spread on it. The black uranium oxide powder is held on the tray with glue, to make sure it does not spill.

Lift the glass window of your electroscope and put the uranium oxide source on the floor inside it. Close the window.

Charge your electroscope again and watch the leaf.

Uranium is a heavy metal. Its atoms fling out alpha particles which are not very energetic – but they may make enough ions for you to see the effect.

If you like, you could compare two sources of different strengths by timing the fall of the leaf with each.

Note: Although uranium oxide is not regarded as dangerous radioactive material you should obey the general rule for *all* people handling radioactive material: AFTER THE EXPERIMENT, WASH YOUR HANDS BEFORE YOU EAT.

Radiation and distance As you have seen, alpha particles are stopped by a few cm of air, a thin sheet of paper, your skin. Beta particles are stopped by a few cm of metal sheet. But gamma rays are not.

However, the effect does become less at greater distances. And your old friend, the inverse square law, applies to gamma radiation as well as to light and to gravity. So, if you ever have to safeguard yourself from gamma radiation you should move further away, and the law will give you considerable reassurance.

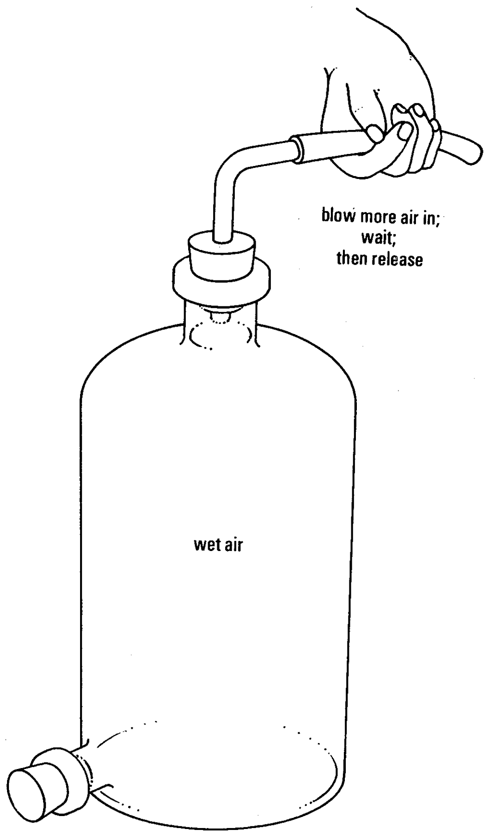
EVIDENCE?

You have seen evidence of something coming from certain materials (called radioactive) in random events which can be counted. But when we say that radioactive atoms are shooting out particles still smaller than atoms, carrying electric charges and moving at great speeds, it looks so far like story telling. But we can now bring in evidence that you have already seen: tracks in a cloud chamber.

CLOUD CHAMBER

If you cool a sample of wet air, a cloud of water drops will form. You can make the cooling happen by letting the air expand as it pushes a piston *out*. (This is the opposite of the heating when a piston is pushed *in* to compress a gas. Then the temperature rises and can even fire the fuel in a diesel engine's cylinder.)

This is how clouds form: warm wet air is pushed up and as it goes higher its pressure decreases and it gets colder. The colder air cannot contain so much water vapour: the vapour* becomes *super-saturated* and then condenses to water drops in a cloud. In the demonstration sketched, you can see wet air forming a cloud when it expands and cools.



Demonstration 86a
Making a cloud

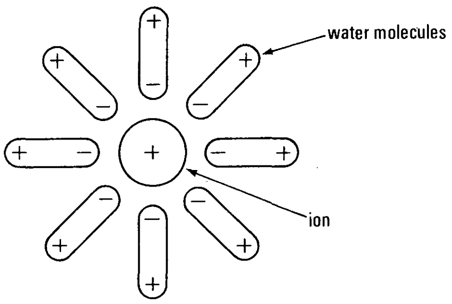
The water drops of a cloud need something to start on. An extremely small droplet, just a few molecules, cannot form all by itself. Its molecules would escape from each other again. If the air

*We sometimes speak of 'saturated air', meaning air with saturated water vapour – the vapour so thick that if any more is added some will try to condense. The air is just there anyway and it helps in the cooling by expansion. When the temperature is lowered, the air-space can hold even less vapour for saturation; the vapour becomes super-saturated (more than ready to start a cloud).

contains attractive particles that water can wet (usually minute particles of salt), they can serve as centres on which larger water drops can start to form.

If most of the attractive particles are cleared out, it becomes difficult to make even supersaturated air produce a cloud of drops.

However, if there are ions in the air, they serve as excellent centres for starting a drop. Water

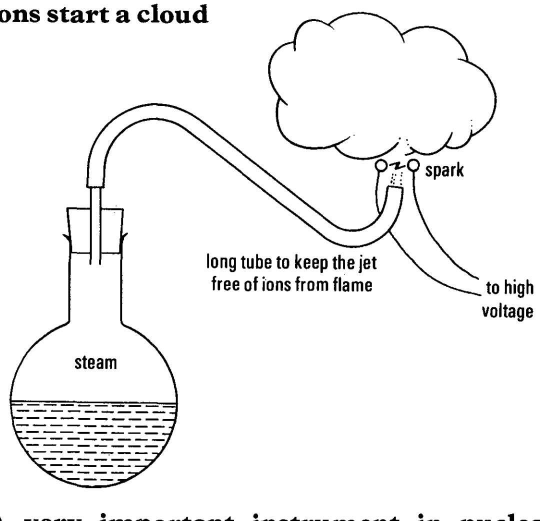


molecules are electrically oblong with + and − charges at the ends. So they can cluster easily round a charged particle.

If you repeat the experiment of making a cloud in a flask you will find that when all attractive particles have been removed it is difficult to make much of a cloud until you supply ions with a small flame. Throw in a lighted match.

You may perhaps see a demonstration of an electric spark making ions in a jet of steam: the spark enables dense cloud to form.

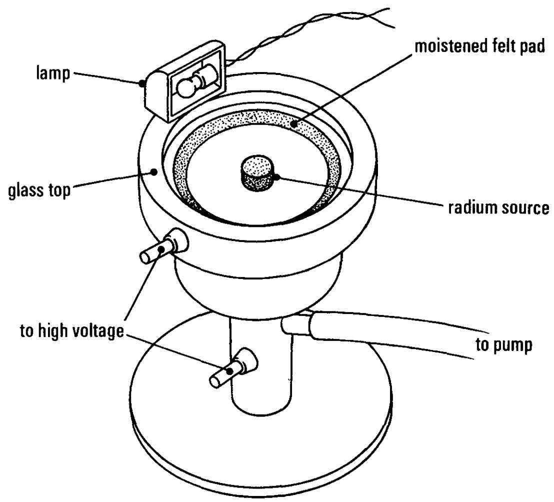
Demonstration 86b
Ions start a cloud



A very important instrument in nuclear physics You already know that ions are produced in the air near radioactive material. So try a sample of such material in a flask where a cloud is to be made. We call this a *cloud chamber*.

Demonstration 86c
Expansion cloud chamber

Even if you have seen this many times before, watch the expansion cloud chamber when the wet air suddenly cools. An electric field must be applied from top to bottom of the chamber to clear away any ions that have been formed earlier. When a small source sends out alpha particles you can see their tracks. The alpha particle has rushed through the wet air making many ions which are left in its

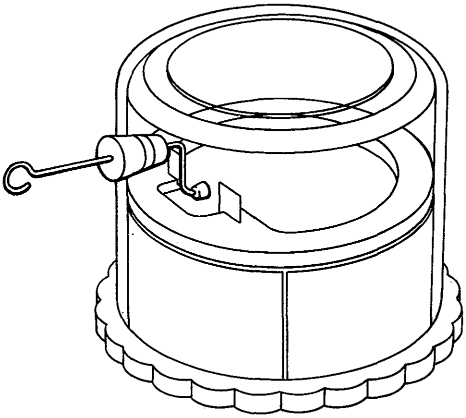


trail. Then (long after the alpha particle has passed by) water drops form on those ions, marking the track.

You can see that alpha particles travel short distances in straight lines; then the tracks end. If you could count the number of water drops formed in a single track, you would find that the alpha particle must have made more than 100 000 pairs of ions. It must have drawn electrons off 100 000 or more atoms as it passed by or through them. *Yet* none of those collisions bend the path of the projectile enough to show. Therefore the alpha particle must have a much greater mass than the electrons that it pulls out of atoms. You never saw it make a serious collision with anything massive. From that, we conclude that atoms must be mostly hollow. Any large mass, comparable with the mass of an alpha particle, must be too tiny a target to hit often. But electrons could be anywhere outside that central core or nucleus.

Experiment 87
Diffusion cloud chamber

Try setting up and watching your own cloud chamber. In this form the air in the plastic box contains saturated vapour of alcohol instead of water vapour. And instead of cooling the air by sudden expansion, dry ice under the floor cools the lower layers of the quiet air so that alpha particles from a small source can make tracks of alcohol droplets at that level.



To set up the chamber, put methylated spirit on the padding inside the top of the chamber, using an eye-dropper. Also put a drop or two on the black base of the whole apparatus.

Ask your teacher to put a little dry ice from the CO_2 cylinder in contact with the plate. Screw the base cap on again and invert the chamber. The cloud chamber must be level. Place it on the three wedges provided, and adjust them to get it level. (If it is not level, you may see air currents moving in the chamber which you can use as guides in levelling.)

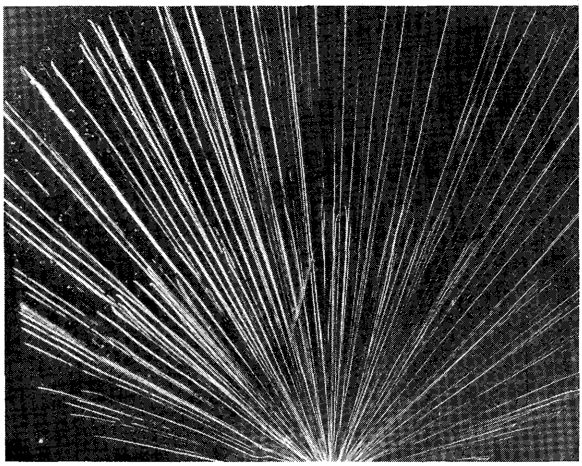
Put the top back on the chamber and give it an electric charge by rubbing it with a handkerchief or a finger nail. That will charge it sufficiently to make a strong enough electric field inside to sweep away old ions quickly and drive some ions of a new track into the sensitive layer.

Illumination is important Adjust the lamp to illuminate a layer a few millimetres above the base plate.

Soon, usually within 30 seconds of setting up the cloud chamber, you will see alpha particle tracks coming from the weak radioactive source in the side of the chamber.

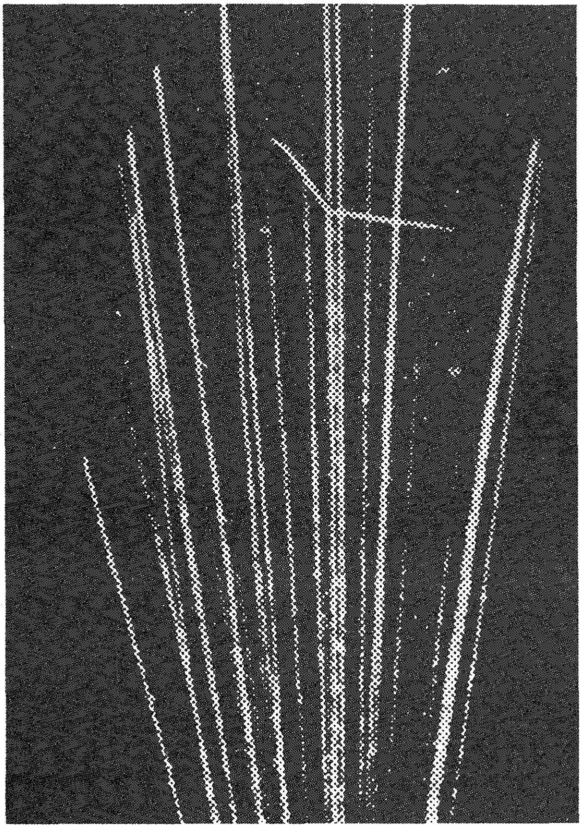
If the tracks are not sharp, rub the top again to improve the electric field.

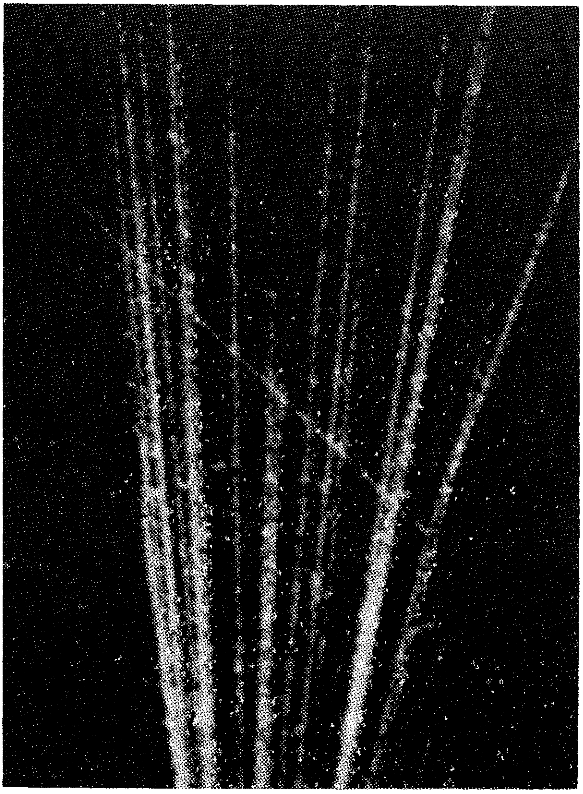
A rare event Very rarely, we see an alpha particle track make a sharp bend. At the bend, another track appears: the track of a recoiling target. In such a collision the alpha particle has hit something of its own mass or much greater.



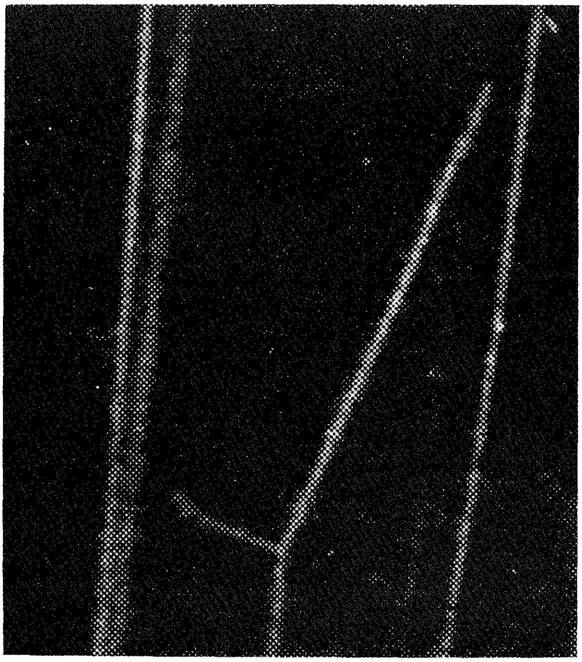
Alpha particle tracks from a small source. Note that there are two lots of alpha particles, one with a shorter range than the other.
J. Chadwick, Cavendish Laboratory, University of Cambridge.

Alpha particle tracks in wet nitrogen. One collided with a nitrogen nucleus and moved to the right. The recoiling nitrogen nucleus made the short thick track.
P. M. S. Blackett (1925) Proc. Roy. Soc., A, vol. 107, Pl.6.





Alpha particle tracks in wet hydrogen. One collided with a hydrogen nucleus, which recoiled forward and upward, making a thin track.
P. M. S. Blackett (1925) Proc. Roy. Soc., A, vol. 107, Pl. 6.



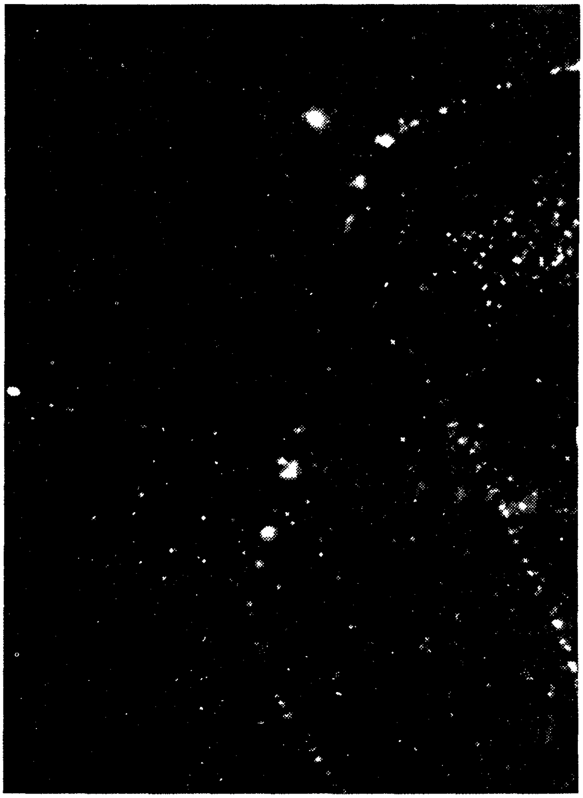
Alpha particle tracks in wet helium. One collided with a helium nucleus. After the collision the two tracks make 90° with each other. As you saw in Year 4, that angle only occurs when the colliding bodies have equal masses. The photograph is a lucky choice of a case when the fork occurred directly facing the camera.
N. Feather (1933) Proc. Roy. Soc., A, vol. 141, Pl. 2.

Such *forks* occur so rarely that you have little chance of seeing one in the expansion cloud chamber unless you take a long series of photographs. So, instead of waiting to see one you should look at some selected photographs. From the angles, *assuming conservation of momentum in the collision (as always) and assuming conservation of kinetic energy*, we can work out the relative masses of the alpha particle and the target it hits. That is how the notes on the photographs were settled.

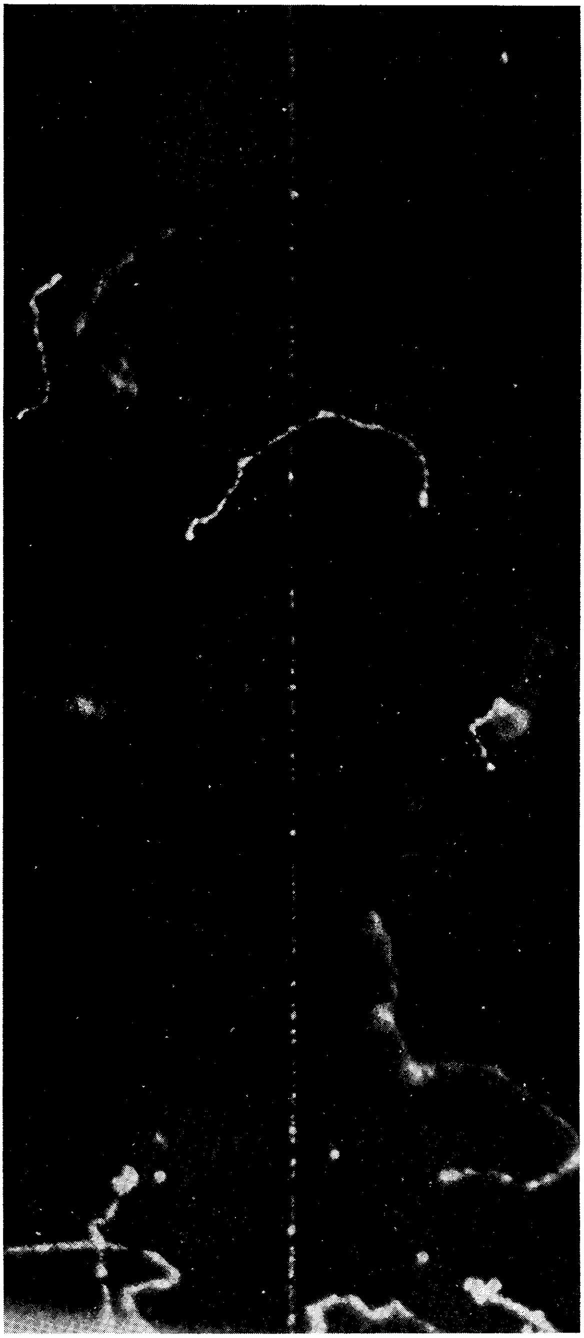
Here is the evidence for the new atom model: the nuclear atom. The many straight tracks tell you that *atoms are mostly hollow* and the few forked tracks tell us *there is a tiny massive core.*

OTHER TRACKS

Beta particles (fast electrons) Look at the photo of a cloud chamber track made by a beta particle. It fails to keep a straight path. It is much

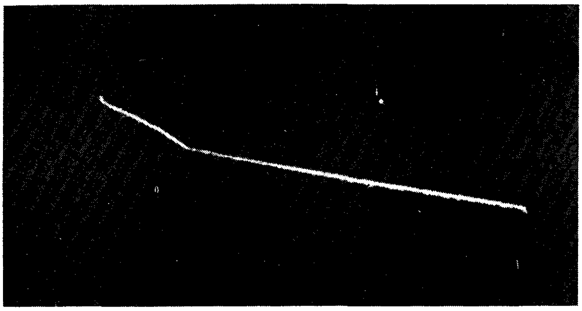


Track of a beta particle in wet air.
C. T. R. Wilson (1912) Proc. Roy. Soc., A, vol, 87, Pl. 7.



Beta particle tracks. One fast particle crossed the tracks of several slow ones.
C. T. R. Wilson (1923) Proc. Roy. Soc., A, vol. 104, Pl.16. Photo, Science Museum, London.

X-rays passing through wet air eject electrons which leave tracks. Gamma rays produce a similar effect with longer tracks.
C. T. R. Wilson (1912) Proc. Roy. Soc., A, vol. 87, Pl.8.



A neutron which came from a source below the picture and left no track, hit a nitrogen nucleus and was absorbed: the resulting nucleus ejected an alpha particle, and the remainder recoiled.
N. Feather (1933) Proc. Roy. Soc., A, vol. 142, Pl. 7. Photo, Science Museum, London.

less massive ($\frac{1}{7000}$ of an alpha particle's mass) and unless it is flying extremely fast it is easily deflected by the electric fields of electrons as it passes by.

X-rays and gamma rays These make no tracks as they travel straight ahead. But when one stops at some atom in its path and flings out an electron, the electron makes a track – short and curly because it is not moving very fast, so it is easily deflected.

An invisible track One photo shows something specially important. Something travelling up from below the picture made no visible track but suddenly a pair of tracks appear, showing by their directions that some upward momentum had been received from an invisible source. The unseen particle was a *neutron* – see the discussion later.

VITAL STATISTICS OF THE PARTICLES

You measured the speed and e/m for electrons. In the same kind of way, experimenters measured speed and the CHARGE/MASS ratio for alpha particles. They also measured the CHARGE of each alpha particle by counting a large number of them and catching the total charge. The result: an alpha particle has a positive charge $2e$, where e is the size of the electron charge. It has the mass of a helium atom, four times the mass of a hydrogen atom. So we may call an alpha particle He^{2+}.

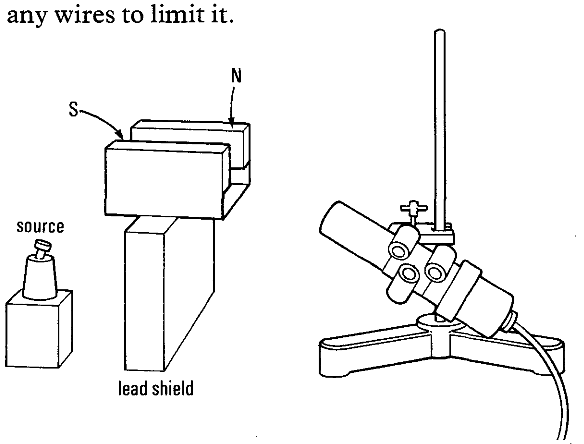
The measured speed of alpha particles is huge: up to 15000 kilometres per second (about 34 million miles per hour).

Beta particles from radioactive material that emits something with a larger range turn out to have the same e/m as electrons. In fact they *are* electrons, moving at enormous speeds* – even as great as 98 per cent of the speed of light.

Gamma rays Attempts to measure the properties of gamma rays show that they are not charged particles but are X-rays of very short wavelength. They go straight out, on and on in straight lines at the full speed of light, and never stop until they meet some atom from which they hurl out an electron with the crack of a terrific electromagnetic whip.

Demonstration 88
Bending beta particles' tracks

You may see the demonstration sketched. A small source of beta particles fires them towards a counter tube, but blocks of lead are put in the way, and practically none of the particles reaches the counter. Then a magnet is placed so that its field crosses the path of the beta particles. Their stream is like an electric current – it *is* a current without any wires to limit it.



With the magnet suitably placed, many particles reach the counter and you will hear or see the effect of the magnet.

Turn the magnet round so that its field runs the opposite way (unsuitably placed!) and you will see the effect of that.

If you like, see whether you can argue from the magnet's 'suitable' placing to settle whether the electric charge on the moving particles is positive or negative.

* Speed measurements on some of the fastest beta particles give smaller values of e/m – though the particles have normal values after they have been slowed down by many collisions. This suggests that they have greater mass at higher speeds – fitting with the idea suggested by Relativity.

(Nowadays we know of many new radioactive materials that emit beta particles of the opposite sign – *positrons*, as we call them, or e^+. How would you have to place the magnet for a stream of positrons?)

Bending the tracks of alpha particles? If you try to bend the track of an alpha particle with the same magnet, you will be disappointed – there is no noticeable bending. An enormously stronger magnetic field is needed; then there *is* bending, as the cloud-chamber picture here shows.

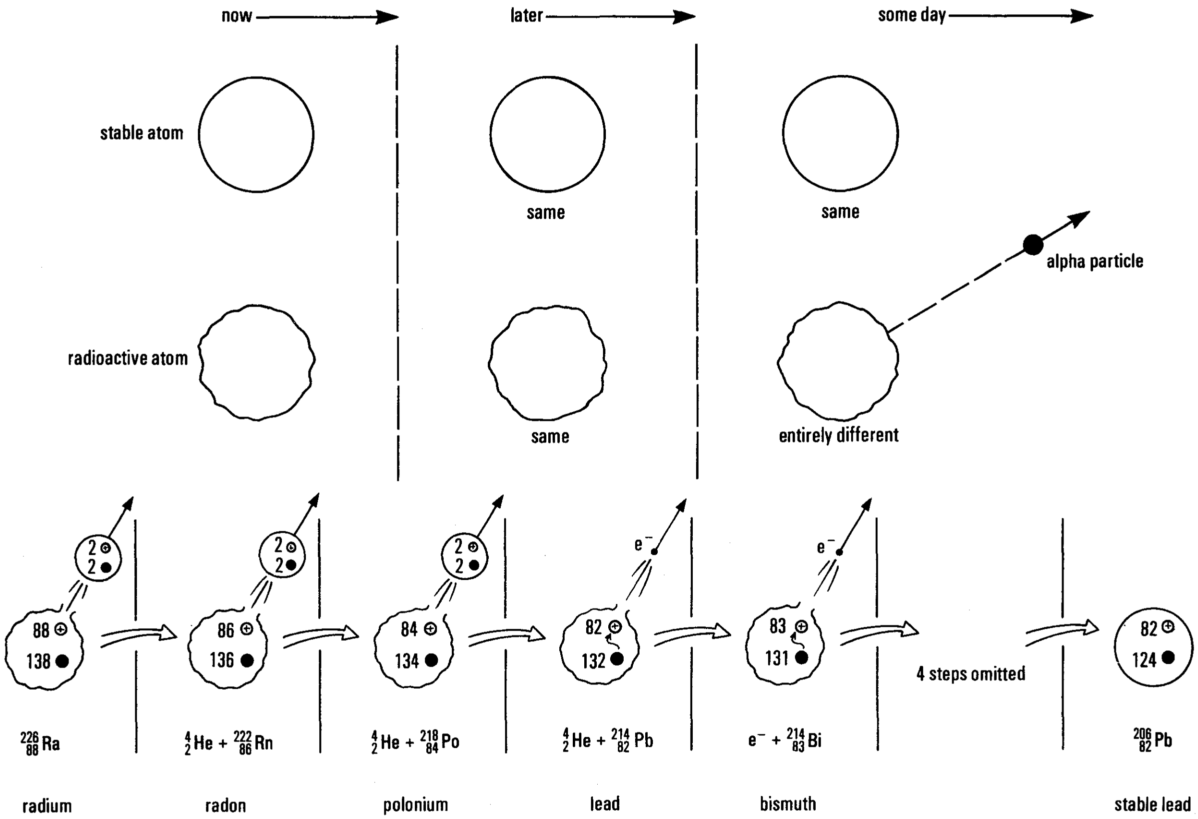
Alpha particle tracks in a very strong magnetic field.
P. Kapitza (1924) Proc. Roy. Soc., A, vol. 106, Pl.9.

That picture was made by the Russian Kapitza who built a huge battery, and later a huge dynamo, to make big enough currents (on short circuit!). The alpha particles were not moving as fast as beta particles, so the difficulty of bending their paths shows that they must be much more massive – in fact, they are about 7000 times as massive as beta particles.

CHANGES OF ATOMS?

In ordinary chemical changes, atoms of one element leave one compound to join with atoms of another element in a different compound – or they may join together as molecules of gas which bubbles out of some chemical brew. But in all that, *the atoms of each element remain unchanged*, except for minor exchanges of outer electrons. (For example, when atoms of hydrogen and oxygen explode to form water, there are just as many hydrogen atoms in the final product as there were before the explosion.) We record this when we write:

$$2H_2 + O_2 \rightarrow 2H_2O$$



There are just as many Hs on the righthand side as on the left. We may add a term ($+10^{-18}$ joule) to describe the explosion. Not a very impressive number! Take 2 kg of hydrogen instead of 2 molecules and the energy released is 300×10^6 J. Chemical explosives *are* powerful. And that is also the energy that has to be supplied to drag the water molecules apart to make molecules of their constituents.

Radioactive changes are greatly different: the energies involved (which will be discussed later) are millions of times greater, and the atoms do *not* stay the same – there is a sudden change to a completely different element.

THE RADIUM FAMILY

Unstable atoms Soon after the discovery of radioactivity in 1896, Marie Curie and her husband Pierre discovered a new element which they named *radium*. They extracted dangerously large samples of radium from vast quantities of rock and experimented on its radioactive behaviour.

A radium atom remains a radium atom, with the chemical behaviour of a heavy metal, until it suddenly hurls out an alpha particle. The remainder of the radium atom is no longer a heavy metal, but quite a different element. This 'daughter' of radium is an atom of a heavy inert gas, the end of the helium, neon, argon, krypton, xenon series. It is called *radon*. (See bottom diagram, p. 161.)

The atomic masses have been measured directly, radium 226, radon 222 – a difference of 4, suggesting that the lost alpha particle is a helium nucleus. Separate measurements confirm this.

Radon gas is itself unstable and radioactive. Each of its atoms suddenly, unexpectedly, hurls out an alpha particle. The remainder is a new atom, very unstable, which is called *polonium* – the 'daughter' of radon, and 'granddaughter' of radium.

The polonium atoms soon break up, suddenly, unexpectedly. Each hurls out a very energetic alpha particle and becomes a new atom, also unstable, which behaves chemically just like *lead*: it is a radioactive isotope of lead until it in turn breaks up.

Each lead atom breaks up hurling out a beta particle, a very fast electron, with a gamma ray to carry away some extra nuclear energy. The new atom is an unstable isotope of *bismuth*.

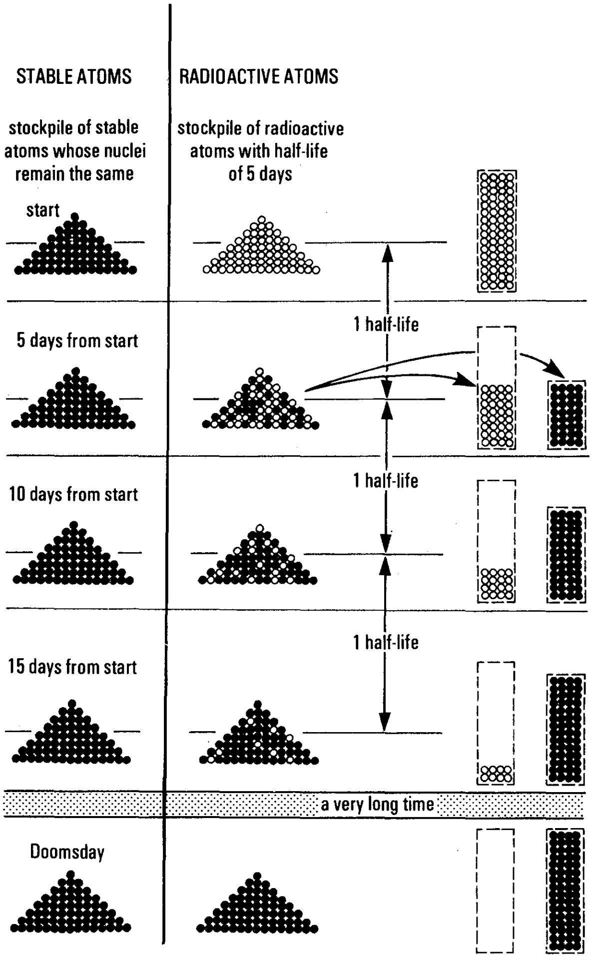
The series continues through several more radioactive elements and stops at a stable form of *lead*.

The series does not begin with radium: it begins with uranium, several stages earlier. There are several other such families which run more or less parallel with this uranium family.

CONSTANT INSTABILITY: 'HALF-LIFE'

All the unstable members of these strange families have a constant, reliable characteristic: the atoms show no sign of ageing, or growing weaker, however long they last. Each radioactive element has a constant chance of breaking up in each succeeding second.

We describe this by a useful length of time, the 'half-life' of the radioactive element. For each individual atom the betting is 50:50 for and



against its breaking up at any time up to one half-life from now. The break up seems to be controlled by pure chance. And that chance does not change and make break-up more likely for atoms that happen to survive longer. The sketch illustrates this process, for a radioactive element with a stable (non-radioactive) daughter element.

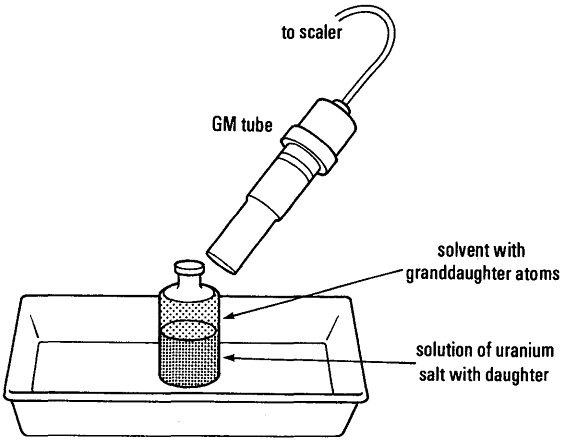
For radium the half-life is 1650 years. Start with 1000 milligrams of radium now, and 1650 years later you will have only 500 milligrams left. And, after a further 1650 years, only 250 milligrams will be left; and so on.

For radium's daughter, radon, the half-life is only 3.8 days. In less than 4 days half the radon gas will have disappeared. You will find helium gas there instead, with the solid products.

Demonstration 89
Decay of a radioactive element

See a demonstration of radioactive decay, with measurements to see whether the element does have a constant half-life.

A solution of a uranium (^{238}U) salt is placed in a plastic bottle with a thin wall. Since radioactivity is a property of the innermost nucleus of the atom it is not affected by chemical combination.



With its very long half-life the uranium continues to break up yielding a meagre stream of daughter elements. The daughters break up also, with a half-life of 24 days, but the stockpile of the daughter atoms is being replenished continually by the uranium. The granddaughters are also breaking up, though their stockpile is being replenished continually, as long as the daughters are there.

A special organic solvent is poured in above the uranium salt solution and the bottle shaken quickly. The *granddaughter atoms* are picked up by the solvent, but *not the daughter atoms*. So a Geiger counter tube held above the bottle responds only to the beta particles from the granddaughter atoms. Those high speed electrons shoot up through the thin top of the bottle into the tube and are counted by the scaler.

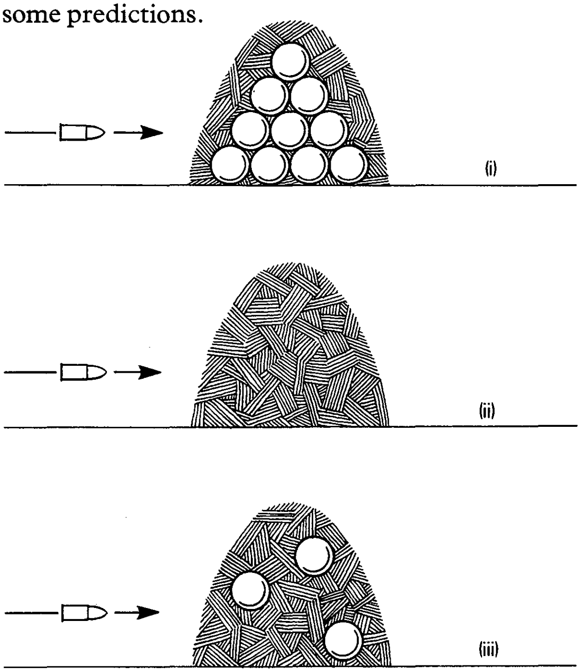
Record the count of beta particles for a 10 second period, again and again. Note the 'time-of-day' for each 10s counting period as well.

About 10 minutes later, make a 'background' measurement with the tube and scaler. Allow for the background, which is always present, in each of the main counts.

Plot a graph of corrected 10 s counts against 'time-of-day'. Can you find the half-life?

THE GREAT INVESTIGATION

Alpha particles as tools Suppose you wished to investigate the shape and size of some concealed object. Pretend you have a large mound or truss of hay and you suspect that there are some small but massive iron cannon balls hidden in it. Suppose you are not allowed to pull the hay aside. You might still investigate its secret store by firing a stream of machine-gun bullets into it. Let us make some predictions.



(*i*) *If* the hay is only a thin covering on a solid mound of cannon balls, what will the bullets do?

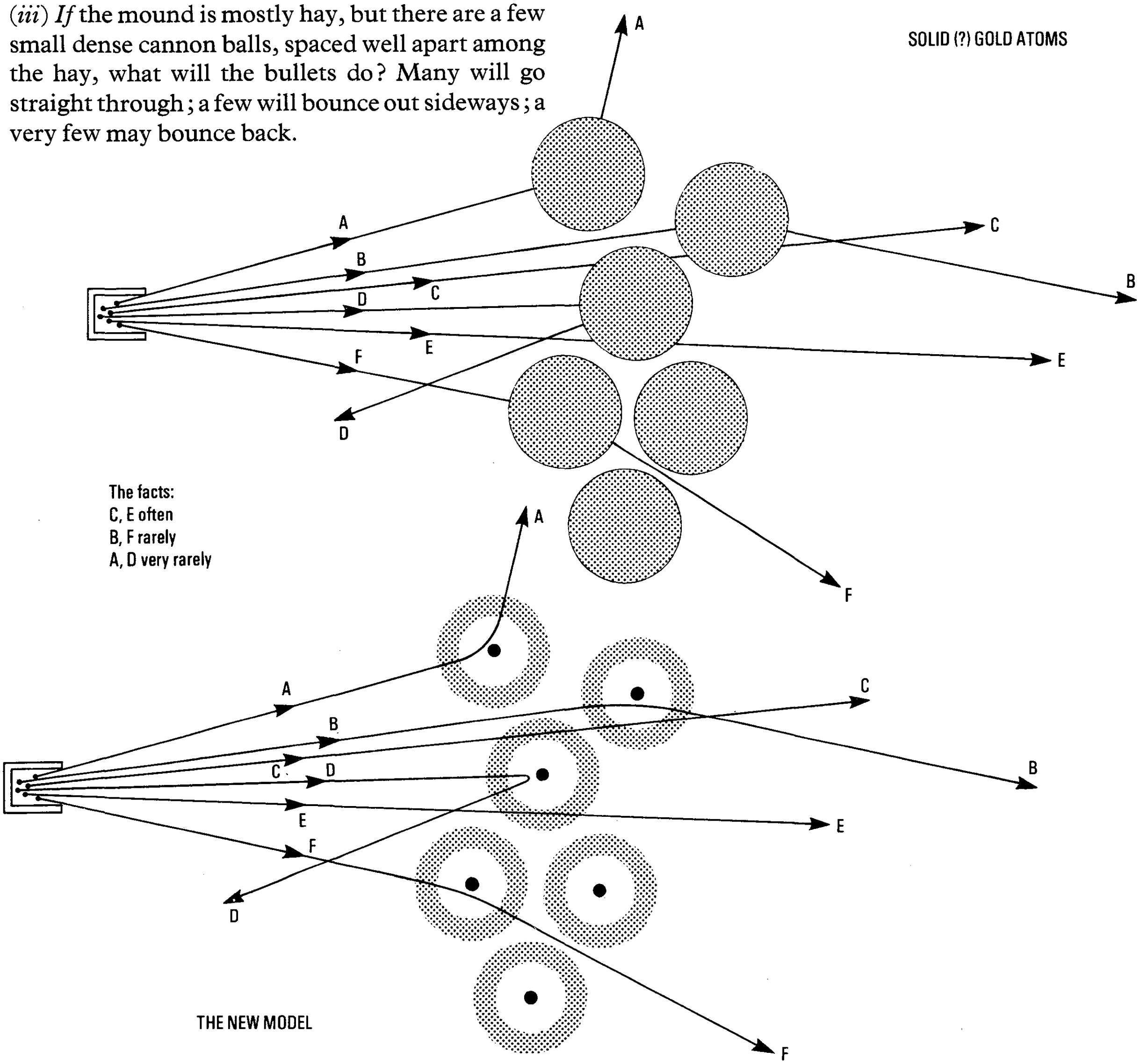
All will bounce back, or perhaps stop and never reappear.

(*ii*) *If* there is only hay, and no cannon balls, what will the bullets do? All will go practically straight through and come out on the far side of the hay, moving almost as fast as before they went in.

(*iii*) *If* the mound is mostly hay, but there are a few small dense cannon balls, spaced well apart among the hay, what will the bullets do? Many will go straight through; a few will bounce out sideways; a very few may bounce back.

with electrons embedded in it. (That fitted the facts of extracting electrons and making ions.)

An alpha particle, known to carry a 2+ charge, could easily pull negative electrons out of such a pudding as it flies past, but it could not be pushed far off its own course by such a large positive ball. It could not get sufficiently near to enough of the total positive charge to experience a strong repulsion.



Rutherford, who had done many of the early, very fruitful investigations of radioactivity, tried an experiment like that on an atomic scale. He encouraged two young colleagues, Geiger and Marsden, to fire a stream of alpha particles at a very thin leaf of gold. They already knew that alpha particles could get through such a thin leaf and they expected none to bounce away at large angles. The 'thinking model' for atoms at that time was like a plum pudding: a ball of positive charge

So Rutherford and his colleagues expected a result like (*ii*) above for the mound of hay. But, to everyone's amazement, while most of the alpha particles went practically straight through the gold, a few bounced away at large angles and a very few even bounced back.

The new model Rutherford, surprised and enthusiastic, was *forced* to devise a new thinking model. All the positive charge of a gold atom, and most of its mass, *must* be concentrated in a *very small core* so small that an alpha particle aimed very close could be bounced back. That is the nuclear atom model.

At once two important questions arose: (*i*) what is the force between the flying alpha particle and a gold nucleus? And (*ii*) if the force is electrical, how big is the charge on that nucleus?

In ordinary experiments with electric charges such as you might try in the lab, the two like charges repel with an inverse-square law force – just as two masses attract gravitationally.

For (*i*), Rutherford tried the simplest guess first: that the same inverse-square law of electrical repulsion holds for the positive charges on the alpha particle and the gold atom's nucleus.

For (*ii*) Rutherford adopted a rash guess. In the making of ions there were already hints of the maximum number of electrons that could be extracted from some atoms: hydrogen 1; helium 2; carbon probably 6. Then those would also be the number of basic positive charges ($+e$) on the nucleus. The numbers suggested above are the *serial numbers* of the elements in the chemical list of atoms in order of atomic masses. Look at the periodic table in a Chemistry text.

So Rutherford adopted the guess that the number of basic positive charges on the core or nucleus of the atom is the atom's serial number, now called the *atomic number* and given the symbol *Z*.

Gold is number 79 on the list. Rutherford tried assuming that an alpha particle with charge $+2e$ made a close encounter with a tiny gold nucleus with charge $+79e$.

The test of Rutherford's nuclear model Rutherford pictured a stream of alpha particles being fired at a very thin slab of gold atoms (see the sketch). Many would miss any close encounter with a gold nucleus and go straight through like C and E in the sketch. A few would pass close enough to be seriously deflected, like B and F. And a few few like A and D would bounce back.

Rutherford made a target-hitting calculation of the chances of some alpha particles being aimed close enough to the bull's eye to suffer various large deflections. Geiger and Marsden made a long series of measurements to test Rutherford's prediction. They counted tiny flashes of light (scintillations) made by alpha particles hitting a special screen.

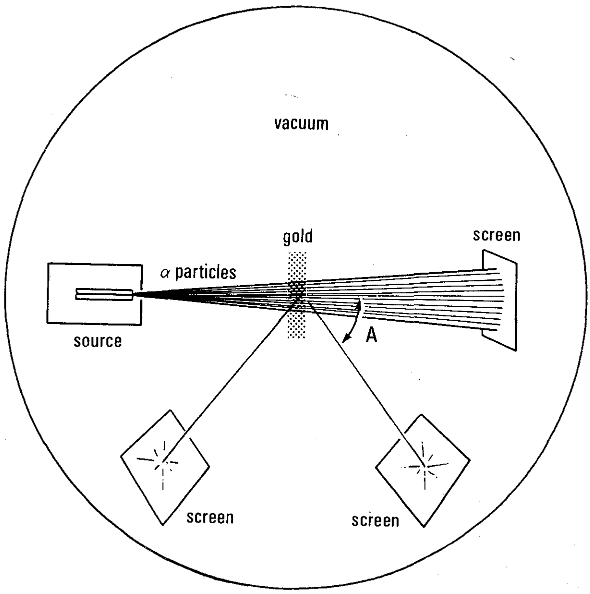
The test is shown below.

SCATTERING OF ALPHA PARTICLES BY GOLD
(Experimental test by Geiger and Marsden)

EXPERIMENTAL MEASUREMENTS		TEST OF THEORETICAL PREDICTION	
Angle of Deflection A*	*Experimental Count† N*	*Proportion predicted (on a special scale)*	*The test* $\frac{N}{\text{proportion predicted}}$
150°	33	1.15	29
135°	43	1.15	31
120°	52	1.79	29
105°	69.5	2.53	28
75°	211	7.25	29
60°	477	16.0	30
45°	1 435	46.6	31
30°	7 800	223	33
15°	120 570	3 445	35
10°	502 570	17 330	29
5°	8 289 000	276 300	30

* Of path of alpha-particles.
† Number of scintillations seen, for deflection $A°$, in a standard time.
Note: In the actual experiments Geiger and Marsden made one set of measurements for the larger angles of deflection, and another set, with a much smaller radioactive source, for the smaller angles. To make one complete set in the table above, the numbers for smaller angles have been multiplied up to fit the set for larger angles. The multiplying factor was provided by experiment because counting was done for 30° in *both* sets.

Considering that the test was made by counting tiny flashes of light seen with a microscope in a



dark room, experiment agreed with theory as closely as could be expected.

Rutherford's theory also predicted the way the count on a fixed screen would depend on the speed of the alpha particles:

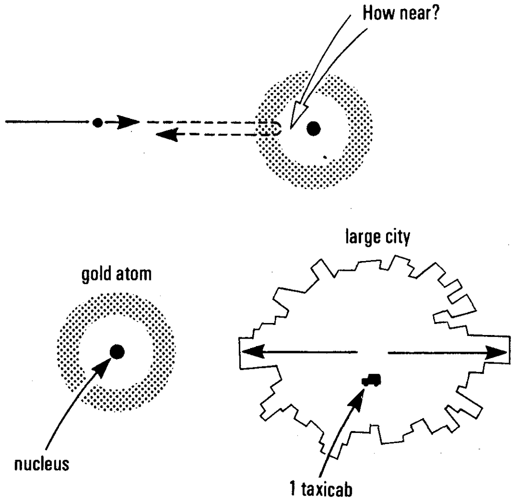
$$N \propto 1/v^4$$

and on the electric charge of the scattering nucleus:

$$N \propto (Ze)^2$$

Experimental tests with several speeds and with thin sheets of copper, silver, and platinum instead of gold, all confirmed those predictions.

Then from the known mass and speed of the alpha particles Rutherford could at once calculate the distance of closest approach (the distance from a gold atom's centre at which an alpha particle



The proportions are similar.

making a very rare head-on collision would come to rest momentarily and bounce straight back). With his assumptions, that distance came out to be *ten thousand times smaller* than the radius of an atom.

Your oil-film measurement and your estimate for air molecules led to atomic *radii* of 1 or 2×10^{-10} metre. Rutherford's estimate of closest approach was about 0.0001×10^{-10} metre. The gold nucleus must be as small as that or smaller!*

In a neutral gold atom there are 79 electrons which the nucleus holds and controls with its charge of $+79e$.

The experimental test of the alpha particle scattering prediction keeps its constant result all the way from 180° deflection to 10° or even 5°. So there must be completely empty space – vacuum – for some distance out from the nucleus, then the cloud of electrons further out (in the suburbs of the comparison sketch with the taxicab in the city). And except for those light-weight electrons there is empty space all the way out from the nucleus to the outside edge of the atom at a radius of a few 10^{-10} metres. That is why we call the nuclear atom 'hollow'.

The outermost of the electrons live mostly at the outer edge – they *form* the outer edge! Those are quite easily detached, to make ions or take part in chemical exchanges. We *know* they are easily detached because we can bombard atoms and make ions experimentally, and we *expect* them to be easily detached because they are not held by the binding attraction of the full nuclear charge. When such an outermost electron 'looks in towards the nucleus' it 'sees' the $+79e$ charge shielded by 70 or more $-e$ charges of other electrons between it and the nucleus.

Thus Rutherford used the orbits of alpha particles to test the inverse-square law of electric force over a range of sub-atomic distances, much as Newton used the orbits of planets and comets to test the inverse-square law of gravitational force.

MAN-MADE NUCLEAR CHANGES

In the early days of radioactive experiments stable elements seemed permanently stable. Then some atoms were changed by bombardment with high speed nuclei.

Alpha particles upset nitrogen Forks in cloud chamber tracks showing elastic nuclear collisions are rare, but Rutherford found even rarer events in which an alpha particle (He^{2+}) entered a nitrogen nucleus (N) and disappeared while a proton (H^+) came out. The collision was *not* elastic: K.E. was not conserved because there was a change in energy stored in the nucleus. In a search for examples of such an event, a quarter of a million expansions of an automatic cloud chamber were photographed. The picture shows one of the seven examples that were found.

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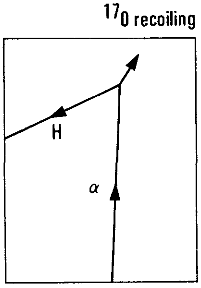
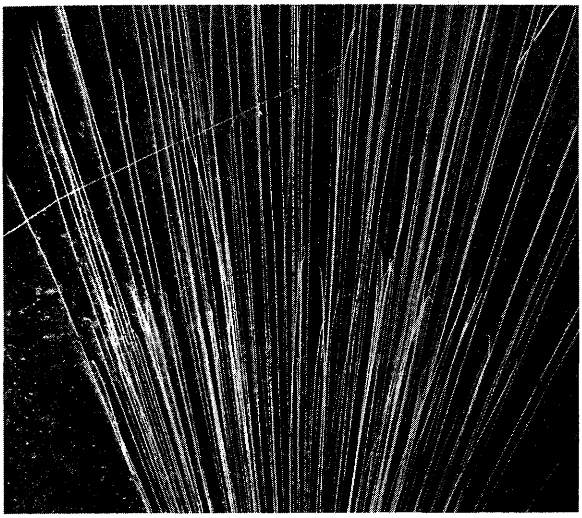
* Nuclear material has enormous density. 'A large mountain, if it could be compressed so that all the nuclei of its atoms were touching would fit on a teaspoon.' (Quoted from the Open University's Science Foundation Course, Unit 31.)





Nuclear change by bombardment. A cloud chamber photograph of Rutherford's discovery. An alpha particle hits a nitrogen nucleus and disappears. A proton (H) is emitted and the resulting oxygen nucleus recoils. *P. M. S. Blackett and D. S. Lees (1932) Proc. Roy. Soc., A, vol. 136, Pl. 7.*

This was a forerunner of hundreds of nuclear changes that were found when protons and other particles were accelerated to high speeds in 'guns' working at up to 10^9 V or even more. Targets of any element can be bombarded: and many, many radioactive isotopes have been produced.

Clues: radioactive tracers Some of these radioactive isotopes are of great value in investigations in biology, medicine, engineering, ... They behave in exactly the same way in chemical reactions as their stable 'brothers', the ordinary isotopes. A tiny amount of the radioactive isotope mixed with a lot of the common one will travel with the common one wherever it goes – and so can be 'traced' with a Geiger counter.

Bombardment with a strange result When alpha particles bombard the light metal beryllium the alpha particle sometimes disappears and a strange invisible, penetrating radiation, which leave no trace in a cloud chamber, travels ahead. If some hydrogen (perhaps in a block of paraffin wax) is placed in the way, we see protons hurled forward. Chadwick, an expert colleague of Rutherford's, showed about fifty years ago that these invisible missiles were neutral particles with a mass which was almost the same as the mass of a proton. This was the discovery of a new nuclear particle – the *neutron.*

NEUTRONS

A neutron, small as any nucleus, flies through matter easily because it has no electric charge so that it feels no electrical repulsion or attraction. Yet when it makes a very close encounter with a nucleus it may bounce away in an elastic collision, sharing momentum and energy with the target. So it is possible to slow down a fast neutron by a series of such elastic collisions – best of all, the light nuclei (hydrogen, for example) close to the neutron's mass.

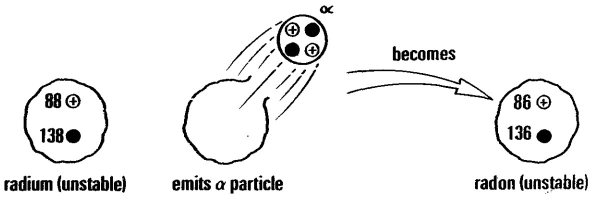
Neutrons make sneak raids on nuclei With some target nuclei, neutrons with some speeds can make quite a different collision. Free from discouraging electrical forces it can sail in so close that the nuclear forces of the target clutch it. It enters the target nucleus and stays there, perhaps ejecting another particle. It has thus converted the target nucleus into a new, different nucleus, often an unstable, radioactive one.

The building bricks of nuclei Remember how some elements have atomic masses that are whole multiples of a proton's mass – or nearly so. When mass spectrometers revealed isotopes, many more whole number masses appeared. Neutrons are only slightly more massive than protons and we now picture every atomic nucleus as made up of protons and neutrons – nucleons as we now call both of them.

The number of protons in a nucleus tells us the number of positive electron charges on it. That number is Z, the ATOMIC NUMBER or serial number of the element in the periodic table. The nucleus has charge $+Ze$.

The total number of nucleons (protons and neutrons) is called the MASS NUMBER, A – a whole number close to the atomic mass of the isotope.

Pictures of nuclei We can sketch a nucleus as a round bottle with the numbers of nucleons

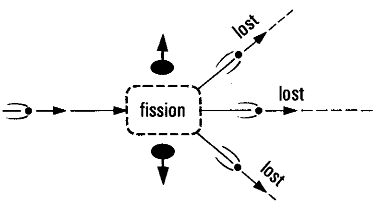


inscribed. Then for a radioactive change we can sketch the bottle opening and spitting out an alpha particle or a fast electron.

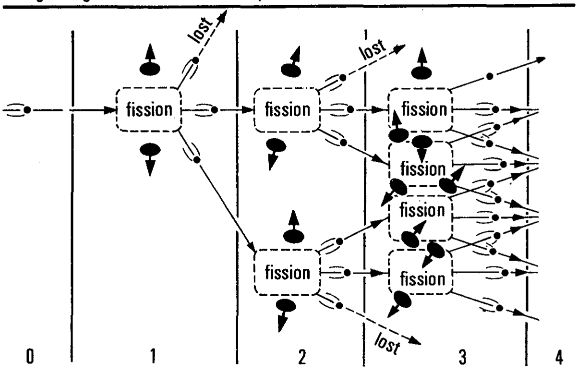
A STILL GREATER SURPRISE – NEUTRONS AND FISSION

Uranium, as we obtain it from minerals, is a mixture of two isotopes ${}^{238}_{92}U$ (99.3 per cent) and ${}^{235}_{92}U$ (0.7 per cent), both radioactive with very long half-lives. The plentiful isotope (U-238) can capture a neutron and become ${}^{239}_{92}U$, also radioactive. The rarer isotope (U-235) can capture a neutron but only if it is moving slowly. The new nucleus thus formed is quite unstable. It divides almost at once into two large unequal fragments. The charge of the nucleus, $+92e$, divides and goes with those fragments. So the fragments are hurled apart with tremendous repulsion. We call that change 'fission' using the name biologists give to the process in which a simple creature reproduces by dividing into two.

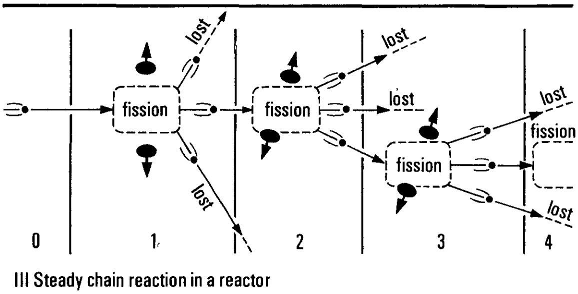
The kinetic energy of the fragments ultimately appears as heat. That heat, together with some gamma rays and other radiations amounts to a total release of almost 200 million eV* from the internal store of a single uranium-235 nucleus. Compare that with the 4 eV from the burning of 1 atom of carbon.



I Single stage: one fission in a small piece of ${}^{235}U$



II Explosive chain reaction growing in a large piece of ${}^{235}U$



III Steady chain reaction in a reactor

Uranium fission: chain reactions
The box marked 'fission' is just a label for that event. The neutrons released fly out in all directions. They are shown shooting forward here, to enable the sketches to show successive stages.

'Could we make use of that huge release of nuclear energy? Only if . . .' All the energy supplies that we use are in a sense fuel – food for man and animals, oil, gas, coal to run furnaces for power stations, locomotives, cars, engines of all sorts.

To be of practical use, a fuel should meet two requirements:
(*i*) The energy a fuel releases must be greater than the energy it costs mankind to produce or obtain that fuel.†
(*ii*) The fuel's burning (or its equivalent) should be self-maintaining: one piece of fuel should, as it burns, ignite the next.

This is obvious in a coal fire: fresh coal is set alight by the coal already burning. A gas flame continues to burn. But what about a petrol engine? Each explosion needs a new spark to start it. But once started, the whole cylinder-full of fuel (petrol and air) does burn completely. We don't have to make a spark to start each molecule of petrol burning. With few exceptions, it is a chain reaction which maintains the flow of energy.

* An electron-volt is a unit of energy: the energy transfer when one electron charge, *e*, is moved through a potential difference of 1 volt (1 joule/coulomb). It is used when thinking about atomic or nuclear particles which carry whole electron charges.
1 eV is [1(electron charge) × 1(volt)]
or [1.6×10^{-19} coulomb × 1 joule/coulomb]
or 1.6×10^{-19} joule

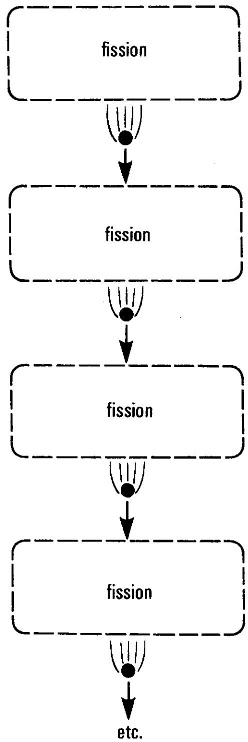
† This is *not* a demand for a perpetual motion machine. We are asking for ready-made fuel from an outside source: coal, oil, trees, or radiation from the provider of all those, the Sun – itself a huge nuclear reactor.

The 'Only if . . .' above means 'Only if there is a chain reaction in which each event triggers a similar event to carry on the flame.'

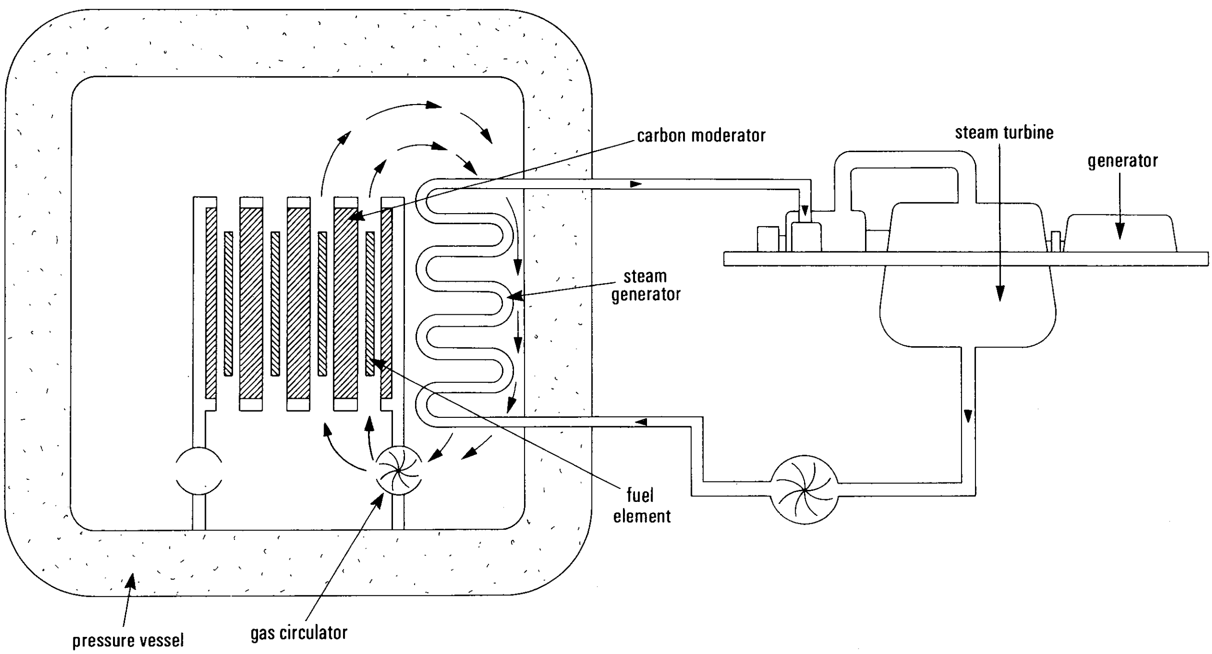
A nuclear chain reaction Return to the fission of a nucleus of uranium-235. This is easily triggered when it clutches a slow neutron. The vital discovery was this: when fission occurs neutrons are also flung out – one, two, or more. Then there can be a chain reaction in which a neutron from one fission acts as a trigger to start another fission.

A steady chain reaction for a power station needs only one successful neutron to fly from each fission to the next. But remember how easily neutrons, being uncharged, can pass through thick walls and get lost. We need to arrange somehow to give neutrons a good chance of being caught by uranium-235 atoms.

For a bomb, more than one neutron from each fission must be caught by other uranium-235 atoms so that there is an explosive chain reaction. Such a bomb must be made of fairly pure fissionable material. If that is uranium-235 it must be separated from the plentiful isotope uranium-238 which would grab fast neutrons. This is difficult since both isotopes have exactly the same chemical behaviour.



Fission: chain reaction
In these simplified sketches the box marked 'fission' is just a label for that event. The neutrons fly out in all directions. Just one is shown moving downwards here to maintain the chain.



Schematic diagram of an advanced gas-cooled nuclear reactor. Only one steam generator is shown, and all control rods have been omitted.

But for a power station we can build a reactor (a 'nuclear furnace') with the natural uranium mixture. However a fuel enriched with a little extra uranium-235 is used in the Advanced Gas-cooled type.

Pellets of uranium oxide are sealed in metal tubes which are then arrayed like a giant crystal, with blocks of carbon filling all the space between them. Neutrons from a fission of uranium-235 stagger through the carbon, being slowed down by a series of elastic collisions. Then, when they are moving very slowly they have a better chance of entering another uranium-235 nucleus than of being grabbed by a nucleus of uranium-238.

As fissions continue to occur, enormous amounts of heat are released. This is carried away by the cooling gas system and used to boil water to steam. Then the steam drives turbines which run electric generators.

Whenever neutrons fly out from the fission of a uranium-235 nucleus, we want one of those neutrons to reach and enter another uranium-235 nucleus and start another fission – and so on, in a continuing, steady chain reaction.

Thus the reactor needs very careful designing to make sure the series of fissions neither die out nor multiply. Control rods of material that absorbs neutrons are moved in and out for final adjustments.

The actual quantity of uranium-235 in the reactor is important too. A small enough block of uranium-235 cannot keep a chain reaction going. There is a 'critical size'. With common uranium and carbon as 'moderator' slowing down the neutrons, the reactor will be as big as a house. Such a reactor needs large, massive shielding to safeguard people working nearby from gamma rays, stray neutrons, and other radioactive radiation.

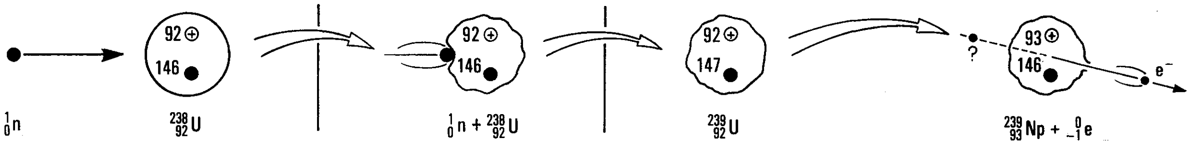
When burned a kilogram of coal releases 8 kilowatt hours. But a kilogram of uranium-235 used in a reactor releases 20 000 000 kW h – enough energy to run a fair-sized factory for four months!

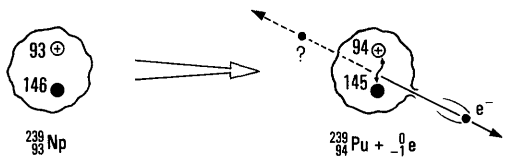
What happens to the uranium-238 nuclei? Although the carbon moderator slows the neutrons down so that there is a better chance of one passing by uranium-238 nuclei and entering a uranium-235 nucleus, some neutrons are caught by uranium-238 nuclei. In most cases, such neutrons are absorbed by the nucleus which becomes a very unstable uranium-239 nucleus. This nucleus soon emits a beta particle and becomes a nucleus of neptunium which is also unstable. It soon emits a beta particle, becoming a nucleus of plutonium, a new element which turns out to be fissionable. Therefore while the reactor is running, by using fissions of uranium-235 some neutrons, taken by uranium-238, are producing new fissionable material. This new material can be separated from the rest by industrial chemistry, since plutonium is a different element from uranium.

Plutonium The plutonium is valuable for reactors now and in the future since it draws on the plentiful isotope uranium-238; but it is also dangerous since it can be put to warlike uses and it is highly toxic. It must be stored with very strong precautions for security.

FISSION AND FUSION: THE WORLD'S ENERGY SUPPLIES

Present-day nuclear reactors rely on fission: energy is released as the nucleus tears itself apart. The resulting fragments are themselves strongly radioactive and present great handling and storage problems. Even so, uranium fuelled fission reactors are already providing vast supplies of energy to help meet the World's needs.





Fusion for the future? The Sun, which pours out immense amounts of energy, is a vast nuclear reactor of a different type from the fission reactors. That solar energy is released when light nuclei are driven together to form heavier nuclei. Very high temperatures are necessary for this to occur. The process has already been operated by man but only in the so-called hydrogen bomb which releases the energy in a rapid, uncontrolled explosion. Nevertheless the problems of maintaining a nuclear fusion reaction in a steadily running reactor are being investigated, at enormous expense, in several parts of the world.

The expense is considered justified because *if* such reactors could be designed and built and run steadily, mankind would have an energy supply that could last far longer than any other fuel, except sunshine.

RISKS AND BENEFITS

Damage Any radiation that can pull, rip, or tear electrons from atoms in flesh can produce irritation by making what are chemical changes. Small amounts of such irritation do not matter: we all suffer from them all our lives – there is ultra-violet light in sunlight, and there always has been a tiny amount of radioactive material in the air and earth around us. But large, unusual doses of radiation can do harm. Ultra-violet light, X-rays, alpha particles, beta particles, all make ions by knocking electrons out of atoms as they go by. Those ions upset the chemistry of cells and may kill some cells. Alpha particles are stopped by a thin layer of skin – as they are stopped by paper – and any damage they do is in that layer. Beta particles, faster electrons, spread their damage deeper.

Ultra-violet light, *X-rays*, and *gamma rays* are all electromagnetic radiation like light, except for having shorter wavelengths, and packaging their energy in larger units. They cause irritation or damage by making ions, but in passing through us they have a strange selective behaviour. A medieval arrow did a lot of damage to a man when it pierced its way through him, and so does a modern rifle bullet; each of those loses some energy and momentum, doing some damage on the way. But electromagnetic radiations seem to carry their energy in a tight packet: they give up *all of it or none*, as they meet an atom inside us.

So when a stream of X-rays or gamma rays falls upon our body, the 'rays' that pass right through us and come out on the other side have done no harm. But those that have stopped inside us have usually devoted all their energy to making ions.

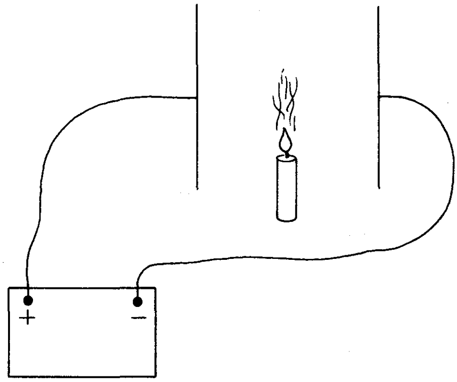
Neutrons find most of the atoms in our bodies very tiny targets, so they make few damaging encounters. Sometimes a neutron knocks a proton forward and that then makes ions. Occasionally a neutron is clutched by the nucleus of an atom that was harmless but which then becomes a new radioactive atom.

All the particles and radiations involved in radioactivity can do harm if we receive them in large enough quantity; but the precautions to make sure of safety are well understood and are enforced with huge margins of extra safety so that the hazards that you are likely to meet from man's nuclear engineering are small compared with the unavoidable small effects that come to us from earth, air, and even the Sun.

Cures Sometimes an *un*healthy cell appears in a human or animal body and then multiplies into a very unpleasant growth. This is called *cancer*. In some forms cancer can be stopped or cured by using X-rays or radioactive radiations to kill the unhealthy cells. Some healthy cells in the region treated are also killed, but by good fortune the unhealthy cells are more often damaged than healthy ones.

Progress Questions

1. Here is a diagram of a candle-flame experiment.
a. Describe what you see in the hot air above the flame when the electric field is switched on.



b. We believe that there are positive and negative ions in the candle flame. What does the word 'ion' mean?
c. Copy the diagram and add arrows to show which way
(*i*) a positive ion, (*ii*) a negative ion.

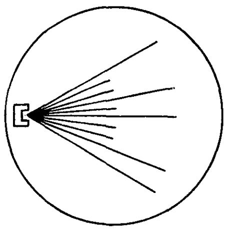
will travel between the charged plates.

2. A plastic rod has been given a negative charge by rubbing. It is scraped over the cap of an uncharged gold leaf electroscope which becomes negatively charged.
a. You sit and look at it. Does the leaf move?
b. A match flame is held near the cap of the electroscope. What does the leaf do now?
c. (*i*) What sort of charge would take away the negative charge on the electroscope?
(*ii*) Where have these charges come from?
d. If you give the electroscope a positive charge, you see exactly the same thing. What does that tell you?

3. An electroscope is charged positively. Some material labelled 'radioactive' is held near the cap.
a. What does the leaf do?
b. We say 'The radioactive source must be producing positive and negative ions in the air'. Explain what this means.
c. What happens to the negative ions produced, to cause the effect in **a**?

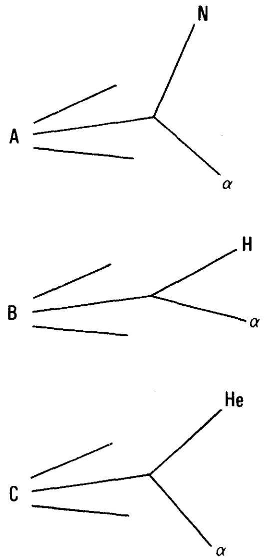
4. Radioactive sources may give off three kinds of radiation.
a. Which of these radiations travels the farthes. in ordinary air?
b. Which one is negatively charged?
c. Which one is the most massive?
d. Which one has a wavelength which is shorter than that of X-rays?
e. Which one cannot pass through the skin?

5. A radioactive source is placed in a cloud chamber. The tracks obtained are shown here.



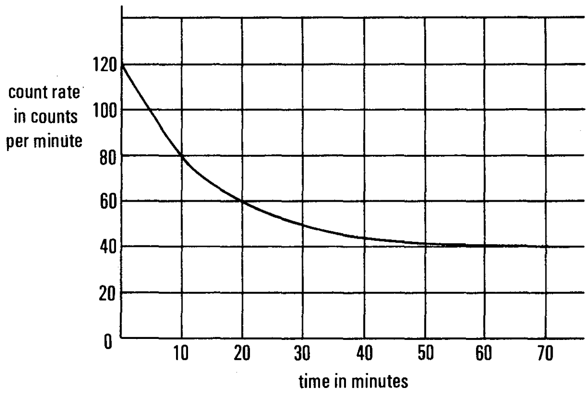
a. Which kind of radiation caused these tracks?
b. Five of the tracks shown are 2 cm long and another five are 1.2 cm long. What does this tell you about the source?

6. When an alpha particle collides head on with an atom, its track makes a fork in a cloud chamber. The sketches show some forked tracks. A is in nitrogen gas, B in hydrogen gas and C in helium gas.



a. Which sort of atom (stripped of its electrons and so a nucleus) has a smaller mass than an alpha particle? How can you tell?
b. Which sort of atom has a bigger mass than an alpha particle? How can you tell?
c. (*i*) Which sort of atom has the same mass as an alpha particle? How can you tell?
(*ii*) What does that tell you about alpha particles?

7. The count rate near a radioactive source is measured over a period of time. The results are shown on the graph.



a. The graph does not fall to zero because of 'background radiation'. What does 'background radiation' mean?
b. The source used had a half-life of ten minutes. What does 'half-life' mean?
c. Use the graph to estimate the count rate due to background radiation.
d. Explain how you would use the graph to find the half-life of the radioactive source.

8. The activity of a radioactive source was measured at intervals in a place where the background radiation could be ignored. The results were:

Time in minutes	0	20	40	60	80	100	120	140
Counts per second	80	60	45	34	26	20	15	11

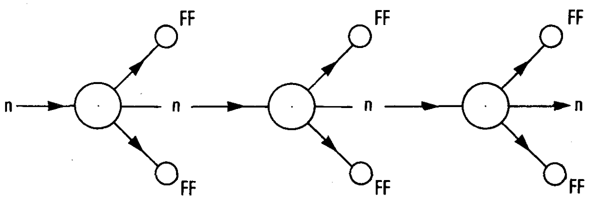
a. Plot a graph of the counts per second against time.
b. Find from your graph:
(*i*) how long it takes for an activity of 80 counts per second to drop to 40 counts per second;
(*ii*) how long it takes for 40 counts per second to fall to 20 counts per second.
c. What do you notice about these times?
d. Make a test to see if the pattern you noticed in **c** is true for other counts.
e. How do you know from the graph that the background radiation could be ignored?

9. The half-life of radium is 1620 years. If you have 1 gram of radium now, how much would you have left after
(*i*) 1620 years from now?
(*ii*) 3240 years from now?
(*iii*) 6480 years from now?

10a. The half-life of uranium-238 is 4.5×10^9 years; the half-life of polonium is 0.00016 second. Which element is more stable?
b. What is the half-life of a perfectly stable element like common copper?

11. Radioactive sodium, with a half-life of 15 hours, decays to magnesium. How much sodium and how much magnesium will there be in a sample of 100 mg of radioactive sodium after 15 hours? After 30 hours?

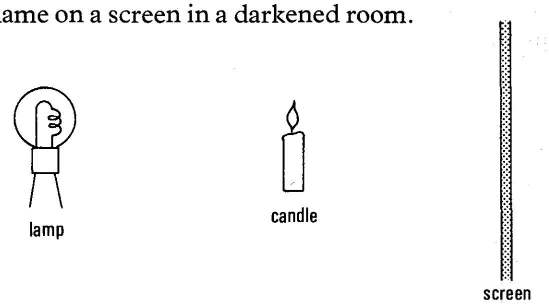
12. The sketch shows what happens when a single neutron enters the nucleus of a uranium-235 atom. FF are the fission fragments and 'n' represents a single neutron. In the nucleus shown the fission



produced just a single neutron. But the number might have been two or three or even more. Make a sketch to show what might happen if each fission produces three neutrons, two of which then enter a uranium-235 nucleus.

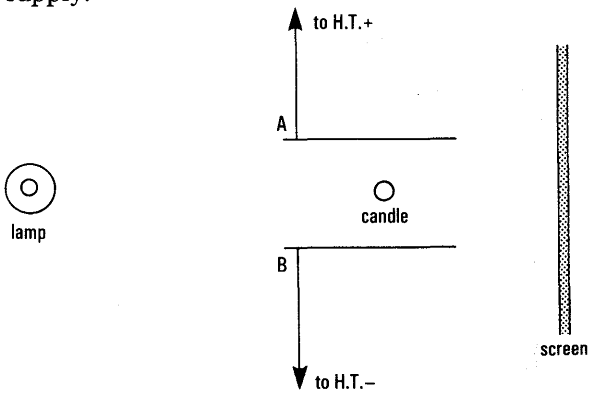
Questions

13. You have seen an experiment in which a lamp with a small filament casts a 'shadow' of a candle flame on a screen in a darkened room.



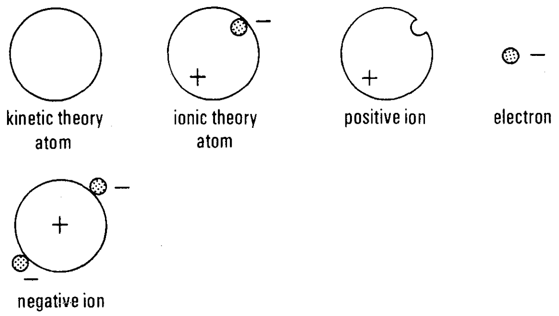
a. What did you see on the screen?
b. Explain what you saw. You may assume that (*i*) hot gases are less dense than cold gases, (*ii*) bending (refraction) of light rays occurs where there are changes in the density (and temperature) of the air or gas through which it passes.

14. The sketch shows the next stage in the demonstration described in Question 13. Vertical plates A and B are placed on either side of the candle flame and are connected to a high voltage supply.



a. What did you see on the screen?
b. Explain what you saw.

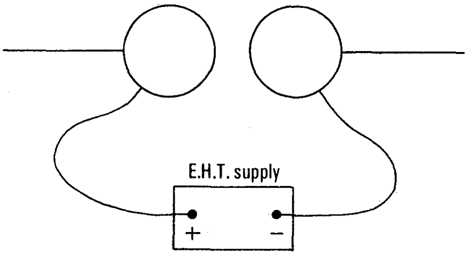
15a. Think of each of the particles pictured in the sketch, placed, *in a vacuum*, between two parallel metal plates joined to the terminals of a high voltage source. What happens to each of the five particles? Say whether it stays still, moves with constant speed, oscillates to and fro, moves with constant acceleration, starts and stops, or whatever you think; and say in which direction it moves.



b. What difference would it make if the voltage between the plates is only a few volts, instead of a few thousand? We are still thinking of just one particle in the vacuum between the plates.
c. What difference would there be between the motion of an electron and the motion of a negative ion (atom + electron), in the same electric field, still in a vacuum? Why is there this difference?
d. Suppose there were many positive and negative ions in the electric field between two parallel plates, what would happen? Would they all reach one or other of the plates? If not, why not?

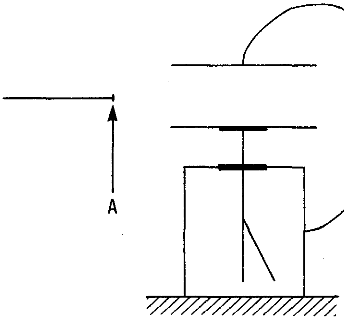
16a. Think of just one ion, positive or negative but not an electron, between charged parallel plates *in air*, not in a vacuum. How does its motion in air differ from its motion in the vacuum? Why does it differ? (Assume that the voltage between the plates is much less than the voltage which would cause a spark.)
b. (*Advanced*) Suppose the pressure of the air is reduced to half atmospheric pressure. What difference does this make to the motion of an ion? Why?
c. Suppose the voltage between the plates is halved, what difference does that make?
d. An electron would reach the positive plate much more quickly, in air, than a larger negative ion would. Give *two* reasons for this.

17. Imagine a positive ion between two metal balls connected to a very high voltage supply.



a. The positive ion is attracted towards the negative sphere. If, on the way there, it hits an ordinary neutral atom *at high speed*, what is likely to happen to the atom?
b. There are now two ions being accelerated. Explain how the number of ions can very soon become four, then eight, and so on, making an avalanche of ions, which is a spark.

Radioactive radiations
18a. A small piece of radioactive material, A, is inserted between plates joined to a charged electroscope. What happens? What else, placed between the plates but not touching them, would have produced the same effect?



b. You probably used a different arrangement to show the same thing: briefly describe, giving a diagram, how you showed that uranium oxide has the property of discharging an electroscope.

19. In order to discharge an electroscope, electric charge of opposite sign must be taken to it, or charge of the same sign must be taken from it. This can happen, in air, if *ions* are present. We conclude that the uranium in the uranium oxide has the property of producing 'ionization', that is, of making ions.

A friend says, 'It might equally well be the oxide part of the uranium oxide, and not the uranium at all.' What immediate reply might you make to that? And what conclusive experiments might be done to prove your point?

20. If we want to count, by means of sparks, single alpha particles from a radioactive source we must have something sensitive. Sketch a 'spark counter' you have seen or used.
a. Say how it is connected to a high voltage supply, and say how it is used.
b. Why is a spark counter able to respond with a visible spark to a single alpha particle?

21. The best protection from a gamma source, apart from having it surrounded by a very thick and heavy casing of lead, is to be as far away as possible from it. If you are 20 metres away instead of 2 metres you may be said to be '100 times as safe'. Why is this?

22a. Give a brief description of one type of cloud chamber you have used or seen, and say how you operate it. Draw a diagram to illustrate what you might see if a speck of radium is inside the chamber. Which type of chamber is this?
b. Describe briefly the other type of cloud chamber which you did not describe in **a**.

23. A cloud chamber does not *make* alpha particle tracks, but it does make them visible. How does this come about? (Your explanation should make use of the fact that water or alcohol vapour, when it is near to 'saturation' – that is, near to condensing into liquid – easily condenses in drops around electrically charged particles.)

24. Alpha particle tracks from radium, observed in a cloud chamber, show that the range of an alpha particle in air at ordinary pressures is a few centimetres.
a. What do you think happens to an alpha particle that forms a straight track, from the moment it leaves the radium atom until it reaches the end of the track?
b. What difference would it make to the range of an alpha particle if the pressure of the air is reduced? What would be the range in a complete vacuum?
c. How could you use a spark counter to find the range of an alpha particle in air?
d. You could use a Geiger counter to measure ranges, but you would have to make allowance for ... what? Why?

25. How would you show that alpha particles are stopped by a piece of paper of ordinary thickness, but can penetrate through very thin paper, e.g. cigarette paper? Why is it that a thin sheet of solid material has much more 'stopping power' than several centimetres of air? (All the same, the alpha particles go through the thin paper without making holes – have a look.)

26. How could you use a Geiger counter to show that another kind of radiation, different from alpha particles, also comes from a radium source?

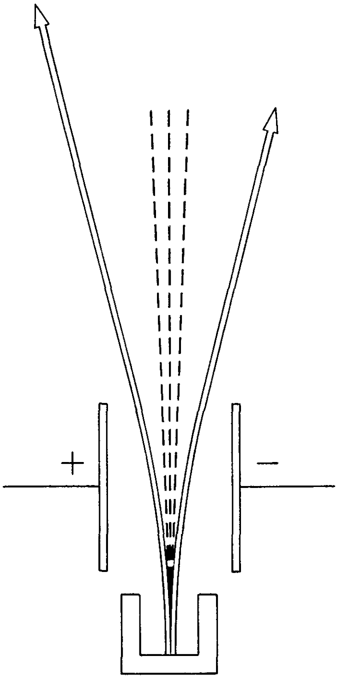
(*Note.* Most of the effects noticed will be due to beta particles from such a source. Some other radioactive sources, e.g., strontium-90, eject only beta particles.)

27. The photographs on pages 157–8 show alpha particle tracks from a small radioactive source (not radium). What is unusual about these tracks in the first photograph, and what do you deduce from the photograph?

The second, third and fourth photographs call for detective work. They are photographs of events that occur very infrequently. In *b* there has been a direct collision between an alpha particle and a nitrogen atom. *c* shows a collision with a hydrogen atom and *d* shows a collision with a helium atom.
a. Sketch the track that shows the collision in each case. Label the tracks α (for alpha particle), N (for nitrogen nucleus), H (for hydrogen nucleus, or proton), He (for helium nucleus). α appears on two tracks in each diagram, of course. You have to decide where to put the symbols.
b. What can you deduce about the mass of an alpha particle, compared with each of the three nuclei? Give a reason for each answer.

28. Experiments on beta and gamma radiations in magnetic fields show that beta particle tracks are bent in the *same* direction as an electron beam would be, while gamma rays are not deflected at all.
a. What do you deduce about beta and gamma radiations *from this alone*? (Do not deduce too much!)
b. If you have seen an experiment with a Geiger counter to show the deflection of beta particles by a magnetic field, give a brief description, with a diagram, explaining what was done.

29. The figure (p. 176) is a diagram of alpha, beta, and gamma rays, from a source such as radium, in the electric field between two plates. The diagram is not supposed to be accurate; the amount of bending depends not only on the strength of the electric field but also on the charge on each particle, e, the speed, v, and the mass, m (actually deflection is proportional to e/mv^2).
a. Copy the diagram and label the three sets of lines α, β, γ, as you think correct.
b. For alpha particles and beta particles of the same *kinetic energy* (K.E. $= \frac{1}{2}mv^2$), how would you expect the deflections to compare in size?
c. What can you say about the comparison of kinetic energies of alpha and beta particles in this diagram? Why?



30. The medical care of mothers and their babies has increased throughout this century and its success is indicated by the fall in the death rate of babies before and soon after birth. This table shows the decrease in the rate of infant mortality in the U.K. since 1901.

Year	1901	1911	1921	1931	1941	1951	1961	1971
Mortality per 1000 live births	144	111	81	60	44	32.5	22.5	16

Plot a graph of these figures with the years along the x-axis. In how many years did the infant mortality fall from 120 per 1000 to 60 per 1000? From 60 to 30 per 1000? From 80 to 40 per 1000? What do you notice about your answers?

31. Give an outline of what was done when you determined the half-life of the grand-daughter of uranium. Say how you calculated the half-life.

32. In an experiment with a scaler and a Geiger counter near to a radioactive source the following count rates were obtained:

Time in minutes	0	10	20	30	40	50	60
Count rate in counts/minute	540	400	290	220	165	130	102

a. Plot a graph of these figures with the time along the x-axis.

In a second experiment the radioactive source was taken away and the background count rate measured. The figures obtained were:

Time in minutes	0	10	20	30	40	50	60
Count rate in counts/minute	37	41	40	38	42	43	39

b. What is the best approximation to the background count rate?
c. Now use your graph and your figure for the background count rate to find the half-life of the source used in the first experiment.

33. Helium has an atomic number of 2 and an atomic mass of 4. What would you expect to happen to (*i*) the atomic number, and (*ii*) the atomic mass of a radioactive atom that ejects an alpha particle?

34. Uranium-238 has a half-life of 4500 million years, radium of 1620 years, and radon of 56 seconds.
a. If you have 1 g of radium now, how long would it be before this was reduced to 0.25 g? How much longer would it take before this quarter gram became one-sixteenth gram?
b. Would there ever be nothing left of your original gram of radium?
c. The Earth is many millions of years old. How then do you account for any measurable quantity of radium being discoverable in natural rocks?
d. Uranium-238 goes through many changes and ends up as lead-206. Beta and gamma radiations have negligible mass compared with alpha particles of mass 4. Calculate the number of alpha particles emitted in this series of changes.

Rutherford model of an atom

35. From the cloud chamber tracks you have seen:
a. what do you deduce about the mass of an alpha particle compared with the mass of an electron?
b. what do you deduce about the region where the mass of a gas atom is concentrated?
c. On a scale which makes the mass of a hydrogen atom 1, the mass of an electron is $\frac{1}{1800}$ and of a helium atom is 4. Do these figures agree with your conclusion in **a**? Explain.

36. Suppose a more modern version of Geiger and Marsden's experiment is done with a Geiger counter (with a very thin end window) instead of the screen. Make a sketch of the experiment and use it to explain in general terms the idea of the experiment on the scattering of alpha particles by a thin sheet of gold.

37. The number, Z, of positive 'electron charges' on the nucleus of an atom can be calculated from scattering experiments. This was done by Chadwick (1920) for copper, silver, and platinum. He found 29.3 electron charges on copper, 46.3 on silver, and 77.4 on platinum. The experimental error was 1 per cent.

The atomic numbers of copper, silver, and platinum are 29, 47, and 78.

a. What does this suggest about the charge on the nucleus of an atom?

b. If you can, suggest a reason why the chemical properties of an element depend very much on its atomic number and not at all on its atomic mass.

c. Previously we defined atomic number as the number of the element in the periodic table. You can now give a better definition. What is it?

Chain reactions

38. Suppose that three neutrons are released whenever a nucleus of uranium-235 undergoes fission, and that *each* of these three neutrons enters another uranium-235 nucleus after an average time of 10^{-8} second. Each of these nuclei then undergoes fission at once and so on.

A single neutron enters a block of uranium-235 at time $t = 0$.

a. How many neutrons will there be in the block just after 3×10^{-8} second?

b. Just after 5×10^{-8} second? (Stop here, unless you know a quick method for **c**.)

c. After 100×10^{-8} second (that is 1 microsecond)?

d. Why is the answer to **c** nonsense?

CHAPTER 11
Waves and particles

LIGHT WAVES

Here, near the end of our Nuffield Physics course, you have studied several fruitful theories – among them the wave theory (or model) of light, and the particle theory (or model) of matter. You have seen how useful the wave theory is when applied to the behaviour of light. Light often *does* behave like a wave: it can be reflected, refracted, and diffracted, and sometimes two beams of light can make an interference pattern.

ELECTRON PARTICLES

You have seen how Millikan found that all electric charges come in whole number multiples of one basic charge, 1.6×10^{-19} coulomb. This was taken to be the charge on the electron. All electrons carry this charge and all have the same charge/mass ratio e/m. So it was reasonable to assume that all electrons have the same mass and therefore that electrons are particles.

Millikan's oil-drops had 1, 2, 3, ... basic charges on them: that is, they carried 1, 2, 3, ... electrons in excess (or defect). So now, when we think about a negatively charged metal ball we think of that ball carrying many, many extra electrons in just the same way as the oil drops carried a few.

You have seen how Rutherford made such good use of this particle model of electricity that he was able to explore the electric field inside the atom and so deduce that each atom had a positively charged nucleus, and far out from that, a number of electrons. The nucleus was made up of protons and neutrons. Electrons, protons, neutrons, atoms – all behave as particles of matter.

Two grand theories, and yet there were problems in fitting them to the facts especially in cases where light interacts with matter or where electrons interact with matter. Neither theory alone was able to accommodate all the experimental results which were obtained. Unfortunately these different aspects of the behaviour of waves and particles are very difficult to demonstrate in the school laboratory. If you wish to bring the story of the atom a little nearer to the present day you will have to rely on evidence gathered by other experimenters rather than seeing for yourselves.

Before embarking on the later story of waves and particles we have to explore one important phenomenon which was first examined in about the year 1900. It is called the photoelectric effect.

The photoelectric effect

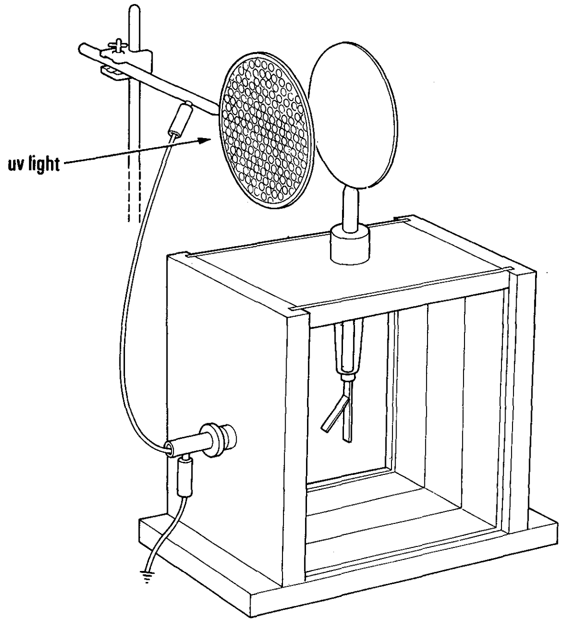
Today there are many practical devices which use the photoelectric effect. In the simplest examples, a photoelectric detector transmits information about interruptions of the light falling upon it. This is used in such cases as counting people entering an exhibition or in detecting intruders (as in burglar alarms). More complex detectors use this effect to measure the intensity of the light falling upon them; this is used in controlling lights and in the recording and playback of the sound track on films. Other devices can use the photoelectric effect to generate electric power, as in the solar cells used to power satellites in orbit.

It seems that a beam of light is able to flick electrons out of metals. The shorter the wavelength of the light, the more energetic the ejected electron is. So gamma rays are more effective than ultraviolet light, and ultraviolet is more effective than visible light. Indeed photoelectric cells used in visible light beam devices have to have specially prepared surfaces in a vacuum. But ultraviolet light is able to eject electrons from a common metal such as zinc, if the surface is carefully cleaned first.

Demonstration 90
Waves interacting with matter; the photoelectric effect

See the effect when ultraviolet light falls on a clean zinc plate which is resting on the cap of a charged electroscope. Put a sheet of glass in the way and no effect is seen.

This demonstration shows that the light from the ultraviolet lamp is able to drive carriers with



negative charges out of the zinc. It is simplest to assume that these carriers are electrons – and measurements of the charge/mass ratio (e/m) confirm this.

It is just as if the ultraviolet light had cracked a whip at the zinc and flicked an electron out of it. Such an event calls for much more careful experiments with light of various wavelengths, of varying intensity, and in carefully controlled conditions. These experiments show that the electrons emerge from the metals with a range of energies to which there is a definite maximum and that all the electrons had to pay some sort of 'exit tax' to leave the metal. Electrons coming from atoms beneath the metal surface had to lose still more energy to struggle through than electrons leaving from the surface. The electrons which were whipped out of the surface itself and had only the 'exit tax' to pay came out with the maximum energy.

In gases, only the 'exit tax' has to be paid and all the electrons are ejected from the atoms with the same energy. The photograph shows the effect in a cloud chamber when a narrow beam of monochromatic X-rays passes through argon gas. The tracks are made by the photoelectrons ejected from argon atoms. The radiation comes from the left, and as it travels from left to right, fewer and fewer photoelectrons are emitted.

The maximum energy was related to the wavelength of the light used. The longer the wavelength (that is, the lower the frequency) the less energetic were the electrons. And, for each metal surface, there was a threshold of energy. Light of a longer wavelength did not give the electrons enough energy to pay the 'exit tax'. For zinc the situation was:

Wavelength of light	Gamma	X-rays	U.V.	Blue	Green	Yellow	Red
Electron emission	Yes	Yes	Yes	No	No	No	No

A strange thing about this 'photoelectric emission' of electrons was that the electrons appeared to be flicked out at random. Even stranger, a beam of very weak light might flick an electron out immediately it was switched on. There was no time delay. Increasing the intensity of the light produced more electrons but not more energetic electrons. To get those, light of a shorter wavelength had to be used.

Now an earlier problem in understanding how radiation is emitted by hot bodies had led Max Planck, a German physicist, to suggest that the energy is given out in tiny packets, each called a quantum. The energy of each packet (or quantum) is directly proportional to the frequency of the radiation emitted so that

A QUANTUM OF ENERGY =
A UNIVERSAL CONSTANT × FREQUENCY OF RADIATION

Planck himself was unhappy about this suggestion and only introduced it as a desperate measure

Absorption of X-ray radiation in argon.
E. J. Williams. From Gentner, W., Maier-Leibnitz, H., and Bothe, W. (1954)
An atlas of typical expansion chamber photographs. *Pergamon.*

to make sense of some recent experimental results. But it did enable him to propose a very satisfactory theory for the spectrum of the radiation from hot bodies.

Today we name the constant in Planck's honour and write it h. It is extremely small: 6.6×10^{-34} J/Hz.

Einstein's explanation of the photoelectric effect

It was already agreed that light can behave like a wave. Now Einstein took up Planck's idea and suggested that light can also behave like a particle – and that it does so in the case of the photoelectric effect. He supposed that these particles, which we now call photons, 'penetrate into the surface layer of the body and their energy is transformed into kinetic energy of the electrons. The simplest way to imagine this is that a light quantum delivers its entire energy to a single electron'. In terms of their energies, the particles of visible light (photons) are very, very small (see Table 1). To eject an electron from the surface of a metal like zinc needs a definite, but small quantity of energy. If the photon has this quantity of energy it can eject an electron. If it hasn't, then it cannot.

The bus-ticket analogy

This may remind us of the way in which we pay for bus journeys. There is a minimum fare – say, 10p. Any number of pence from 1 to 9 fails to buy a ticket for a ride. But 10 pence does entitle you to ride a definite distance.

Atoms of zinc, like the bus conductor, cannot accept quanta with energies below about 5 eV and eject an electron. They merely absorb those quanta by a series of elastic collisions. Try an ultraviolet photon with just 5 eV and out will drip an electron. Try one with 8 eV and electrons will be flipped out with energies between zero and a maximum of $(8-5)$ eV, that is 3 eV.

Are there photons? If Einstein was right and 'photons' really existed, it should be possible, even if difficult, to detect them in a beam of light and to count them one by one. For that a very weak light source has to be used and very sensitive detectors. For the more energetic photons of X-rays or gamma rays, a Geiger counter is suitable as a detector.

Demonstration 91
Counting gamma ray photons

See the effect when a source of gamma radiation is placed near to a Geiger tube connected to a scaler.

At a distance of ten or more cm the number of counts per second is relatively small; that is the number of photons detected in a second is small too. But each photon has a large energy – around 10^6 eV compared to 3 eV for blue light.

At such distances from the source the photons are arriving one at a time – so there must be large spaces between them. G. I. Taylor wondered whether photons spaced so far apart would undergo diffraction or interference. And he set up a classic experiment to find out. He arranged a diffraction experiment using a light source which was so feeble that the exposure time reached three months. Rumour has it that he went on holiday during the experiment. The light from the source was so feeble that, for most of the time, there was only one photon travelling through the light-tight box. And yet the photographic plate, when developed, revealed the usual diffraction pattern and, as Taylor wrote, 'there was no diminution in the sharpness of the pattern'.

So photons can produce the diffraction and interference effects which we have associated with waves.

Photons and photography

Everyone knows that photographers' dark room lamps are red or orange in colour. The wavelength of the light they emit is too long to start the

Table 1
Energies of some photons

	Radio 4	TV	Infra-red	Red	Blue	Ultraviolet	X-rays	γ-rays
Wavelength in m	1500	1	10^{-5}	6×10^{-7}	4×10^{-7}	10^{-7}	10^{-10}	10^{-12}
Frequency in Hz	2×10^5	3×10^8	3×10^{13}	5×10^{14}	7×10^{14}	3×10^{15}	3×10^{18}	3×10^{20}
Energy in J	10^{-28}	10^{-25}	2×10^{-20}	3×10^{-19}	5×10^{-19}	2×10^{-18}	2×10^{-15}	2×10^{-13}
Energy in eV	10^{-9}	10^{-6}	0.1	2	3	5	10^4	10^6

photochemical reactions involved in black and white photography; or, to put it another way, the photons do not have enough energy to trigger the chemical reactions.

Particles interact with matters: X-rays

The very penetrating, short wavelength waves we call X-rays are produced when a beam of fast moving electrons is stopped at a metal target. A little, far less than 1 per cent, of the electrons' kinetic energy is transformed into X-ray quanta. Table 1 shows how energetic these quanta are and it is not surprising, therefore, that the electrons themselves must have very high energies if any X-ray photons are to be produced. Electrons with energies of at least 10 000 eV are needed to produce the X-rays with a wavelength of 10^{-10} m which can pass through ordinary glass.

In Chapter 9 you saw how a finely-ruled grating was used to produce diffraction patterns with visible light. These patterns enabled you to measure the wavelength of the light you used.

The wavelengths of X-rays are very much shorter than those of visible light; but it was found that the sheets of atoms which make up crystals behave exactly as the rulings on the grating did when X-rays were passed through. This discovery provided a most important tool for investigating the arrangements of the atoms in crystals of all sorts. Single crystals give patterns of spots (see photograph A).

What will the pattern look like if there is not a single crystal but many, many tiny crystals arranged higgledy piggledy?

Experiment and Demonstration 92
Patterns from gratings

The diffraction pattern you see when you look through a grating at a distant lamp is made up of a number of spectra spread out into a line. What will you see if you turn the grating through a few degrees? And a few more; and so on?

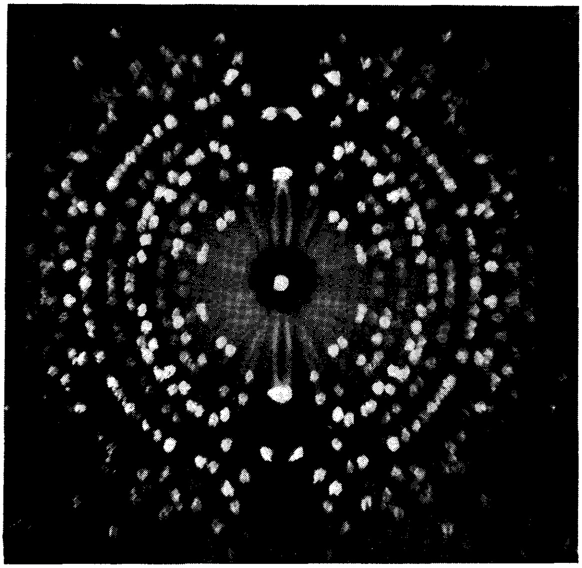
Suppose you could do this very quickly by setting the grating spinning? What will you expect to see? Try it.

[You may see a similar experiment using a grating made of grating material cut up into small pieces and then arranged and glued flat on a sheet of glass so that it looks like crazy paving.]

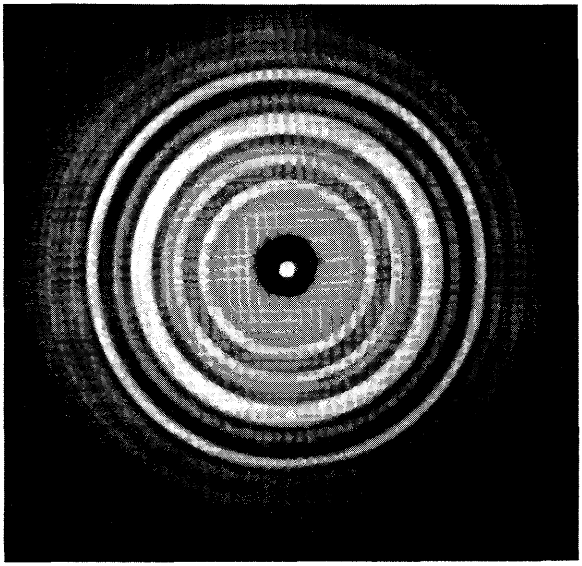
The pattern you see is made up of the individual spots of light moving around on the screen and seen as a set of light and dark rings.

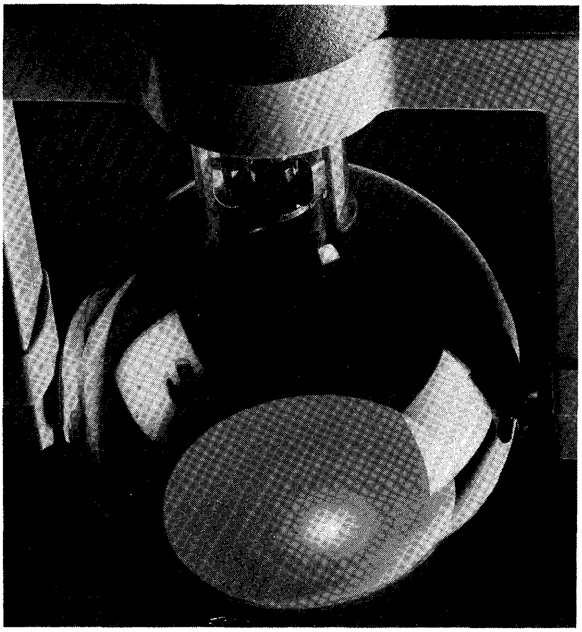
The X-ray diffraction pattern made by a powder of many, many tiny crystals arranged higgledy-piggledy is like that – a set of light and dark rings. A bright spot produced by one crystal facing in a particular direction joins with another bright spot formed by a crystal facing in a slightly different direction and so on until all the spots are seen together as a ring. (See photograph B.)

A X-ray diffraction pattern for a single alum crystal.
Dr. H. J. Milledge, Department of Geology, University College, London.



B X-ray diffraction pattern for powdered alum crystals.
Dr. H. J. Milledge, Department of Geology, University College, London.





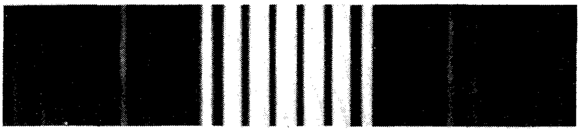
C Electron diffraction tube.
Teltron Ltd.

Look next at photograph C. This is a picture of a screen at the end of an electron tube, and it shows a series of rings on the screen at the far end. At the near end of the tube there is an ordinary electron gun accelerating electrons to energies of several thousand electron-volts. These electrons strike a target made up of a thin layer of graphite crystals spread haphazardly on a thin supporting film. The screen shows a pattern of rings like the one produced by the diffraction of X-rays in photograph B. We are forced to conclude that electrons sometimes behave like light waves and X-rays. Electrons do show wave behaviour under certain circumstances.

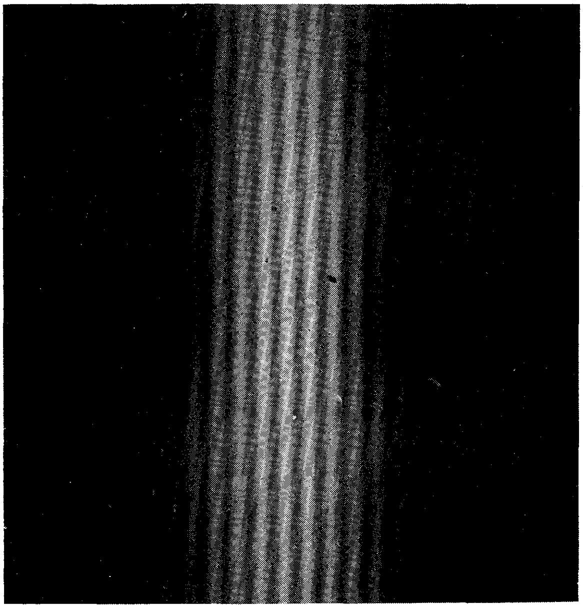
Particles showing wave behaviour; waves showing particle behaviour; this seems to be characteristic of the small-scale world.

In our large-scale world cricket balls and aircraft are particles – we do not notice any wave behaviour, for the wavelengths are far too short. In this world waves are waves – we do not detect any particle behaviour for the energies of the photons are far too small. But in the atomic and the sub-atomic world we have to accept that particles of matter and waves of radiation share common behaviours.

Photographs D and E show interference patterns made by visible light and by electrons. The two photographs have been magnified by different amounts but the similarity lends strong



D A double slit interference pattern of light.
R. S. Longhurst (1973) Geometrical and physical optics. *Longman.*



E A double slit interference pattern of electrons.
Prof. Dr. C. Jönsson (1961) Zeitschrift für Physik. *vol. 161, 454. Springer.*

support to the strange story of the dual behaviour of waves and particles. It is now over fifty years since the French physicist Louis-Victor de Broglie first suggested that this must be so; since then the duality has been shown for streams of neutrons, of protons, of atoms, as well as of electrons. It seems that moving particles *do* follow wave directions and that the wave tells us where to find the particles. The 'matter waves' appeared to guide the electrons in photograph E so that the interference pattern was formed.

These matter waves remind us of the very general descriptions we sometimes read of the way in which people behave. We might say that most people eat their breakfasts between 7.30 and 8 a.m. But this does not tell us precisely when each individual has his breakfast. It may be earlier; it may be later. It remains true that *most* of us eat between those times. That is a general pattern of our behaviour.

Problems with atom models In the last chapter we saw how Rutherford arrived at the idea that the atom had a nucleus with electrons distant from it. The nucleus is positively charged, the electrons negatively charged, and the whole atom is electrically neutral – implying equal numbers of positive and negative charges. These charges must be attracted towards one another. And yet the electrons do not fall in towards the nucleus. If they did the atoms could not survive; but they do!

An early nuclear theory Perhaps the atom is something like a tiny solar system – with electrons in orbits rather like the planets in orbits round the Sun. If so, the electrons have an acceleration towards the nucleus just as the planets are accelerated towards the Sun with centripetal acceleration. But each electron is charged, and whenever an electric charge is accelerated, it loses energy as radiation. Indeed when the electrons in the X-ray tubes hit the target their sudden deceleration produces the X-ray photon. So, once again, atoms will not last very long on *that* model. As their electrons lose their energy they spiral inwards, the atoms get smaller and smaller and . . . But that doesn't happen. Atoms survive!

We need a model for the atom in which the electrons can exist permanently with a fixed, unchanging energy. Can the wave idea help?

Waves, electrons, and atoms The experiments on the diffraction and interference of electrons suggested strongly that 'running electron waves' existed. In our study of waves we saw that there were continuous running waves and also stationary wave patterns with nodes and loops on vibrating strings. Perhaps the electrons in atoms are located by stationary 'matter-waves' so that a stable vibrating pattern determines the path of each electron in the space round the atomic nucleus.

If the electron's wave inside the atom is a stationary wave, it must have just the right wavelength to fit within the boundaries of its region of the atom.

It was de Broglie who first developed this view. He suggested that the wavelength (L) which had to be associated with the electron was related to that electron's momentum (mv) in a very simple way:

$L = h/mv$ where h is Planck's constant.

He reached this startling conclusion from his assumption that 'it is necessary to introduce the particle concept and the wave concept at the same time. The existence of particles accompanied by waves has to be assumed in all cases.' And then he reasoned as follows.

According to Planck the energy of a photon is hf where f is the frequency.

According to Einstein the energy of that photon is mc^2 where c is the speed of light.

So $hf = mc^2$ for that photon.

The momentum of the photon mc is therefore hf/c.

For a light wave
speed, c = frequency $f \times$ wavelength L,
so $f/c = 1/L$

and we see that the momentum of the photon is h/L.

Using de Broglie's assumption that if photons (or light particles) are associated with waves, then waves must be associated with particles, we can also assume that for an electron the momentum $= h/L$.

So, for an electron, $L = h/mv$.

It follows that, not only must the electron have just the right wavelength to fit into the atom's boundaries, it must also have just the right momentum.

But, if the electron has to have just the right momentum to fit, it follows that it must also have just the right energy.

The energy of the moving electron is $\frac{1}{2}mv^2$

That is the same as $\dfrac{(mv)^2}{2m}$ as you can see if you try cancelling.

And that is the same as (momentum)$^2/2m$.

The kinetic energy of the electron depends on the square of its momentum.

To say, then, that the electron must have just the right wavelength to fit into the atom tells us that that electron must also have just the right momentum and just the right energy as well. That is how the electron comes to have a definite energy state within the atom.

De Broglie's wave picture of the electrons within the atom is a half-way house between the older nuclear model and the present quantum-mechanical one. But it does contain some of the accepted views about atoms – that electrons within the atoms are described by stationary waves which have to be well-behaved and which fulfil certain conditions. In fact, that stationary wave is not a real stationary wave telling us that the electron would have to vibrate up and down or from side to side. It is a useful pattern which tells us where we are likely to find the electron. Wherever the pattern 'vibrates' with a large amplitude, we have a good chance of finding the electron. Wherever the pattern has a small amplitude, we have little chance of finding the electron. The new picture of atoms is one of probabilities, of gambling where we are most likely to find an electron – never knowing just where it will be.

If this seems difficult to imagine, here is another idea that might help. Instead of stationary waves on a wire stretched like a violin string between two pegs, think of stationary waves on a ring of wire, or on a 'ring' of water. If there are a whole number of wavelengths in the circumference, the stationary pattern can stay there, just vibrating up and down. However, if the circumference contains an odd fraction of a wavelength extra, the pattern cannot join up in the ring, like a snake swallowing its own tail, and the stationary wave would not last. You may see this illustrated in some form of round tank.

These ideas are difficult to grasp because we find it easy to think about a world of particles – objects with mass, momentum, energy – existing in the world we see everyday. And we find it easy to think about waves – we see them on the sea, on ponds, we know about radio waves and light waves. These two great ideas enable us to describe so much of our world so well – the science we build upon them works.

As we turn from this large-scale world to the small-scale world of electrons and atoms, we naturally try to transfer our very successful large-scale ideas to this micro-world. Why should we be surprised if it leads us into difficulty?

Electrons are such that we can invent a set of experiments to measure their charge, their momentum, their energy; we are asking about things which in our world belong to particles. We can invent another set of experiments to measure their wavelength, their frequency; we are asking about the things which in our large-scale experiments belong to waves. But we find that we cannot do these two things at the same time.

We have to accept that:

(*i*) each description as wave or particle applies when we are dealing with the electron in its particle aspect.

(*ii*) each description excludes the other. While we are using one, we must not try to use the other as well.

De Broglie's was an early picture suggested as the wave electron theory started to be built for atoms. It is very far from the present view because we know that the stationary wave patterns have to be imagined in three-dimensional space. Nevertheless the idea is there: that inside an atom certain wave patterns could last for an indefinite time; and that outside an atom an electron or any other particle flies along with wave as well as particle behaviour.

In the present model of the atom we have a massive, positively charged nucleus with electrons far out in the neighbouring space. The electrons have definite energies, and their matter-wave patterns (written as equations rather than shown as sketches) tell us the chances of finding an electron in a given region of the atom. The patterns tell us the probabilities but never the certainty. But the probability is useful to know for it tells us the energy states, it gives meaning to forms of chemical bonding, it accounts for the random laws of radioactivity, it predicts nuclear events. Like all other good theories, it is useful.

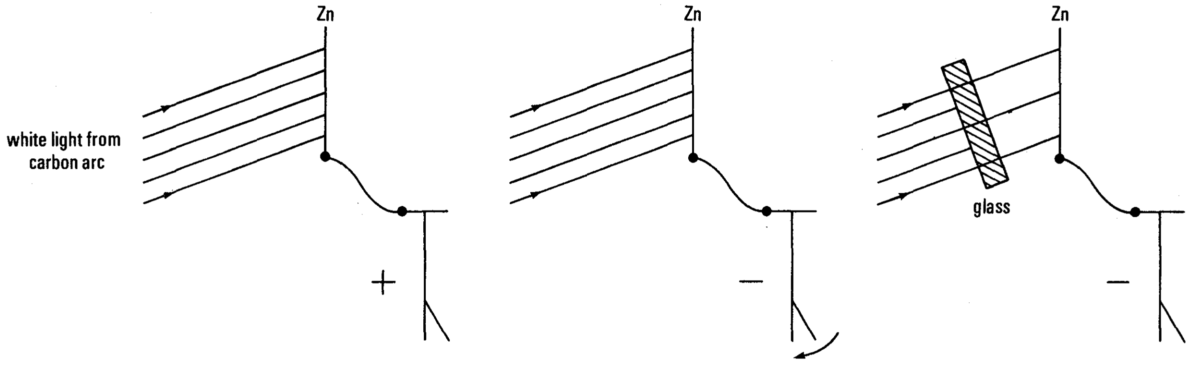
You have now reached the end of this Physics course, which is still asking questions about explanations, about experiments, and about theories. You know that our understanding of Physics is still far from complete, that there is more knowledge to be sought; that there are theories to be developed, perhaps replaced and certainly to be changed. To recognize this is to understand something very important about the nature of science and the work which scientists do.

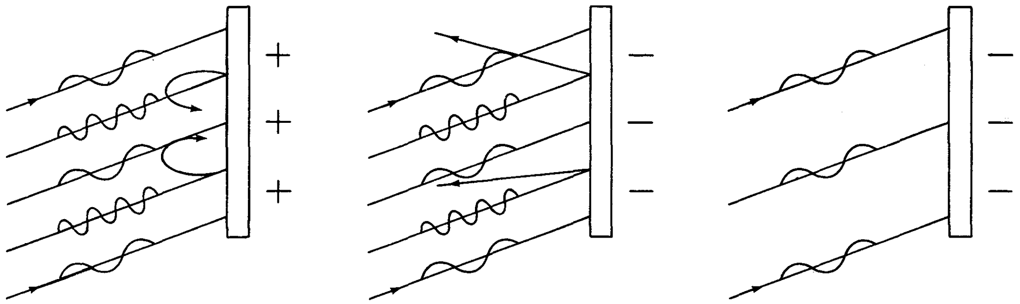
Questions

1. The three pairs of sketches (top right) are to be used in an account of an experiment in which white light from a carbon arc fell on a freshly cleaned zinc plate. The plate was connected to a charged electroscope as shown.

A boy says that the experiment shows that 'light ejects electrons from metallic surfaces'. Although along the right lines, his remark contains three separate overstatements. What do you say the experiment demonstrates? Explain how.

2. The boy in Question 1 was right about electrons although the experiment does not show that *electrons* are ejected. What sort of evidence would convince you that the charges which are flicked out by the light are, in fact, electrons?





(a) (b) (c)

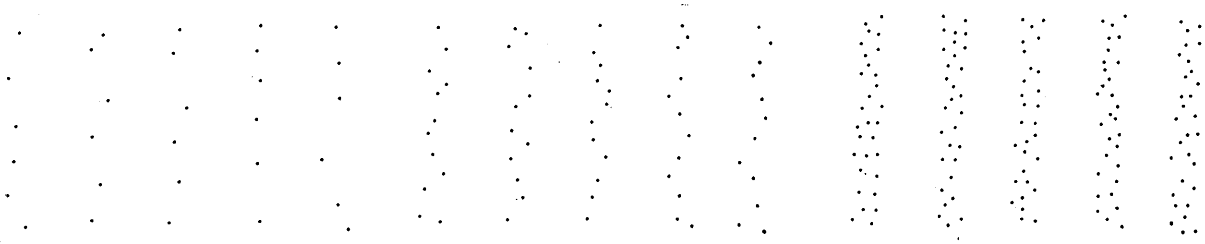
3a. How does the idea of the 'photon' possessing a 'quantum' of energy explain the following?
(*i*) Brighter light produces more electrons but not faster electrons.
(*ii*) Even when the light is very weak, electrons are flicked out of the metal immediately the light reaches it.
b. Why would you expect a delay if the very weak beam of light behaved purely as a stream of continuous waves?

4a. Explain how the spots which make up the pattern seen when light from a distant street lamp passes through the fabric of a stretched handkerchief appear as a set of light and dark circles if the fabric is rotated quickly.
b. X-rays passed through a powdered crystal also produce patterns of light and dark rings. How do you account for this?

5. X-rays can be detected by Geiger tubes and scalers. What does this tell you about the X-rays?

6. Beams of electrons can produce patterns which look very much like the patterns produced when X-rays pass through powdered crystals. What does this suggest about the beam of electrons? Explain.

7. (*Difficult*) A very weak beam of monochromatic light (i.e. light of a single wavelength) passes through a double slit to a photographic film. The three figures show the effect after 0.01, 0.02 and 0.05 seconds.
a. What would you expect to see after a longer



I II III

period of time – say 1 second?

b. Explain these diagrams using the photon model for light.

c. What part does the wave model of light play in the process of building up the final picture?

This volume contains the material for pupils for the fifth and examination year of Revised Nuffield Physics. The main topics are: Motion in an orbit; Measuring electrons; the History of planetary astronomy from early times to Newton's great synthesis of the work of Copernicus, Kepler, and Galileo; Oscillations; simple harmonic motion; Alternating currents; Waves and theories of light; Diffraction gratings, spectra, and the electromagnetic spectrum; Radioactivity; and Waves and particles.

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