

Physics

Students' book **Unit 1**

Materials and structure



Nuffield Advanced Science

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Materials and structure

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Advanced Science

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Nuffield Advanced Physics team

Joint organizers

Dr P. J. Black, Reader in Crystal Physics, University of Birmingham

Jon Ogborn, Worcester College of Education; formerly of Roan School, London SE3

Team members

W. Bolton, formerly of High Wycombe College of Technology and Art

R. W. Fairbrother, Centre for Science Education, Chelsea College; formerly of Hinckley Grammar School

G. E. Foxcroft, Rugby School

Martin Harrap, formerly of Whitgift School, Croydon

Dr John Harris, Centre for Science Education, Chelsea College; formerly of Harvard Project Physics

Dr A. L. Mansell, Centre for Science Education, Chelsea College; formerly of Hatfield College of Technology

A. W. Trotter, North London Science Centre; formerly of Elliott School, Putney

Evaluation

P. R. Lawton, Garnett College, London

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**Materials and
structure**

Nuffield Advanced Science

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Foreword

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

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

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

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

If the Advanced Physics course meets with the success and appreciation I believe it deserves, it will be in no small measure due to a very large number of people, in the team so ably led by Jon Ogborn and Dr Paul Black, in the

consultative committee, and in the schools in which trials have been held. The programme could not have been brought to a successful conclusion without their help and that of the examination boards, local authorities, the universities, and the professional associations of science teachers.

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

K. W. Keohane

Co-ordinator

of the Nuffield Foundation Science Teaching Project

To the student

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

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

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

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

What you are being asked to learn to do

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

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

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

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

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

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

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

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

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

Summary of Unit 1

Materials and structure

This Unit is about materials: how they are used, how they behave, and why they behave as they do. It is also about how physicists find out about the behaviour and nature of materials, and about how the materials engineer sets about making the most of the materials he has, so as to do a better job.

Behaviour of materials

Stretching and breaking

Stress

Strain

The Young modulus

Breaking strength

Plasticity or ductility, brittleness, elasticity.

Finding out

Designing experiments, plotting suitable graphs, measuring constants.

The nature of materials

X-ray evidence for the arrangement of atoms in, for example, copper. Facts about the arrangement of atoms in glass and rubber. Understanding stretching, yielding, and brittle fracture from an atomic point of view.

Understanding how the wave properties of X-rays are used in discovering how atoms are arranged. The Avogadro constant. The springiness of bonds between atoms (used later in the course).

The kind of physics used

Seeing large scale behaviour in terms of atoms as a typical problem in physics. Use of models, are they 'true'?

Useful theory

Bragg's Law, needed later in the course.

Doing better with materials

Composite materials – concrete, fibreglass, toughened glass, plywood.

Learning from books

Finding out about some materials from books and articles. Presenting the information.

What engineers do

How they make the best of what they have, and how they may be able to devise quite new ways of overcoming the natural deficiencies of available materials.

Questions

Part One

The variety and behaviour of materials

Questions 1 to 7

These questions are about how useful materials behave, and about how their behaviour is described and how it is represented on graphs.

1 *For discussion*

a Why do aluminium electric power transmission lines sometimes have steel cores?

b 'The trouble with glass is that although it is strong, it breaks easily.' Explain this seemingly contradictory statement more clearly.

c What would the world be like without rubber?

d What property of metals makes it possible to manufacture wires easily?

2 Imagine that you are blindfolded and a piece of string is put into each of your hands. You are told that the strings are tied to the ends of a specimen which you can stretch. As you start to pull, it hardly extends at all, but when you pull a little harder it starts to stretch very easily and quite rapidly. Then you relax and it contracts again, but not back to its original length.

Sketch a graph to represent these observations.

3 The graphs in figure 1 show how the lengths of various materials vary as the force extending them is increased. For each graph say how you would describe the behaviour over the telephone to a friend (who doesn't understand about graphs). They are all to the same scale.

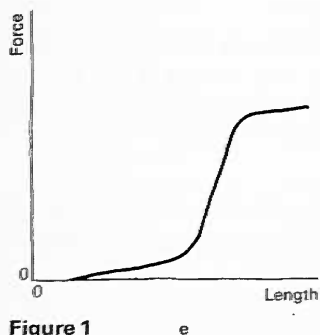
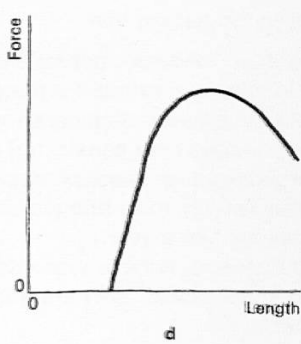
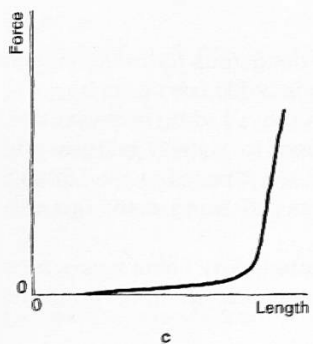
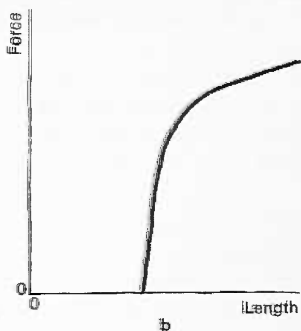
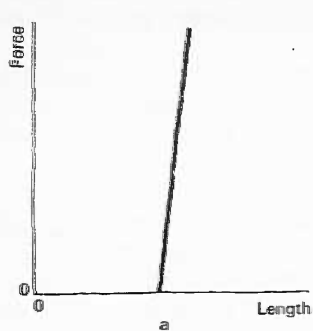
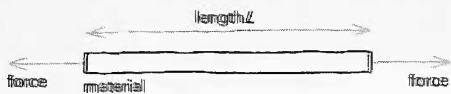


Figure 1

e

4 *For discussion*

- a** Explain what you consider to be the everyday meaning of the word 'elastic', as a description of the behaviour of a material when it is stretched. To what extent can you justify describing each of the following as elastic: polythene, rubber, ordinary copper wire?
- b** A material can be described as 'plastic' if a piece of it keeps to its new shape after being forced to change its previous shape. Which of the following do you consider to be plastic: brick, lead, rubber, Plasticine?

5 A 'strong' material is one that can withstand a large force without breaking. But there are materials which, although they are strong, cannot bend or stretch much without breaking – like cast iron, glass, or stone. Others are 'tough' and do not snap if bent or stretched a little, like steel or nylon fishing line.

Sudden loads or impacts are dangerous for brittle materials: the way to find out if a thing is brittle is to drop it!

- a** Why do you think cast iron proved to be quite satisfactory for bridges over canals, but poor for railway bridges, which are nowadays made of steel? (In America in the 1880s cast iron railway truss bridges were collapsing at the rate of twenty-five a year.)
- b** Before polythene was invented, dirty china was washed up in metal bowls. Why are polythene washing up bowls much better?

6 *For private investigation*

Roll out a uniform 'rod' of Plasticine. Short lengths keep pretty straight as the rod is picked up at one end and held horizontally, but longer lengths droop into a curve. For a rod of some particular thickness, find the length which just droops – the 'droop length'.

Try rods of different thicknesses. What sort of relationship do you **a** expect **b** find, between droop length and thickness?

7 For revision

Each of statements a–k describes the behaviour of a material. For each, say which of the following materials behaves according to the description: rubber, glass, copper, steel (a description might fit one of the materials, several of them, or none).

- a Extends continually under no load.
- b Gets harder to pull after it has been stretched somewhat.
- c Gets easier to pull after it has been stretched a little.
- d Flows like a liquid when it is sufficiently hot.
- e Extends more easily than any of the others.
- f Goes much thinner at the point where it breaks.
- g Breaks in a brittle way or can be treated to make it brittle.
- h Changes temperature appreciably on being stretched.
- i Can be split longways when stretched.
- j Goes back to its original length if released before it gets to breaking point.
- k Doesn't deform at all no matter what the force.

Discuss cases where you are not sure or where you think the statement is only true in some circumstances (e.g. 'Copper only does this if the temperature . . .').

Words are used loosely in this question: you should be able to suggest more definite descriptions.

Part Two

X-rays and structure

Questions 8 to 11 The Avogadro constant and the mole. See also Nuffield Advanced Chemistry, *Amount of substance*.

8 This question is about what 'a mole' means.

The Avogadro constant is approximately 6×10^{23} items per mole ('per mole' is written ' mol^{-1} ' as a unit symbol).

- a How many grammes of solid sodium chloride contain one mole of sodium ions?
- b How many grammes of solid sodium chloride contain one mole of chlorine ions?
- c How many pairs of Na^+ and Cl^- ions are there in 58.5 g of sodium chloride?

d If one mole of sodium atoms and one mole of chlorine atoms combine to form NaCl, made of ions Na^+ and Cl^- , one mole of electrons is transferred from sodium atoms to chlorine atoms. How much electric charge is carried by a mole of electrons? (Charge on one electron = 1.6×10^{-19} C.)

e How much is a mole of salt? Give an answer like 'enough to cover a penny piece'.

9 If all the atoms in a 22 s.w.g. copper wire suddenly grew to 50 mm in diameter, what would be the diameter of the wire? Take the diameter of a copper atom as 2.5×10^{-10} m. 22 s.w.g. copper wire has a diameter of 0.711 mm.

10 If one kilogramme of a metal whose density is $10\,000 \text{ kg m}^{-3}$ contains 10^{25} atoms, what is the volume effectively occupied by one atom? If an atom of this volume were a sphere, what would be its diameter?

11 Estimate how many sodium ions there are in a grain of salt. What would be the mass of a mole of grains of salt (that is 6×10^{23} grains)?

Questions 12 to 16 Atoms in solids

These questions are about how atoms may pack together in solids.

12 Suppose a physicist is trying to think about how atoms in a metal might be arranged. He builds a model made of *spheres*, each sphere representing an atom. The spheres are all the *same size*. He first tries to find ways of packing them together *as closely as possible* (to fill as much of the space as possible).

a Discuss whether the simplifying assumptions he is making (in *italics*) are sensible ones.

b His spheres have to be glued together. He regards it as obvious that atoms in a metal attract one another. Is this sensible?

c His spheres are hard, and do not squash easily. He regards it as obvious that the atoms cannot get too close to one another. Is this sensible?

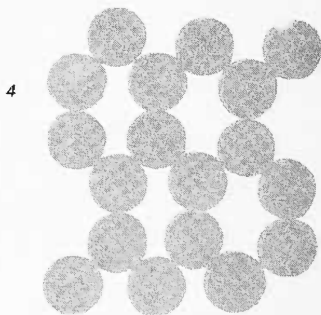
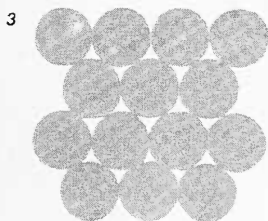
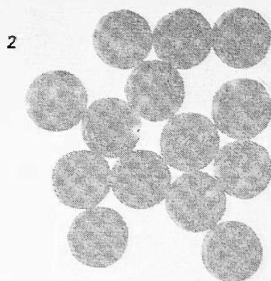
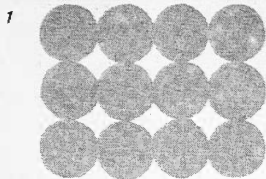


Figure 2

13 a Which of the diagrams in figure 2 represents a layer of soap bubbles?

b Why do you think soap bubbles take up the pattern you have picked out?

c Since layers like the soap bubble layer occur in many metals, what might be concluded about the forces between the atoms in such metals? (Think about their directions.)

14 *For discussion*

In 1665 Robert Hooke showed how musket balls could be stacked in piles, as in figure 3, to simulate the characteristic shapes of crystals. Such a pile would nowadays be said to be a model of the beautiful arrangement of atoms in a simple close-packed structure.

a How does the pile do what Hooke wanted it to?

b In what sense is it 'simple'?

c About one quarter of the volume of the pile is empty space between balls. In what sense is it 'close-packed'?

d Attack or defend the use of the word 'beautiful'.

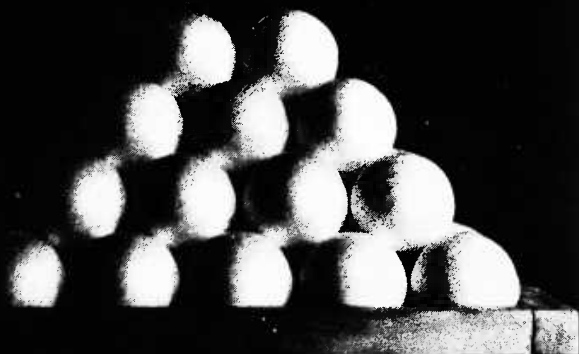


Figure 3

Questions 15 and 16 take you through a piece of theoretical argument that can be used to measure the Avogadro constant if the size of atoms and their arrangement in some solid is known from experiment.

15 A very large rectangular box has its bottom, of side a and b , covered with balls of diameter D , arranged in a square formation with the rows of balls touching one another and parallel to the sides of the box. The box is filled with layers of balls, each ball resting on four balls below it. The centre of each ball is D/k above the plane containing the centres of balls in the layer immediately below it. (Do not calculate k .) The height of the box is c . Write expressions for **a** the number of balls in the box; **b** the number of balls packed per unit volume.

16 Experimental work with X-rays suggests that copper atoms have a diameter of about 2.5×10^{-10} m, and that they are arranged in the way shown in figure 3, which is the way described in question 15 and is also the way greengrocers stack oranges.

a Use figure 4 to argue that the centre of each ball is a distance $D/\sqrt{2}$ above the plane containing the centres of balls in the layer immediately below it.

b Work out the volume occupied by one mole of copper atoms. (Atomic mass of copper, 63.6 g. Density of copper, $8930 \text{ kg} \cdot \text{m}^{-3}$.)

c Use the answer to question 15, with $k = \sqrt{2}$, to find the number of atoms in one mole, the Avogadro constant.

a

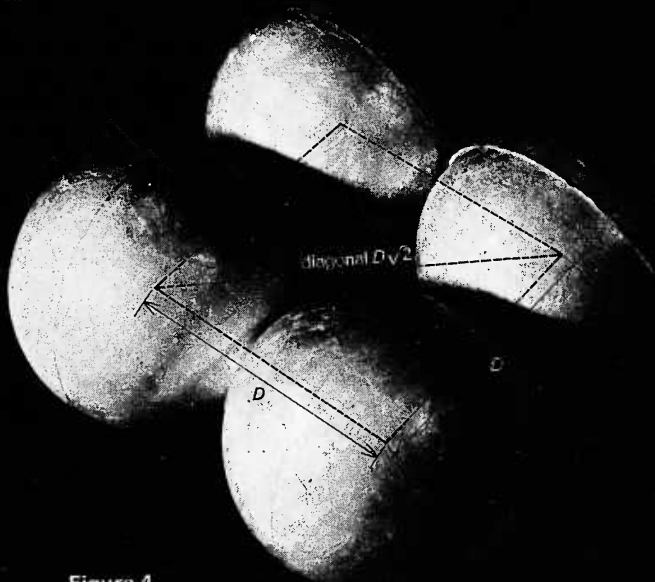
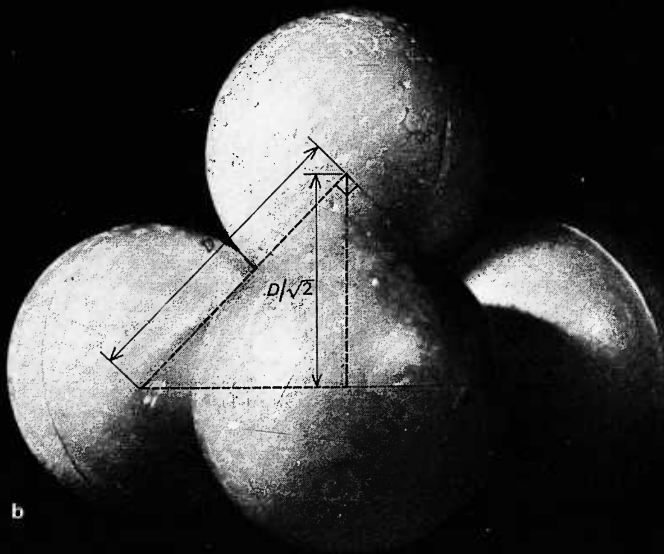


Figure 4

- a Four balls in square array.
b One new ball resting above four others.



b

Questions 17 to 22 Using X-rays to investigate atoms in solids.

Questions 17–19 revise ideas about the interference of waves. Question 22 develops a piece of theoretical argument, needed later in the course.

17 *Introductory*

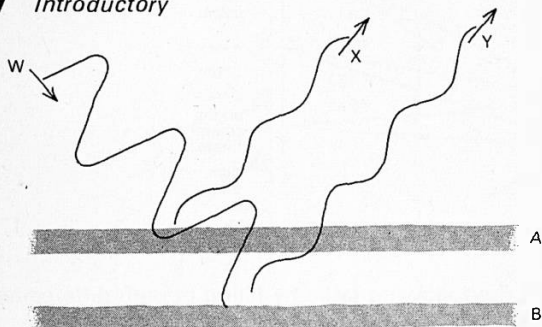


Figure 5

A beam of waves *W* falls on two layers *A*, *B* – perhaps layers of atoms – which scatter some wave energy, *X* and *Y* respectively.

a Will a wave crest in wave *W* be partly scattered into wave *X* later or earlier than into wave *Y*?

b Will waves *X*, *Y* *in general* be in step?

c Is it possible for waves *X*, *Y* *ever* to be in step?

18 For revision, from Nuffield O-level, *Questions book V*
a Explain what figure 6 is about.

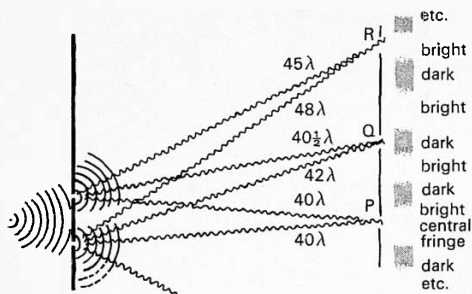


Figure 6

b 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	$1\frac{1}{2}\lambda$
second bright	
third dark	
third bright	3λ

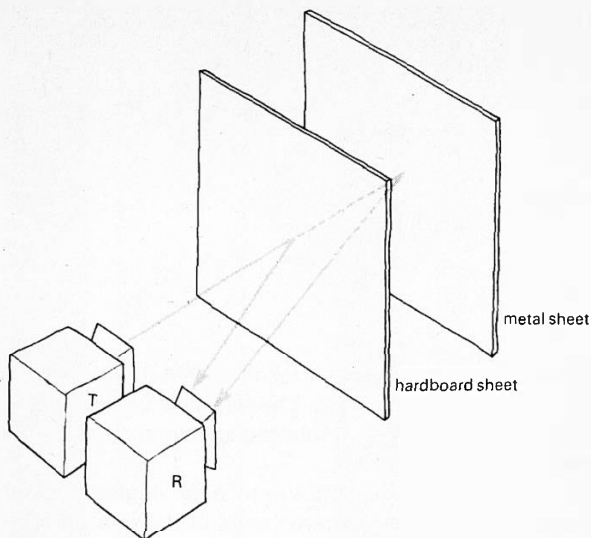


Figure 7

19 A microwave transmitter faces a hardboard sheet, behind which is a metal sheet. Microwaves are part reflected, part transmitted through hardboard. (Figure 7.)

What is detected by a receiver R, which faces the two sheets, as the metal sheet is moved away from T and R?

Would similar results be obtained if the hardboard sheet were moved towards the metal sheet?

20 This question is about X-ray diffraction; **a** is about powder photography and **b** uses the ideas to obtain the size of a copper atom.

a In experiments which you may have seen on film, a single crystal of sodium chloride diffracts strong beams of X-rays in certain directions only. One such beam is at an angle of 31.8° to the original beam, meeting and leaving the face of the crystal at an angle of half as much, 15.9° . (Figure 8.)

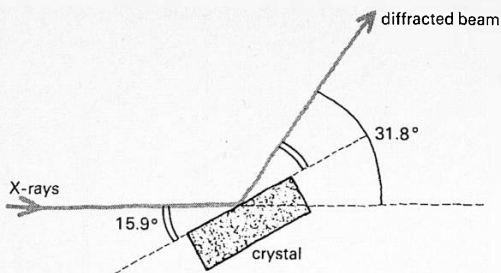


Figure 8

Figure 9 shows a photograph taken with a powdered specimen of sodium chloride. The film was wrapped in a cylinder of radius 45 mm round the specimen, and then laid out flat to make the print.

- 1 How could lines corresponding to *small* angles of beam deflection appear at the extreme *ends* of the photograph?
- 2 Find the line corresponding to the beam deflection angle of 31.8° .
- 3 If you know the relationship $\lambda = 2d \sin \theta$, find d (θ is *not* 31.8°).

b Figure 10 shows a similar powder camera result for a copper wire.

- 1 Give a reason to support the view that a copper wire is made up of many small pieces of crystalline copper.
- 2 Show that the angles through which the X-ray beam was turned to produce the lines marked 1, 2, and 3 are nearly 44° , 50° , and 74° respectively.

The angles through which microwaves of wavelength 3.15×10^{-2} m are diffracted by a model of polystyrene spheres built up in the structure shown in figure 3 are 44° , 50° , 74° , if the spheres are 50 mm in diameter. These angles should be the same as those in 2.

- 3 Give a reason for supposing that copper atoms are piled up in the arrangement of figure 3.
- 4 The X-rays had wavelength 1.54×10^{-10} m. What is the ratio of the microwave wavelength to the X-ray wavelength?

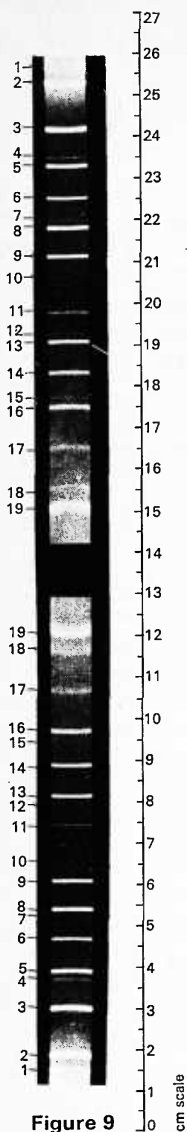


Figure 9

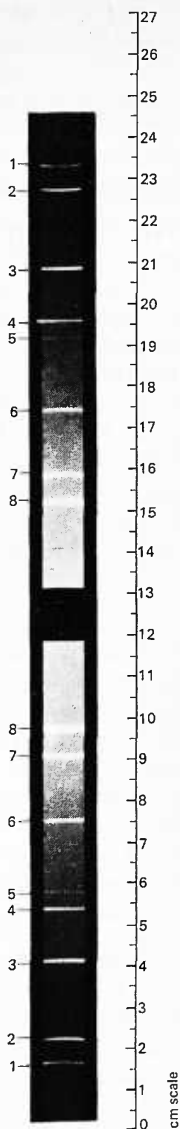


Figure 10

5 If the diffraction angles are the same, what is the ratio of the diameter of the 50 mm spheres to the diameter of copper atoms?

6 What is the diameter of a copper atom?

21 The following passage comes from an article by Sir Lawrence Bragg. Some questions follow it.

The atomic structure of a crystal is deduced from the way it diffracts a beam of X-rays in different directions. A crystal is built of countless small structural units, each consisting of the same arrangement of atoms; the units are repeated regularly like the pattern of a wallpaper, except that in a crystal the pattern extends in three dimensions in space. The directions of the diffracted beams depend on the repeat distances of the pattern. The strengths of the diffracted beams, on the other hand, depend on the arrangement of atoms in each unit. The wavelets scattered by the atoms interfere to give a strong resultant in some directions and a weak resultant in others. The goal of X-ray analysis is to find the atomic arrangement that accounts for the observed strengths of the many diffracted beams.

This brings us to the question of why X-rays, of all the available forms of electromagnetic radiation, are indispensable for this method of investigation. In order for the interference of the diffracted beams to produce marked changes in the amount of scattering in different directions, the differences in the paths taken by reflected beams must be on the order of a wavelength. Only X-rays have wavelengths short enough to satisfy this condition. For example, the distance between neighbouring sodium and chlorine atoms in a crystal of sodium chloride (ordinary table salt) is 2.81×10^{-10} m, whereas the most commonly used wavelength in X-ray analysis is 1.54×10^{-10} m.

Actually crystals came into the picture only because they are a convenient means to an end. The resultant scattering of X-rays would be hopelessly confused and impossible to interpret if the scattering units were randomly distributed in all orientations. In a crystal the units are all similarly oriented and hence scatter the

X-rays in the same way; as a result a total scattering measurement made with a whole crystal leads directly to a determination of the amount scattered by an individual unit.

(Bragg, Sir L., 1968, 'X-ray crystallography', Scientific American Offprint No. 325.)

a What evidence is there to support the statement (first paragraph) that 'A crystal is built of countless small structural units, each consisting of the same arrangement of atoms'?

b How and why are X-ray diffraction photographs quite unlike the X-ray shadow photographs taken by doctors of bones or by metallurgists of flawed castings?

c Why must 'the differences in the paths taken by reflected beams . . . be on the order of a wavelength' (second paragraph)?

d ' . . . X-rays, of all the available forms of electromagnetic radiation, are indispensable for this method of investigation' (second paragraph). Why not use light?

e The third paragraph says why crystals, with their orderly arrangement of atoms, are used with X-rays for diffraction experiments. Can you say something about how X-rays might be diffracted by water? (Molecules in a liquid are not tidily arranged.)

f X-rays are well known for their ability to penetrate deep inside solids. Is this property essential for the success of X-ray diffraction?

22 This question is about the Bragg equation $\lambda = 2d \sin \theta$.

The first X-ray diffraction photographs were taken by von Laue. It was soon realized that diffraction by atoms arranged in three dimensions was a complicated problem. Bragg simplified the problem by thinking about X-rays being reflected by layers of atoms.

The kind of argument Bragg developed is presented in many books, and is somewhat as follows.

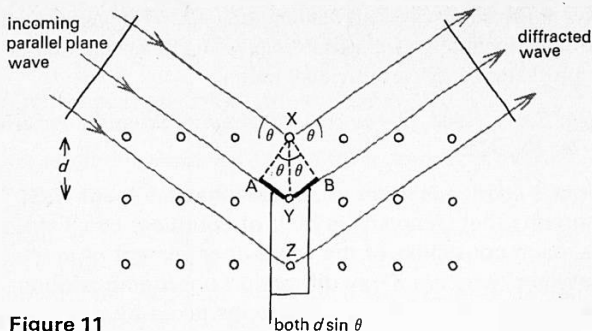


Figure 11

An incoming parallel beam of X-rays, at angle θ to layers of atoms, is assumed to be reflected at an equal angle θ . The part of the beam scattered from Y in the second layer travels a distance AYB further than the part scattered at X in the first layer. If the extra distance is equal to one wavelength, the beam will be strong, since the waves will be in step. As $AY = YB = d \sin \theta$, the condition is $\lambda = 2d \sin \theta$.

You are now asked to consider the argument critically.

Indirectly, doing so may help you to understand its nature.

- As the beam is parallel, waves from X, Y, or Z never meet and so can not interfere. What has gone wrong?
- What about reflections from the other layers below X and Y?
- Why draw layers of individual atoms? Couldn't the same effects be produced by layers of clumps of atoms? Or by any regularly repeating pattern of atomic arrangements?
- Why should a layer of atoms reflect a plane wave as a mirror would?
- Wouldn't one layer of regularly arranged atoms produce, on its own, strong beams in other directions, as a diffraction grating would do? (Figure 12 shows the simple case of waves coming in at right angles to the surface.)

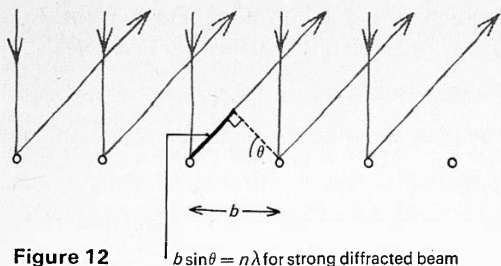


Figure 12

Question 23 Models

23 The following passage also comes from Sir Lawrence Bragg's article, 'X-ray crystallography'.

X-ray crystallography is a strange branch of science. The result of an investigation lasting many years can be summed up in a 'model'. I have often been asked: 'Why are you always showing and talking about models? Other kinds of scientists do not do this.' The answer is that what the investigator has been seeking all along is simply a structural plan, a map if you will, that shows all the atoms in their relative positions in space. No other branch of science is so completely geographical; a list of spatial co-ordinates is all that is needed to tell the world what has been discovered.

a There are some models whose job is to remind one of what things are like: a model of a petrol engine, a circuit diagram, or a sketch map, for example. Do the models Bragg describes have anything in common with this type?

b Is it true that other scientists do not use models at all? If they do, do they use them only in the way described, or in other ways as well?)

c Write a sentence or two about the differences between model and reality in some of the following examples:

A model railway layout.

A railway map showing the lines neatly straightened out.

A dolls' house.

A model boat hull built for tests in a tank before building the real thing.

Molecular models used by chemists.

The use of a computer to simulate the random flow of traffic, so as to improve the design of a road system.

Balls joined by springs to represent vibrating atoms in a solid.

An atom as a hard small sphere.

A shop window dummy as an idealized human figure.

Part Three

Stretching and breaking

Questions 24 to 30 Stretching and breaking materials

24 This question is about 'stress' and 'strain'. So is question 25.

a 'Tensile stress' is tension per unit area of cross-section. A long strip of rubber whose cross-section measures 12 mm by 0.25 mm is pulled with a force of 3 N. What is the tensile stress in the rubber? Give the units.

b 'Tensile strain' is the increase in length as a fraction of the original length. A strip of rubber originally 90 mm long is stretched until it is 120 mm long. What is the tensile strain? Why has the answer no unit?

c The greatest tensile stress which steel of a particular sort can withstand without breaking is about 10^9 N m^{-2} . What is the greatest load that can be supported on a wire of cross-sectional area 0.01 mm^2 made of this steel? (You may use the original cross-section in calculation, as if it were not reduced.)

d Estimate the diameter of a single steel wire which would suspend a car without breaking.

e A wire 2 m long is given a strain of 0.01. By how much has its length increased?

f Rubber needs a stress of roughly 10^6 N m^{-2} for each unit increase in strain. What is the tension in a rubber band 1 mm thick and 3 mm wide stretched to three times its original length? (The question is ambiguous. Can you see why?)

g A student finds that a particular steel wire needs a force of 10^2 N to stretch it by an extra one-hundredth of its original length, and records this as 10^4 N per unit strain. Another student thinks this result means that 10^4 N are needed to double the length of the wire. What is wrong with his interpretation? Is the record sensible in the form given?

25 a A specimen of rubber of cross-sectional area 2 mm^2 is extended in length from 0.1 m to 0.15 m by a force of 0.4 N. Use these results to predict the force needed to extend a piece of the same material with 4 mm^2 cross-section from a length of 0.50 m to 0.75 m.

b Could you, on the basis of the above data, *either* calculate exactly *or* estimate roughly the force needed to stretch the second piece of rubber

1 from 0.50 m to 0.55 m?

2 from 0.50 m to 3.50 m?

c If a 20 kilogramme mass hanging on a steel wire of 1 mm^2 cross-section produces a 0.1 per cent strain in the wire, what mass hanging on the wire would give it a strain of 10 per cent?

Comment on your answer.



26 Figure 13 shows subsidence in a road in a mining area. What kinds of deformation and fracture can you see?

27 This question is about laws in physics; when they are true and when they are not.

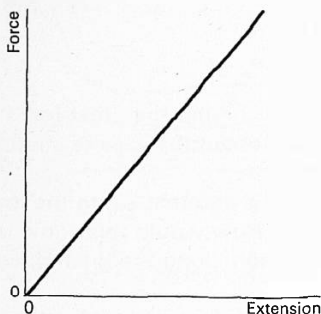


Figure 14

Hooke's Law is often expressed graphically as in figure 14.

Draw graphs for copper and rubber, up to their breaking points. Comment on the following statements:

- 1 Hooke was wrong. His 'law' is not true.
- 2 Hooke's Law is true, but only for small strains.
- 3 Hooke was right only for the things he tested.
- 4 Every material has a Hooke's Law region and then departs from it.
- 5 Hooke's results should not be called a 'law': what kind of a 'law' is it that is so widely disobeyed?

Compare other uses of the word 'law'.

Books

Arons, *Development of concepts of physics*. (P. 165 quotes from Hooke himself.)

Rogers, *Physics for the inquiring mind*. (Chapter 5 is very relevant to this question.)

Figure 13

Photograph, The Guardian.

28 Material	Young modulus/ N m^{-2}
cast iron	15×10^{10}
mild steel	21×10^{10}
wood, spruce:	
along grain	$1.0\text{--}1.6 \times 10^{10}$
across grain	$0.04\text{--}0.09 \times 10^{10}$
glass	8×10^{10}
Perspex	0.6×10^{10}

a The Young modulus for glass is higher than that for Perspex. What does this tell you about the ease of stretching glass compared with Perspex?

b The Young modulus for wood is different along the grain compared with across the grain. How would this show up when you flex a thin sheet of wood along the grain direction and then across the grain?

c Wood has a much lower value of Young modulus than steel. Which would be the easier to stretch?

29 *Hard*

Estimate roughly how much energy is transformed in stretching a rubber band until it breaks.

30 This is another question intended to help you to learn to read and interpret graphical information.

Figure 15 shows stress–strain graphs for samples of polythene at different temperatures.

a At about room temperature what stress is needed to produce a strain of 100 per cent in polythene?

b If I have a sample of polythene 0.2 m long and stretch it until the strain is 100 per cent, how long will the sample be at this strain?

c If the sample is 100 mm wide and 1 mm thick what force has to be applied, at room temperature, to give 100 per cent strain?

d A student finds that the stress in a sample of polythene as the strain is steadily increased rises, falls, and then slowly rises again. What can you say about the temperature of the sample?

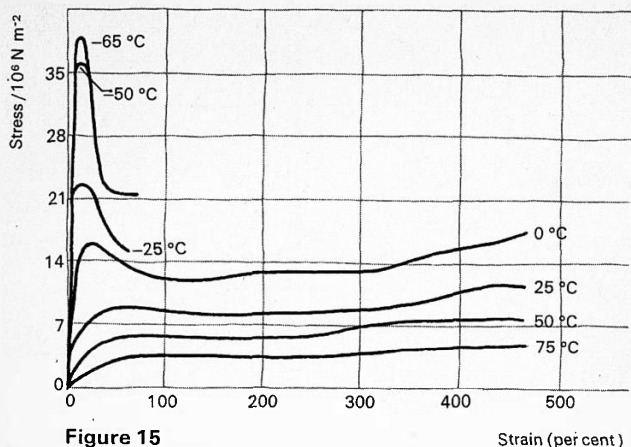


Figure 15

By courtesy of I.C.I. Plastics Division.

Questions 31 to 36 Atoms and the behaviour of materials.

31 This question may help with the next one, which is more serious.

A school laboratory has a demonstration model, shown in figure 16, which is meant to illustrate the stretching of bonds between atoms as a piece of material is stretched. The model has four horizontal planes of small balls linked horizontally by rods and vertically by springs. All the springs are identical and may be taken to be 50 mm long. The dimensions are shown, all in millimetres. When a vertical stretching force of 12 N is applied, the length of 150 mm increases to 165 mm.

What is the force constant (restoring force for unit displacement) for a single spring? What is the restoring force for 10 per cent strain for a single spring?

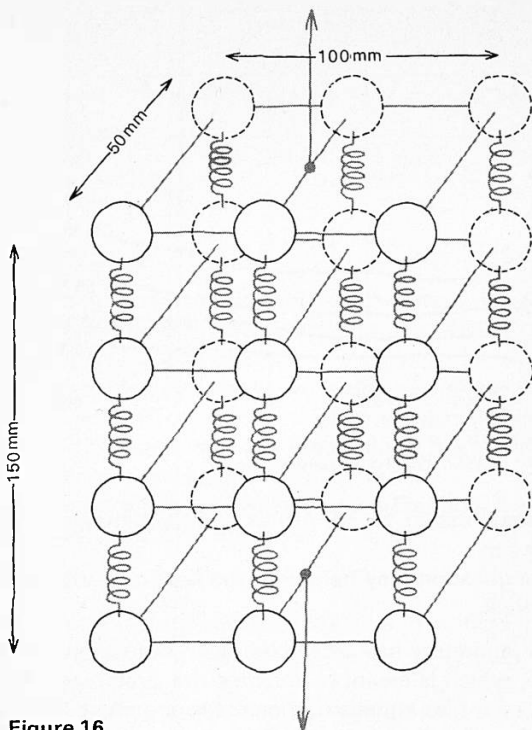


Figure 16

32 This question makes a link between the elastic modulus of a metal (stress–strain) and the springiness of bonds between atoms.

Imagine layers of atoms in square array, each atom distance x from its nearest neighbours both in its own layer and in layers above or below.

Suppose a long wire, with many layers, is stretched a little so that each layer is now $x + \Delta x$ from those above or below it.

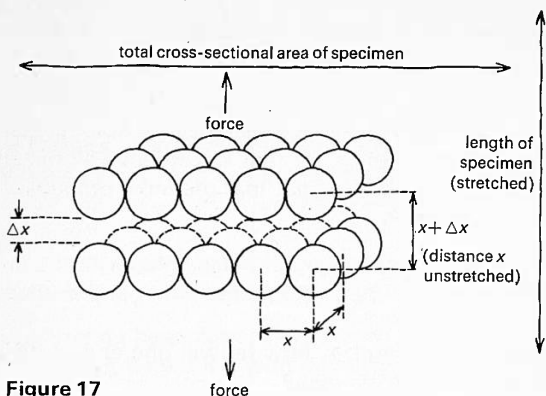


Figure 17

a If there are n layers in the length of the wire, how long is the wire before it is stretched?

b By how much has the wire extended?

c What is the *strain* in terms of x and Δx ?

Now think of the bonds holding each atom as being like a spring, so that there is a force of $k\Delta x$ pulling a pair of atoms together.

d k is the stiffness of the spring. What are its units?

e If there are m atoms in each layer, what is the force pulling adjacent layers together?

f The stress is the force per square metre. In terms of the spacing x , how many atoms are there per square metre of a layer?

g What is the stress in terms of k , Δx , and x ?

h What is the elastic modulus (stress–strain)?

i For steel, the elastic modulus is 20×10^{10} newtons per square metre. The spacing x is about 3×10^{-10} metre. What is the stiffness, k , of the springy bond?

33 This question is about rubber, but it uses an idea from the kinetic theory of gases.

A molecule bouncing about from collision to collision in steps of length x will not usually be a distance nx from its starting point after making n steps, for that would need all the steps to be in a straight line. It turns out that the most probable distance is about $x\sqrt{n}$.

A rubber molecule is a long chain of n links, with the links free to swivel so that the chain points hither and thither along its length.

a If each link is of length x , how far will one end of the chain be from the other, on average?

b How long can the chain possibly be, fully stretched out?

c If $n = 100$, at what strain will rubber become very hard to pull out any further?

34 *For discussion*

This question is about using words well enough to be understood in discussion.

A 'Now let's get this clear. You say that this grain of NaCl here is a little block of one crystal.'

B 'Yes.'

A 'And this piece of copper wire is also crystalline.'

B 'Yes, but it's polycrystalline.'

A 'Ah, so there is crystalline and polycrystalline. Is rubber polycrystalline?'

B 'No. Rubber is amorphous until you stretch it.'

A 'Amorphous – you mean like a liquid?'

B 'Yes.'

A 'A liquid doesn't become crystalline when you stretch it?'

B 'Perhaps we'd better go back to the beginning.'

Can you help B ?

35 When cutting a sheet of glass an expert holds the glass cutter so that it moves in a *vertical plane*; he then applies *just enough* pressure to make the cutting edge bite, and draws it *just once* across the glass. Then he picks up the glass, holding it at the *near edge*, one hand on each side of the 'cut' with thumbs on top, and keeping a firm grip on the glass *turns his hands outwards*. When cutting thicker, say 5 mm glass, *he may need to tap the glass* under the 'cut', *beginning at the near edge* and chasing the crack across. Explain the above procedure, especially the words in italics.

You could get a cheap cutter (a diamond is unnecessary) and try cutting glass, beginning with microscope slides. Perhaps you might even try cutting a circular hole!

(You might like to investigate the cutting of bricks, pavement slabs, glazed tiles, etc. to see that the traditional skills are, in fact, the most suitable.)

36 'So here is the dislocation, and now imagine that we try to slide the top this way and the bottom this way – then the atoms around the dislocation can rearrange themselves so in the next picture . . . '.

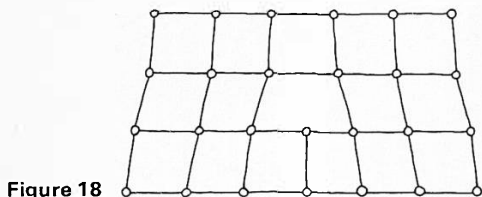


Figure 18

Can you draw the next picture? And the next? And the next? Can you also write out the rest of the talk which might accompany the pictures?

Questions 37 to 44 Composite materials and some general questions

37 The typical tensile strengths of some materials are given below in round numbers:

Material	Tensile strength/ N m^{-2}
mild steel	10×10^8
wrought iron	5×10^8
wood, spruce:	
along grain	1×10^8
across grain	0.3×10^8
glass	$0.3 - 1.7 \times 10^8$
concrete	0.04×10^8

a The upper value for glass compares quite favourably with iron and wood. Why isn't glass used in the same way that iron and wood are used (e.g. why are railway lines not made of glass instead of wrought iron; or boats made of glass instead of wood)?

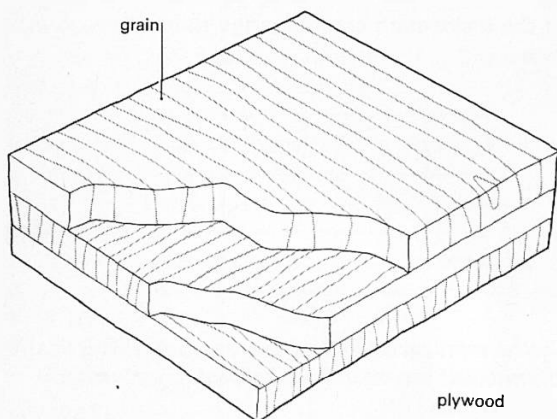


Figure 19

b Why is plywood made the way it is?

Where would you expect to see plywood being used? Why? Why isn't plywood used for all purposes where wood is employed?

c Concrete has the lowest tensile strength of all the materials listed. How do you explain the widespread use of concrete in building?

Books

Gordon, *The new science of strong materials*. (See Chapter 7, on glues and plywood, and Chapter 5 on cracks.)

Loftas and Gwynne, *Advances in materials science*. (See page 65 for a chapter on new materials in building.)

38 This is a question about materials; though it seems to be about architecture.

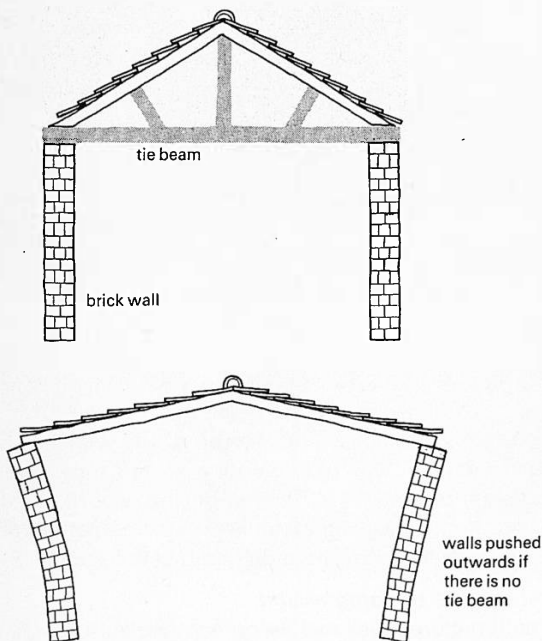


Figure 20

Figure 20 is a sketch of a conventional brick house with a tiled roof carried on timber rafters. The brick walls are in compression, supporting the roof load. But part of the

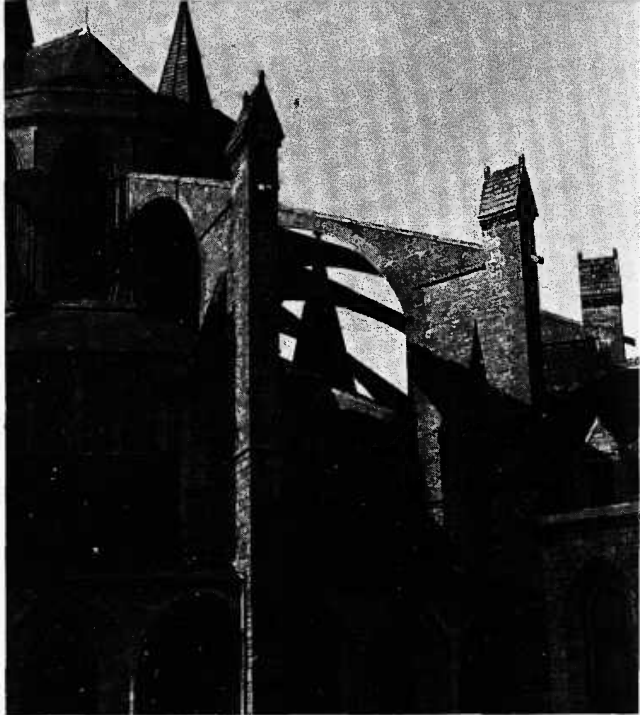


Figure 21

Coutances Cathedral.

building must be in tension — the tie beam across the roof that prevents the roof from pushing the top of the walls outwards. An alternative way of preventing walls from bending uses compression, by providing buttresses outside the walls. The beautiful flying buttresses used by some cathedral builders are a fine example of the principle. (See figure 21.)

The architecture of compression

Much early architecture relies mainly on compression for the stability of its buildings, because stone and brick are brittle materials, good in compression but poor in tension. (Wood was for a long time the only tough material, good in tension, that was available in quantity. But wood rots, and was often avoided in buildings that were to be as permanent as possible.)



Figure 22

St Bartholomew's Church, Smithfield.

Photograph, Edwin Smith.

The 'romanesque' arch is a fine example of the architecture of compression, the compression often being expressed visually in the massive, thick pillars and short arches. See figure 22.



Figure 23 Paestum. The temple of Ceres. *Photograph, J. Allan Cash.*

Greek temples used stone columns in compression, carrying short thick stone beams bridging the tops of the columns.

The architecture of tension

The arrival of steel as a structural material meant that parts of a structure could be in tension without risk of fracture, for steel is tough, not brittle. The most obvious example is the suspension bridge.



Figure 24
The Severn Bridge.
Photograph, William Tribe.

A less obvious example of the architecture of tension is the modern tall tower block of offices or flats. In a conventional house, the walls hold up the roof; in a tower block the roof holds up the walls. The block has a central spine from which cantilever arms of steel-reinforced concrete or steel stick out. The top cantilever arm carries the roof, and the walls, often of glass in alloy frames, are hung between the lower arms. The arms also take the load of the successive floors, by withstanding bending forces. (Figure 25.)

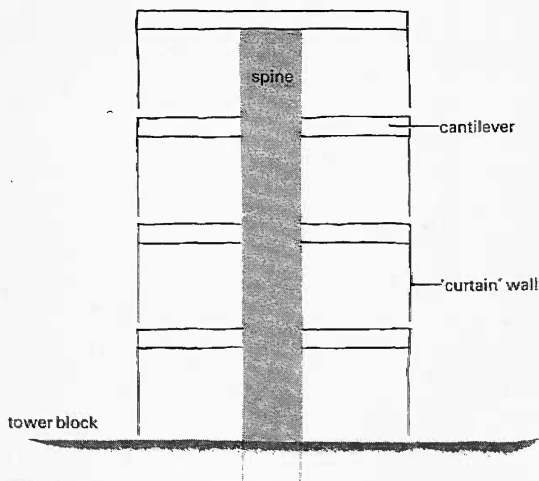


Figure 25

- a** Why is part of a beam that is being bent, in tension? Which part?
- b** Why had the stone beams joining the tops of columns in a Greek temple to be short and thick?
- c** Give some more example of the architectures of compression and of tension.
- d** Fit the modern motorway flyover into this pattern.
- e** Find out about large domes and the problems of building them.
- f** 'The tree is nature's precursor of the modern office block.' Does this make sense?

g Pre-stressed concrete beams have steel rods or cables passing through them which are tightened so as to compress the beam before it is loaded. What advantage does this method have over unstressed concrete?

39 Read the information below from the *Scientific American* book, *Materials*, and answer the questions that follow.

The familiar forms of ceramics are represented by glass, chalk, and sand; by abrasive powders such as corundum and carborundum, and by gems such as diamond and ruby. It is because ceramic crystals are so vulnerable to cracks that ceramic materials are often used in the form of a powder, to which they are easily reduced. Even as a powder they scratch steel because in fact they are stronger than steel.

In sum, if a ceramic material is unscratched, it can be very strong. If it is flawed in any way, however, it breaks easily. The lack of resistance to cracks is called brittleness. Ceramics are usually fragile because ceramic crystals are almost always marred by cracks or surface irregularities. Even if they are not, such imperfections can be introduced all too readily.

In order to use a ceramic in a modern composite material it is necessary to divide it into small pieces, so that any cracks present cannot find a continuous path through the material, and to bind the pieces together in a matrix. The ceramic is often put into the composite in the form of fibres. The properties of the matrix are of vital importance. First, it must not damage the fibres by scratching them, which would introduce cracks. Second, it must act as the medium by which stress is transmitted to the fibres; it should be plastic and adhesive so that it holds the fibres much as deep, soft mud holds one's leg when one steps into it. Third, the matrix must deflect and control cracks in the composite itself.

a Why is a ceramic not a suitable material, on its own, for use in an application where it is in tension?

b Why is ceramic material, in small pieces bound in a soft matrix, less brittle than the solid ceramic?

c Concrete contains small pieces of a ceramic, stone, bound in a matrix, cement. Why is concrete not a tough composite of the sort described above?

d Why must the matrix adhere to the fibres within it to produce a useful composite?

40 It has been suggested that, to cut down fatal road accidents, car passengers should be enclosed in a 'bubble'. In a head-on collision this bubble would ride up and over the car engine, so preventing the occupants from being crushed.

a Discuss the properties that would be required of the materials from which the bubble was made.

b How would you package the passengers inside the 'bubble' to prevent injury in an accident?

41 This question is about the influence of the properties of materials on design.

The four chairs in figure 26 are all recognized by designers as classics of modern design.

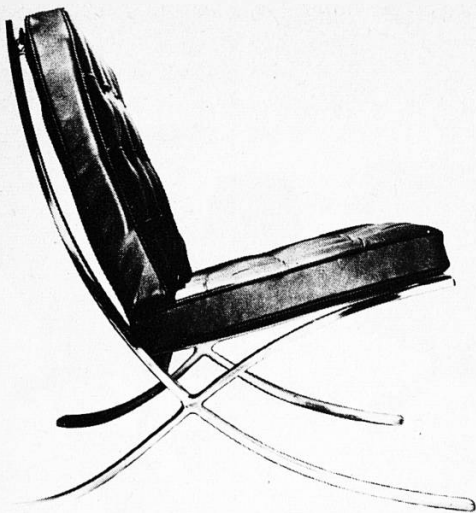
The chairs in **a** and **b** both use steel, together with leather, and were designed by Mies van der Rohe and by Marcel Breuer respectively. The one in **c**, designed by Charles Eames, has a plywood shell with leather cushions. Chair **d**, by Arne Jacobsen, has a glass fibre shell, covered with foam plastic under a stretch fabric, or leather.

1 What properties of steel are used to advantage in **a** and **b**? (Consider whether wood could have done the job.)

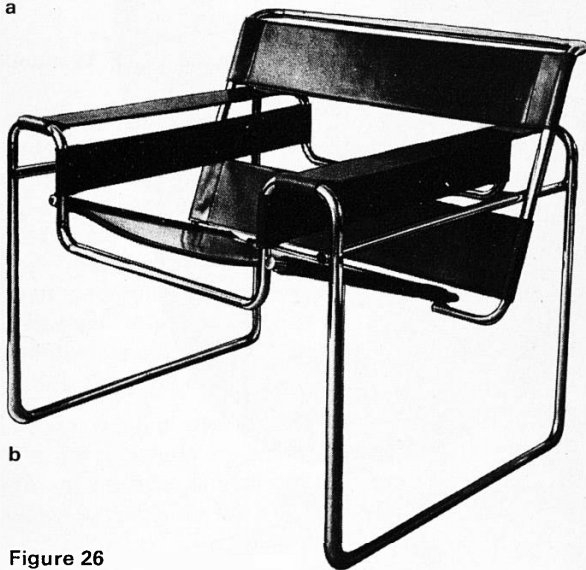
2 How would you describe the differences between **a** and **b** on the one hand and wooden chairs on the other?

3 Both **c** and **d** are based on curved shells. What properties of the materials of which they are made lead to this form?

4 The shell of chair **c** is curved in one direction (it is made of several linked shells), while the shell of chair **d** is curved in two directions. Explain the difference, in terms of the materials.



a



b

Figure 26

Four designs of chairs.

Photograph b, by courtesy of Aram Designs Ltd.

(Continued)



c



d

Figure 26 continued
Photograph d, by courtesy of Dennis Hooker.

42 The strength of a rod, like the bones in an animal's legs, increases in proportion to the cross-sectional area. Discuss possible reasons why animals more than 10 metres high do not exist on Earth. Do similar arguments apply to trees? Would the argument be different for animals living on Jupiter?

See PSSC *Physics*, 2nd edition (Chapter 4).

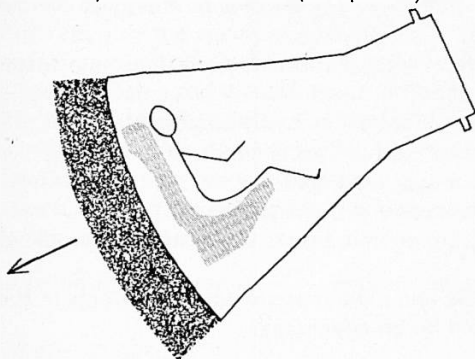


Figure 27

43 *Hard*

The shaded slab on the drawing of the spacecraft (figure 27) represents the 'heat shield'. (The kinetic energy of the orbiting craft is substantially more than the energy needed to evaporate it, yet this energy – and the potential energy the craft has – must be transformed into other forms of energy if the craft is to come to rest.) As the craft passes through the atmosphere on 're-entry', air near the craft, and the craft itself, will be heated, and the blunt end with the shield will be heated more than the other parts.

What do you think of the following suggestions for desirable properties for a material for such a shield? You might agree or disagree, saying why; or pick out the ones that seem particularly desirable; or say that no material is likely to exist

to have this property; or make other comments. (You may only be able to say that some ideas in the list seem likely or unlikely.)

a It should be soft, to cushion the craft against the impact with the atmosphere.

b It should melt at a very high temperature indeed (brick-like substances).

c It should require a very great deal of energy to melt and to vaporize it.

d It should be very tough, like steel, so that the pressure of the air does not dent it or bend it.

e It should conduct heat as badly as possible.

f It should be a good electrical conductor.

g It should conduct heat well.

h It must not crack under sharp blows.

i Very strong interatomic bonds in the material would be an advantage.

j A very simple and regular arrangement of atoms in the material would be an advantage.

44 *Hard*

In a number of experiments, people have tried to rotate objects as fast as possible (some experiments were concerned with high speed friction, others with relativity).

a If any shaped object is spun fast enough, it breaks or yields. Explain why.

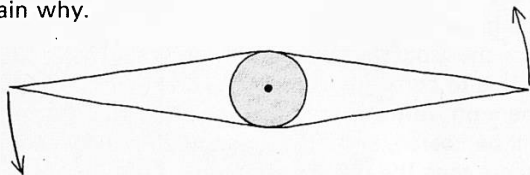


Figure 28

b Some of the rotors used have been shaped as in figure 28. Why is the shape in figure 28 better than a simple rod shape?

c What do you think would be the best possible shape for spinning very fast? Why?

d Which combination of properties of the material is desirable: low density and high breaking stress; high density and high breaking stress; extreme hardness, with low extension for a given stress?

e If a particular shape were made twice as big in all directions, do you think it would break up at a larger or smaller speed, or at the same speed as the smaller scale version?

f Estimate roughly the speed at which a round rod of steel 100 mm long, area 100 mm², which breaks at 10⁹ N m⁻², would break. Such a rod weighs about 80 g. You could try allowing for the fact that different pieces of rod are at different distances from the centre, but it might be better to suppose that the mass were at some average distance. If you supposed it to be at the tip, would you get an upper or lower limit for the breaking speed?

(Acceleration towards centre = $\frac{v^2}{r}$, force = mass \times acceleration.)

Answers

1 Not every question in this book has a straight answer. Try Gordon, *The new science of strong materials*, if you can't answer the questions from your own experience.

2 See figure 29.

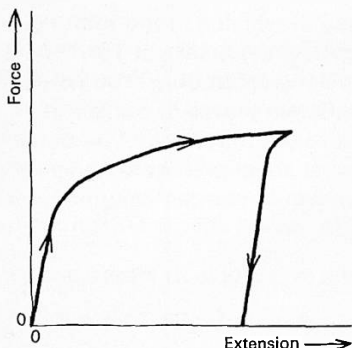


Figure 29

3 Question 2 asked you to translate from words into a graph: this one asks you to go the other way. Being able to 'read' a graph is an important scientific skill, and you will need it often in this course. The only hard one is **d**, but we think you will manage without being given an answer here.

4 a A material is behaving elastically if it returns to its original shape after being bent, stretched, twisted, or compressed. Rubber is highly elastic, copper is elastic for very small changes in shape only. Polythene is not very elastic, though it is elastic for small enough deformations. Anyone who has tried to pull apart a polythene bag knows how readily it is permanently pulled out of shape.

b "'Plastic"' means behaving like Plasticine' is not far wrong.

A material is behaving plastically if it is permanently changed in shape after being deformed. Lead and Plasticine show plastic behaviour; rubber shows hardly any, compared to its large elastic deformation, while brick is brittle, not plastic at all.

5 a A good answer to this question need not have tried to cover all the relevant points. It is enough to have thought of some points which are relevant. These could include:

Canals are narrower than many railway bridge spans. A short bridge will bend less under load than a similar longer bridge, so the bridge material is not subjected to serious flexing, and the brittleness of cast iron does not matter too much.

Many such bridges are massive in comparison with the loads — such as lorries — that cross them, so that the iron is still compressed and therefore not liable to fracture even when a lorry crosses it.

By contrast, a long span railway bridge over, say, a river may not be very much more massive than the load of a train crossing it. Because it is long, and because the load is large, the bridge will flex appreciably and a material like cast iron will be liable to snap, while a tougher one like steel will survive.

Further, the load fluctuates rapidly as the train crosses the bridge and such fluctuating stresses are also liable to fracture brittle materials.

b Your answer should mention the brittleness of china, the toughness of polythene, and the relative weakness of polythene compared with steel, which means that a bowl of polythene deflects more under impact.

6 This is an investigation and we don't know the answer, apart from being sure that thicker rods have larger droop lengths, which is obvious.

7 a None.

b Rubber.

c Copper and steel. (Copper much more so than steel.)

d Glass, and copper and steel when molten. (We didn't know about rubber, so put a match to a rubber band. It caught fire, melted, charred, and made a dreadful smell!)

e Rubber.

f Copper, and some steels.

g Glass and steel.

h Rubber.

i Rubber.

j All will do this to some extent. Rubber will extend much more than the others and still spring back. But copper is easy to deform permanently without breaking it.

k None.

8 a 58.5 g.

b 58.5 g.

c 6×10^{23} .

d 9.6×10^4 coulombs, approximately.

e A spoonful (58.5 g).

9 About 140 km.

10 10^{-29} m^3 , $1.3 \times 10^{-10} \text{ m}$.

11 Such a guess can be made in several ways. There are 6×10^{23} sodium ions in a mole of salt, say 60 g. You could calculate the number of ions in 6 mg, if you think that is about the mass of one grain (6×10^{19} ions). Or you could estimate that the ions are one or two times 10^{-10} m apart, and work out the number in a small cube of salt (about 10^{20} in a millimetre cube).

The mass of 6×10^{23} grains of salt depends on how massive you think one grain is. The mass of the earth is $6 \times 10^{24} \text{ kg}$, for comparison.

12 a A sphere is a simple shape and, if one knows nothing about the shape of atoms, perhaps the simplest choice is the best.

If the metal is an element, it contains atoms of only one kind, so equal-sized spheres also seem sensible.

Not knowing how the atoms pack together, it might be reasonable to try packing the spheres as closely as possible. But there is no certainty that the atoms will pack closely. (The atoms of many metals do, but some do not.)

b, c Solid metals are both hard to stretch and hard to compress, unlike gases, for example. This suggests that the atoms are held at roughly a fixed distance apart by a balance between repulsion and attraction, and that you get extra attraction or extra repulsion if you pull them apart or push them together.

13 a Sketch 3.

b Each bubble attracts other bubbles, and the result is that they cluster as closely as possible. The bubbles are round, and attract other bubbles equally in any direction, whereas, if the forces tended to act in certain special directions, some arrangement like **1** or **4** might result.

c By analogy, it might be true that the attractive forces between atoms in such metals were equal in all directions.

14 a The arrangement of spheres produces regular-shaped faces with *definite angles* between them.

b Open to argument. Perhaps an arrangement like a stack of square boxes might be simpler in one sense. But this and similar arrangements are simple in that they can be built by repeatedly using the simple building rule: 'Put a new ball in the hollow between four other balls.'

c No way has been found of packing balls regularly which gets more of them into the same space.

d Is infinite regularity beautiful or boring? That depends on you.

15 a $\frac{abck}{D^3}$

b $\frac{k}{D^3}$

16 a The geometry is not very hard, once you see that the extra ball on top lies above and between two below it whose centres are $D\sqrt{2}$ apart, and that it touches both so that its centre is a distance D from the centre of each.

A triangle of sides D , D , and $D\sqrt{2}$ has a right angle, and the height, $D/\sqrt{2}$, follows from this.

b $7.1 \times 10^{-6} \text{ m}^3$.

c $6.4 \times 10^{23} \text{ mol}^{-1}$. (You can show that a diameter $2.55 \times 10^{-10} \text{ m}$ gives nearly the accepted value $6.0 \times 10^{23} \text{ mol}^{-1}$.)

17 a Earlier.

b No.

c Yes.

18 a The diagram shows the interference of waves as a result of passing through two slits. At position R a bright patch is produced because the difference in path lengths, 45λ and 48λ , is a whole number of wavelengths. At Q there is a dark patch because the path difference is only half a wavelength.

b	Fringe	Path difference
	central bright	0
	first dark	$\frac{1}{2}\lambda$
	first bright	λ
	second dark	$1\frac{1}{2}\lambda$
	second bright	2λ
	third dark	$2\frac{1}{2}\lambda$
	third bright	3λ

19 Maxima and minima due to interference between the waves reflected from the hardboard and metal sheets. It doesn't matter which sheet is moved.

20 a1 Because the film was cut at the place opposite the point where the X-rays entered the cylindrical camera. X-rays turned through 180° would produce lines in the middle of the unrolled photograph.

2 The lines marked 2 on the figure. They should be $(360 - 2 \times 31.8)$ degrees apart, or about 233 mm apart if the radius is 45 mm.

3 2.81×10^{-10} m, which happens to be the spacing between nearest Na^+ and Cl^- ions.

b1 Compare the photograph from powdered salt with that for copper wire. Other evidence exists; see, for example, the *Scientific American* book *Materials*, the article on metals, page 41.

3 Three diffraction angles are the same. You should argue whether this proves the point, or merely makes it plausible.

4 2.05×10^8 .

5 2.05×10^8 .

6 2.4×10^{-10} m approximately.

21 a You may have mentioned the fact that X-rays are diffracted at definite angles. Before X-rays, the main evidence was the regular shape of crystals.

b Mention: different scale of objects detected; atoms too small to 'see' directly, even with X-rays; no significant diffraction in shadow pictures; diffraction effects only found with atoms in crystals. Shadow pictures show how large objects absorb (stop) X-rays; diffraction pictures show how small objects scatter X-rays.

c See questions 17 to 19.

d The wavelength would be much too large. (Explain why this matters.)

e *Not* at sharp definite angles, certainly. In fact, a random array of similar scattering particles produces a diffuse halo pattern; but you would not be expected to work this out, and the reasons for it are not given here.

f Yes, in a way, because to detect layer on layer of atoms by diffraction, the X-rays must reach them. If they did not penetrate, X-ray pictures would give information about surface atoms only. But this is a subtle point.

22 a True, and a defect of such diagrams. But the photographic plate is some centimetres away from atomic layers, which are about 10^{-10} m apart. On the scale of the diagram, the photographic plate is about a thousand kilometres from the page! So the diagram is nearer the truth than it seems, for the beams which eventually meet at the plate will, on the scale of the diagram, appear to be parallel.

b Reflections from other layers are all-important. If only two layers were involved, and θ had a slightly different value, such that

$$\lambda + \frac{\lambda}{1000} = 2d \sin \theta$$

the waves would be nearly in step and the resultant would be large. But the lower layers also contribute, and the 501st layer gives a wave with path difference:

$$500\lambda + \frac{500\lambda}{1000} = 500\lambda + \frac{\lambda}{2}$$

so reflections from the first and the 501st layers would cancel each other.

Thus the reflection from some deep layer cancels that from each layer nearer the surface, and the angle θ is very sharply defined. Only when

$$\lambda = 2d \sin \theta$$

do the contributions from all layers combine to give a large resultant.

c Yes, any regularly repeating layer structure will do. Here are some more details for any who are interested.

The two-atom structure in figure 30 could give Bragg reflections from each of the sets of layers. Only when the whole structure is worked out can one tell which layer spacings correspond to a distance between atoms. For that matter, the circles in the figure could represent quite large molecules in some crystalline organic material.



Figure 30

d Tests in a ripple tank show that a plane wave striking a row of obstacles produces a plane reflected wave. The reflected wave arises from circular ripples from each obstacle. Those obstacles which the wave reaches first produce circular ripples before those the wave reaches later. One effect of the row of circular waves, with a progressive delay along the row, is a plane wave at the usual angle for reflection. (Figure 31.)

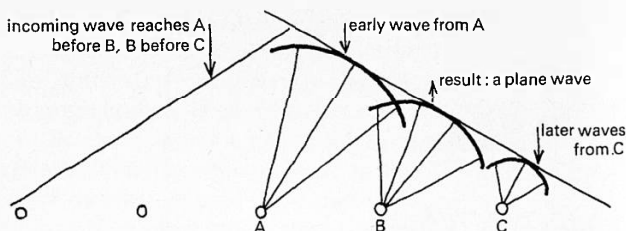


Figure 31

Reflection is not simple, as **e** indicates.

e Yes, this will happen with *one* layer, so that it produces a number of plane waves only one of which is at an angle obeying the law of reflection.

But when there are many layers, it turns out that diffracted waves from each layer destroy each other, except only for the wave at the reflection angle. So it turns out that Bragg's point of view is correct, though for this subtle reason.

Books

You should see whether the argument given in books is any better. For example:

Arons, *Development of concepts of physics*. (Page 827.)

Baez, *The new college physics*. (Page 597.)

Bennet, *Electricity and modern physics*. (Page 274.)

Caro, McDonnell, and Spicer, *Modern physics*. (Page 38.)

PSSC *Physics* 2nd edition. (Page 597, the Bragg Law for neutrons.)

23 a They are all surely very much alike in kind and purpose.

b, c Chemists make 'reminding' models of molecules. The kinetic theory picture of a gas as randomly moving, well-spaced molecules is also a model, but it is capable of making predictions and explanations as well (of such things as the speed and size of molecules, and the reason for diffusion, for example). Some models are not like maps or diagrams at all:

to say that an ion is an atom that has lost an electron does not mean that the ion is an atom with a hole in it. Probably the Greeks did not mean their model of crystal spheres carrying the stars and planets to be a description, but meant it as a machinery for calculating how the planets would move. You may be able to think of other examples of 'models to remind' and 'models to predict'. Even a 'model to remind' can be a 'model to help me think', and may help one to get new ideas.

To make an 'idealized' model means to leave out some real life complications, or peculiarities, for a special purpose.

24 a 10^6 N m^{-2} .

b $1/3$. It is only a ratio. The value would be the same if the lengths were 90 and 120 inches.

c 10 N.

d Estimate the weight of a car in newtons, and see c. Our estimate is 10 mm^2 .

e 0.02 m.

f 6 N if the cross-section were constant, which it is not. If the volume is constant the cross-section goes down to 1 mm^2 .

g The wire would break. 10^4 N per unit increase in strain is satisfactory only as a *recipe* for working out the force to produce an arbitrary small strain.

25 a 0.8 N.

b1 0.16 N.

2 Over 10 N, but very doubtful, as the force will not be proportional to the strain.

c 2000 kilogrammes, if you calculate without thinking properly. But steel wires break at strains well below 10 per cent. Nor need the load be proportional to the strain right up to the breaking point.

26 Plastic yielding of tarmac under bending forces, brittle fracture of tarmac. Notice the cracks propagated through the road surface. The cement bond between road edge and kerbstones has broken easily.

With a material like tarmac, one might guess that the plastic yielding took place where the deformation was slow, as well as not too great. The road drill, giving the tarmac short sharp blows, will fracture it.

27 See figure 32.

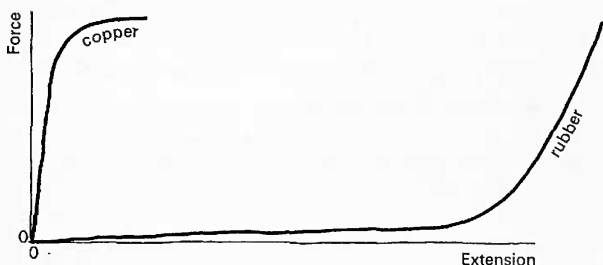


Figure 32

There is room for disagreement about how the word 'law' should be used or restricted.

Hooke's 'Law', like Ohm's 'Law' describes *some* of the behaviour of *some* materials. In particular, it describes their simplest, most law-like behaviour. But if one were writing down 'the Laws of Physics', neither would seem general enough to be included. Consider the following account.

Laws in physics are not much like either the laws of chess or the criminal laws of a country. The laws of chess describe how to play chess, and, if you break them, you are not playing chess. Criminal laws are about what the law-makers think people *ought* not to do. Laws in physics are perhaps more like shorthand notes; they describe simple behaviour where simple behaviour can be found. They can be known to be false, even if we don't know whether a particular law is false. Neither of the other kinds can be false like that.

But don't think that the above comments are exhaustive or are the only acceptable view.

28 a It requires more force, per unit cross-sectional area, to stretch glass than Perspex.

b It is easier to flex the wood in the low modulus direction.

c For unit cross-sectional area it is easier to stretch wood.

29 This is difficult, partly because rubber gets harder and harder to stretch as the strain rises. First you have to estimate, or measure, the forces needed to stretch a particular size of rubber band. For as long as you feel sure that the force is roughly directly proportional to the extension, the energy transformed is equal to the average force multiplied by the total extension so far.

Then it gets more difficult. At large extensions, the force rises more and more rapidly, as shown in the answer to question 27. The energy transformed is the area below the curve drawn in that answer. Having guessed or measured such a curve, you would have to find the area as best you could, perhaps by dividing it roughly into a long low triangle and a short tall one.

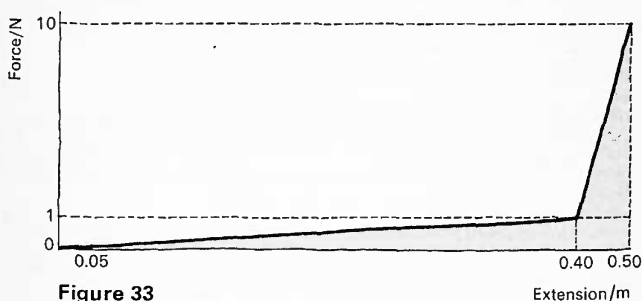


Figure 33

The graph in figure 33 is a very crude attempt to consider a thin rubber band that breaks under a force of 10 N, at a strain of 10. If the band were 50 mm long initially, the energy transformed might be about 0.7 J, say of the order 1 J.

30 a About 10^7 N m^{-2} .

b 0.4 m.

c About 1000 N.

d Below 50°C .

31 400 N m^{-1} ; 2 N.

32 a nx .

b $n\Delta x$.

c $\Delta x/x$.

d Newtons per metre.

e $mk\Delta x$.

f $1/x^2$.

g $k \Delta x/x^2$.

h k/x .

i 60 N m^{-1} .

33 a $x\sqrt{n}$.

b nx .

c Original length of molecule $10 x$; maximum length $100 x$; strain about 10.

34 The *Scientific American* book *Materials* is probably the best single source of help in finding out how to use these terms.

35 Your answer should explain how a notch or crack can concentrate stress and produce fracture, and explain why a fracture crack will travel along a path guided by a ruled notch.

36 '... in the next picture the dislocation has moved on by one atom. In each succeeding picture the dislocation moves on by one atom until it reaches the edge.' (See figure 34.)

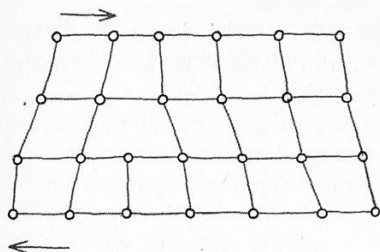
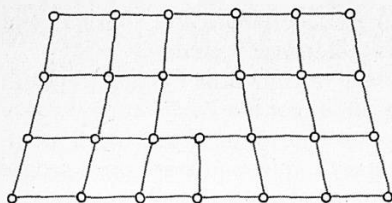


Figure 34

37 to 44

Questions 37 to 44 are designed to see how well you can do all on your own. Try to put down as much 'hard physics' as you can that is relevant. Your answer should not be judged by whether an expert would think it complete and correct, but by whether you have offered clear relevant ideas.

37 See the books mentioned. Try also Fishlock, *The new materials*.

38 See:

Frischmann, 'Tall buildings.'

'The Severn Bridge', Nuffield Advanced Physics *Students' book*, Unit 4.

39 a In tension, small cracks open up and then propagate through the material, so that it snaps suddenly.

b Individual pieces can still fail by brittle fracture, but the failure of one is not disastrous for the whole composite material, because the fracture need not propagate through it.

c The cement matrix is itself brittle, and cracks will propagate through it. A useful matrix must yield enough not to propagate cracks.

d The point of using the ceramic at all is to exploit its strength and stiffness. The matrix must transfer the applied load to the ceramic fibres. If it did not adhere to them, the material would simply pull apart.

Materials and their uses

By F. J. P. Clarke

This article appeared in an earlier form in Esso Magazine and is published here by kind permission of the author and the editor.

Before discussing specific materials developments, two general points should be made. Firstly, the materials of importance in thirty years' time will basically be those we know today. We cannot expect a radically new class of materials to arise. Developments of existing materials, sometimes involving new arrangements of their constituent atoms, will produce a steady improvement in properties; but we cannot expect anything to parallel the developments in synthetics that have occurred over the past forty years.

Secondly, improving the properties of materials is only one way of extending their usefulness.

Another way is to combine materials with each other in such a way as to make the best use of their individually attractive properties. Combining materials in this way can be done by the materials scientist who develops a composite with certain properties which the engineer can buy off the shelf and use. Alternatively, it can be done by the designer. A good example of the latter lies in modern refrigerator design. A self-foaming polyurethane liquid is poured between a thin metal outer-casing and the inside wall of the refrigerator. This fills the inter-casing volume with a foam that both provides the necessary thermal insulation and contributes to the stiffness of the refrigerator body. Developments in the future will allow a much closer tailoring of materials properties, and the engineer will look to the computer to help him select and specify the materials he should use. The days of making a component of certain materials just because they happen to be available are already on the way out, and we can expect rational design to play an important role in materials developments over the next thirty years.

Materials that markedly change the way of life during an age are often used to characterize it (e.g. stone and iron). Future historians may well mark the transition to the synthetics age as having occurred during the 1990s; although the tonnage of synthetics used may not catch up with metals until after the year 2000, the volumes used will probably do so before then.

The largest component in this growth will be in plastics. Since the Second World War, plastics have increasingly replaced or supplemented other materials in a wide range of applications met in everyday life. For example, in the home we have become used to plastics in floor and other surface coverings, baths, water cisterns, electrical switches and cables, rainwater pipes and guttering, paints and adhesives, packaging and other containers, as well as clothing materials of all sorts. Plastics will continue to supplant traditional materials in all these areas and will be increasingly used in engineering applications; but plastics taken by themselves have important limitations that will determine the way their development occurs.

Engineers like stiff, strong, light, creep-resistant and shock-resistant materials. Plastics are not stiff enough because their working strain is about 3 per cent, whereas that of typical engineering materials is below 0.1 per cent (Gordon has pointed out that if an aircraft wing were allowed to flex to 3 per cent strain, the wings would meet above the pilot's head!). In such applications, stiffness can be achieved only by bulky designs wasteful in material and using less than one-tenth of the available strength of the plastic. The combined requirement for stiffness and lightness is equivalent to a high value of the stiffness per unit mass (the Young modulus/density). High values of the stiffness per unit mass are obviously desirable for aircraft structures, and Gabrielli and von Kármán have suggested that, generally, optimum transport efficiency may be linked, *inter alia*, with a high value of stiffness per unit mass of the vehicle's structure. The value for plastics is poor, as shown in the table. Other limitations of many plastics include their lack of chemical stability above 200 °C, poor scratch- and creep-resistance, degradation in

ultra-violet light (vastly reduced in recent years), and, in many building applications, too poor a quality of flame-resistance to meet existing fire regulations. Formidable though this list may seem, most of these limitations are being, or will be, met in various ways.

Material	Density	Stiffness	Stiffness per unit mass (Young modulus/ 10^9 N m^{-2} divided by density)
	10^3 kg m^{-3}	10^9 N m^{-2}	10^3 kg m^{-3}
polystyrene	about 1	4	4
aluminium	2.7	70	26
iron	7.9	200	25
wood	0.8	14	18
glass	2.5	70	28
carbon	2.3	980	430
fibre reinforced glass in aluminium	2.7	70	26
fibre reinforced carbon in aluminium	2.7	560	210

Table 1

The organic chemist will continually be tailoring new molecular structures to produce improved properties. For example, the recent development of a polymer capable of sustained life at temperatures above the boiling point of water may well lead to the use of plastics in central heating systems – especially if the price of copper increases substantially. This is a good example of a modest property improvement leading to a potentially large market. However, many of the new polymers may not be competitive in price with existing materials, and the expected increase in plastics usage will probably result less from new materials than from the more ingenious and thoughtful use of existing ones.

The development of composites has already been picked as a strong growing point and this is particularly true of plastics. To make composites, materials are blended together to produce a body having the most desirable attributes of the separate components, e.g. the warmth and comfort of wool coupled with the relative strength and crease-resistance of the polyesters to produce clothing material; the strength and creep-resistance of glass coupled with the shock-resistance of a resin to produce a fibre reinforced boat hull. In this latter example the glass fibre provides strength and the matrix protects the glass from its inherent brittleness and poor shock- and fracture-resistance. But the stiffness of glass is not good enough for many applications – for example, it limits the size of the fibre reinforced boat hull that can be used – fibres of higher stiffness would be useful. Carbon is an excellent material from this viewpoint because its fibres have over ten times the stiffness of glass and it is among the lightest of materials. Carbon fibres can be made from synthetic fibres by heating them to 2500 °C in an inert atmosphere. As the properties of the resulting fibres and the economics of the process improve, carbon reinforcement will become important for metals as well as plastics.

Reinforced plastics do present manufacturing problems. For example, components cannot readily be joined. Car bodies cannot be automatically pressed into shape and hand-forming methods have to be used; in consequence the materials are economic only in the specialist car market, say those selling less than 100 000 of a particular design. Nevertheless the economics will move steadily to favour the more extensive use of reinforced plastics in such applications, and they will be used increasingly for railway trucks and coaches during the remaining part of the century.

Another way of achieving optimized properties is by the use of laminates or sandwich structures, especially in tonnage applications where the high cost of plastics compared with natural materials militates against their use by themselves (as a very rough figure, traditional materials are one-tenth the cost of plastics on a volume basis). These figures will not stay

static, and the trend of recent years – i.e. for synthetics to drop in price while more traditional materials rise – will continue. But, in addition to this, plastics will be made competitive by developing ways of using them rationally with other materials, e.g. by giving a traditional material a plastic finish or as in the refrigerator example given earlier.

By the year 2000 about 10^9 tonnes per year of synthetics will be made throughout the world, most of it in the technologically advanced countries. This will inevitably create problems in refuse disposal because plastics do not corrode away or rot and, when burned, many create noxious fumes. One way of overcoming this problem would be for local authorities to burn the refuse in special furnaces to provide local heating (plastics and rubbers have a calorific content equivalent to coal).

On the research side we can expect that by the 1990s the science of plastics will have developed to a point where macroscopic processes can be discussed comprehensively in terms of atomic processes, in the same way as the properties of metals can now be discussed in terms of dislocations and their interaction with various atomic and microscopic defects. Work on organic crystals will be particularly important because it gives a link between living and non-living matter. In the last thirty years we have seen the classifications between various types of inorganic matter (e.g. metals, ceramics, semi-conductors) become less and less significant. The same language and atomic mechanisms are now used to discuss many materials, and materials science as a single subject is growing rapidly. We can expect similar developments in respect of living and non-living matter, the foundations for which will be laid over the next thirty years.

Turning now to building structures, can we expect traditional building materials still to be widely used in the 1990s? Here there is likely to be strong competition between bricks and concrete, particularly on account of trends towards industrialized building. But bricks are likely to play an important role for a long time to come, especially for external

walls in private house building. The excellence of easily excavated clays makes British bricks the cheapest in the world, quality for quality, and will help to safeguard their continued use.

Recent developments in the use of glass fibres will probably spread to concrete in the future. Wherever concrete is reinforced by steel, the thickness of the concrete layer has to be sufficient to prevent rusting of the steel by the inward diffusion of water. This, taken with the mechanical properties of concrete by itself, tends to make concrete construction rather bulky. Until very recently it has not been possible to reinforce concrete with glass fibres because existing glasses are readily attacked by the alkali in the concrete. However, alkali-resistant glasses have recently been developed that should overcome this difficulty and the way is open for the more imaginative and elegant use of concrete.

For the remainder of this century the use of many traditional ceramics will increasingly come under attack from plastics or glass ceramics in the mass markets. At present typical tonnage uses of ceramics include tableware, toilet articles, wall surfacings, electrical insulators, and linings for large steel furnaces. No other material can compete with ceramics for furnace linings because of the excellent high temperature properties of ceramics. But in all other areas the long-term future of traditional ceramics lies more in the highly diversified specialist or quality market than in the mass market. Thus, as soon as plastics are made economically that have a really effective stain- and scratch-resistant surface, cups, plates, and toilet articles will increasingly be made of plastics.

Steady developments in existing materials and emphasis on composite structures will be reflected as strongly in metals as in other materials. Steelmaking itself will become much more of a continuous process with molten material being transferred between the various stages, possibly by electromagnetic pumping; existing vacuum casting methods will be considerably extended. A result of the steady development in

manufacturing methods will be cleaner steels with improved properties. Strength increases by a factor of three or four are possible; steels will be tougher and brittle fracture temperatures will be lowered. Such improvements will lead to lighter structures with all the possibilities this gives for more elegant and adventurous design.

The problem of corrosion will be reduced by deposition at the steelworks of coatings of plastics, stainless steel, or non-ferrous metals. Many metals that are at present difficult to fabricate, which have poor ductility or corrosion resistance in certain environments (e.g. titanium, niobium, chromium, molybdenum, beryllium) will be more widely used as metallurgical understanding increases. Typical applications are in aircraft (titanium) and in turbine blades (niobium).

Fibre reinforcement will be used to extend the usefulness of metals and table 1 shows the stiffness improvements that this would give. To discuss one case as an example, aluminium is easily fabricated and light, but its strength and resistance to fatigue cracking are poor. To some extent alloying can improve these properties, but they still deteriorate with increases in temperature. It is this latter shortcoming, particularly, that is ameliorated by the incorporation of fibres, and already the useful temperature range of aluminium has been increased by 100 °C. As mentioned earlier, carbon has even greater potential as a reinforcing agent because of its high stiffness per unit weight (see table 1).

Examples have been given of fibre reinforcement involving metals, plastics, ceramics, glass, and concrete. In every case problems have arisen concerning the atomic bonding at the interface between fibre and matrix. In the cases of silica fibres in aluminium and glass fibres in concrete, the fibre and matrix reacted chemically to degrade the fibre. In the case of glass fibre in resin, water attacks the glass-plastic bond – this problem basically has not been solved. To solve problems of this type frequently involves having a background understanding of the problem at an atomic level; it must be emphasized that even the gradual and undramatic

developments of the type discussed in this article require a parallel development of a sophisticated basic knowledge of the materials. Developments of composite materials are not a simple matter of mixing together the two components!

Some important classes of materials have not been mentioned, because it is impossible to cover them all in the space available. For example, in electronic materials a major development area is *micro-miniaturization* – the move to smaller and smaller devices. Whole circuits can be built into tiny chips of material. The great potential in micro-miniaturization for improved reliability at reduced cost will bring the most sophisticated electronic devices into the everyday life of people in the 1990s.

It was noted at the beginning of this article that developments in materials will be based on those materials we already have. The developments will consist in improving what we have already, in learning to develop the science of using materials with each other, and in rational design with these materials. This pattern of steady development may not seem visionary, but it will nevertheless not be easily attained. As far as materials are concerned, steady development means increasing sophistication; small advances seem to be disproportionately difficult to attain and draw in a wider and wider range of disciplines for their attainment.

Very often the expense of the development and the size of market required to make the resulting product economically viable are beyond the means of private firms. Furthermore, we in Britain cannot compete across the whole spectrum of materials developments, gradual though they may be. For every man we have on such work the North Americans alone have eight or ten. To retain our world industrial position in this situation we have carefully to select the areas at which we are going to excel and concentrate effort therein. The choice of such areas frequently depends on Government decision, and the interdependence of technological development and Government policy will become stronger over the next thirty years. All this can have a very disturbing effect on detailed predictions about materials.

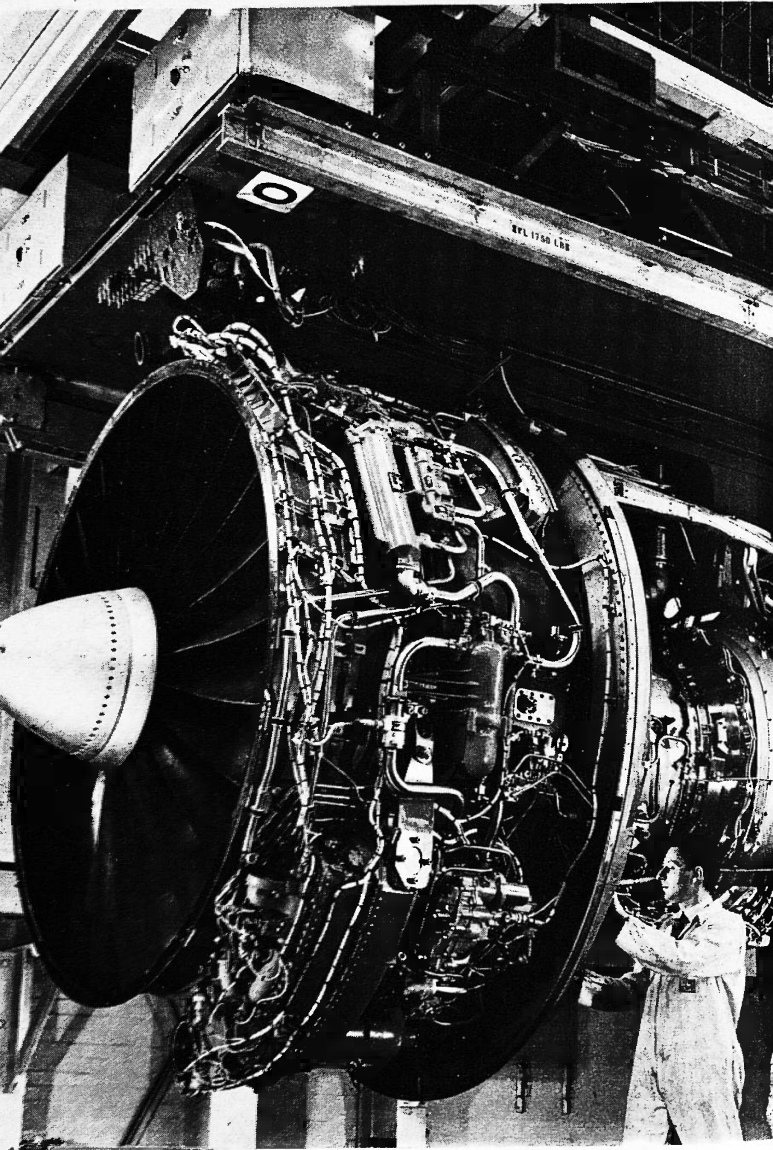
Carbon fibres

By W. T. Gunston

The following article appeared in an earlier form in Science Journal, February 1969, and is published here by kind permission of the author and the Science Journal.

The accelerating pace of man's technology may be judged by the fact that the Stone Age lasted hundreds of thousands of years and the Bronze Age many thousands; yet since the start of the twentieth century man has introduced new steels, high-nickel alloys, aluminium and its alloys, titanium, new glasses and precision-made concrete, laminated woods used as engineering materials, fibre reinforced composites, a vast range of materials lumped under the name of plastics, and an increasingly important range of new ceramics. These new materials have been introduced for various reasons. Some are stronger, some retain strength at high temperatures, some resist weathering and corrosion, some are very light, some can be moulded into different shapes in any desired colour, and some are simply cheap.

Within this amazing array of materials, carbon fibres occupy a clear place. They are very far from being cheap and the only colour they possess is black; but they are the strongest and stiffest things man has ever made, weight for weight, apart from microscopic 'whiskers' which cannot yet be put to much practical use. Structural carbon fibres were first made in 1961 by accident, and in 1963 by design. By 1968, large aero engine components had been made from carbon fibre composite materials. By 1970 carbon fibres were being experimented with in ten thousand companies, research laboratories, and even 'backyard' workshops in dozens of countries all round the world. Because of these fine, silky fibres, many of man's artefacts will in future be made stronger, stiffer, and much lighter than ever before.



Carbon is in many ways a unique element. Nothing else exists in forms which, though chemically the same element, differ so markedly as finely divided carbon black, gleaming diamond (the hardest substance known), solid pyrolytic carbon, or slippery graphite. In graphite the 'slipperiness' arises from the fact that adjacent layers of carbon atoms, arranged in crystalline lattices, can slide over one another with little resistance. In contrast, the diamond contains identical atoms arranged in a three-dimensional tetrahedral (pyramid shape) lattice which confers the ultimate in structural strength and rigidity. It was this ability of the carbon atom to arrange itself in a very stiff crystalline lattice that led to a search by four groups of workers for a way to use carbon as a structural material. If a way could be found to make things out of a pure crystalline form of carbon or graphite, with the atoms arranged in a lattice having a geometrical shape giving great strength and rigidity, the result would be a new engineering material far stronger and stiffer than any metal, much lighter even than aluminium, and also having very high resistance to extremes of temperature and to a wide range of types of chemical attack.

Early in the 1930s Professor Herman Mark, of the Polytechnic Institute of Brooklyn, investigated the structure of various carbonized fibres which he generally made by heating threads of man-made polymers such as nylon. Mark was not concerned to develop industrially important structural materials, and neither was the Japanese team led by Akio Shindo at a textile research institute in Osaka when they did much the same thing in 1961. Shindo's procedure was to cook a wide range of polymer textile fibres to see what would happen, and in particular to measure their electrical conductivity. One of the materials he selected was yarn made of polyacrylonitrile, a common textile much used in modern garments and soft furnishings. He put some in an oven and brought it out jet black in a form of practically pure carbon;

Figure 35

Rolls-Royce RB 211 jet engine. The carbon fibre fan blades used in early versions can be seen at the front of the engine.

By courtesy of Rolls-Royce Ltd.

but all the Japanese workers did was note the properties and take out a patent on what they had done, before going on to cook something else. They did not realize they had produced something of the very greatest importance.

One of the world's largest firms concerned with carbon is Union Carbide, of the U.S.A. Late in the 1950s this company began a research programme aimed at producing strong and stiff carbon fibres, and this work is still continuing. Mainly financed by the U.S. Air Force, Union Carbide eventually devised a method of heating threads of rayon viscose to about 2000 °C and then stretching them carefully. The physical extension of the thread pulled the graphite crystallites into the desired lattice orientation to give the very high strength that was being sought. By 1964 Union Carbide were able to sell small quantities of 'Thornel 25', so numbered because it had a Young modulus of about 25 000 000 lb/sq in ($170 \times 10^9 \text{ N m}^{-2}$). The price was in the neighbourhood of \$3000 per kilogramme, and the product was still very much a laboratory curiosity. But since then Union Carbide have gone on to produce much better types of Thornel, some of them more closely related to the different species of fibre pioneered in Britain.

Research into structural carbon fibres in Britain began at Rolls-Royce. In 1956 research directed towards the development of very light jet engines for use in vertical take-off aircraft had shown that many of the parts of such engines not subjected to high temperatures could be made out of resin bonded glass fibre. Glass fibre composite materials have been used very widely for 20 years for such everyday applications as truck cabs, kitchen sinks, and small boats. In a jet engine, glass fibre composite had to be used as a high precision engineering material, and Rolls-Royce showed this to be possible. Other fibre reinforced composites had also been used by other British companies and by the Royal Aircraft Establishment at Farnborough to make parts of aircraft. In fact, the Royal Aircraft Establishment had even made whole wings out of a material in which the stiffening fibres were of asbestos.

Fibres of asbestos and glass could, by the mid-1950s, be made extremely strong but they suffered from the drawback of poor stiffness. In other words, a composite material composed of large numbers of glass or asbestos fibres held in a matrix of resin adhesive could resist large loads without breaking but tended to deflect so much under load as to be of limited use. For example it was possible to use composite reinforced with glass or asbestos to make blades for a jet engine compressor that would withstand the central forces of high rotational speed without breaking; but the poor stiffness of glass and asbestos fibres could allow such blades to flap about and bend far too much for safe operation. By adding a small amount of beryllia it was possible to make glass much stiffer but, like many compounds of beryllium, this material is toxic to humans. Rolls-Royce did a great deal of research into a completely new composite material consisting of fine fibres of silica in a matrix of light alloy or pure aluminium, but by 1962 had come to the view that the best reinforcing fibre would be carbon. Rolls-Royce thereupon embarked on a research programme to find the best way of making the best carbon fibres. However, a small team at the Royal Aircraft Establishment arrived at a method at about the same time as Rolls-Royce and this team's method had certain advantages over Rolls-Royce's.

In 1963, W. Johnson, L. N. Phillips, and W. Watt reviewed the considerable experience obtained with glass and asbestos fibre composites and decided that for future aerospace structures there was an absolute need for a new reinforcing fibre having the same strength but with a stiffness per unit weight a whole order of magnitude better. Carbon appeared theoretically to offer the best promise of meeting these severe requirements, and the three men at the Royal Aircraft Establishment considered how a practical structural composite could be produced containing millions of immensely strong and rigid fibres of carbon. It seemed that the best starting point would be an organic polymer textile fibre, which is made up of a large number of filaments each composed of huge molecules in the form of long strings of carbon atoms linked with side branches of hydrogen and nitrogen atoms.

The obvious route to the desired carbon fibre appeared to be to cook the polymer filaments until the side branches of hydrogen and nitrogen had been driven off, leaving a series of strings of carbon atoms.

This sounds simple in principle but in practice there were many pitfalls. Clearly it was essential to preserve or enhance the linear orientation of the carbon chains, and so the textile fibre had to be capable of being carbonized without melting. And the workers also had to determine the precise temperature and duration of the cooking process that gave the best quality fibre. Polyacrylonitrile yarn showed itself to be nearly ideal and Courtaulds Ltd supplied a special grade of the yarn which seemed to suit the requirements admirably. After a great deal of experiment it was decided that the best carbonization called for three separate stages of heating. At first, the shiny silvery Courtelle yarn was wrapped round and round a frame like a stretcher and tied tightly so that it could not shrink. The loaded frame was then heated in air in a furnace at only about 300 °C, no hotter than a domestic oven, to emerge no longer silvery white but black, and pulled very tight by the natural tendency to shrink. The tight black fibres were then cut off the frame and heated to at least 1000 °C for many hours until everything but carbon had been driven off in the form of tarry liquids and vapours. The shiny fibres of pure carbon, weighing less than half as much as the original yarn, were finally heat-treated in an inert atmosphere at a temperature well over 1500 °C to acquire either the highest possible tensile strength or the highest possible modulus (stiffness).

Precise details of the process may not be disclosed, as they are subject to commercial security and were patented in the names of Johnson, Phillips, and Watt on April 24, 1964. In fact at that time it was not known precisely how each carbon fibre was constructed. All that can be disclosed is that a single fibre is much finer than a human hair, having a diameter of some 7×10^{-6} m, and is made up of at least 100 even finer filaments of carbon atoms arranged in the form of an orientated crystalline lattice which imparts its immense

strength and stiffness. The precise arrangement of the crystalline lattice depends upon whether the carbon 'graphitizes' to produce a hard form of graphite; but the term carbon fibre is used generally for fibres of both carbon and graphite and no distinction will be made here. The spaces between the individual filaments in each fibre are believed to be filled with amorphous (non-crystalline) carbon which acts as a binding agent. But the loose fibres are quite separate, dry, and springy, and cannot readily be put to any useful purpose. The key to using carbon fibres is to bind them together with an adhesive to form a composite material, just as is done with glass fibres. The difference between carbon fibres and glass fibres is mainly that the former are many times stiffer, as depicted graphically in figure 36. In practice another important difference is that, whereas glass fibres are

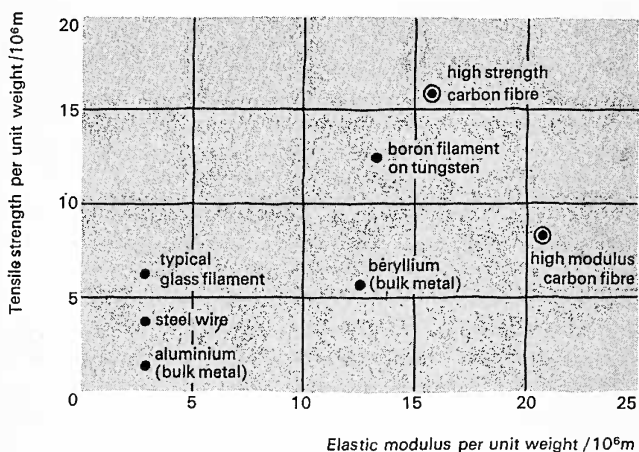


Figure 36

Properties of structural carbon fibres are generally outstanding. Two of the most important mechanical properties are specific tensile strength (ultimate tensile strength divided by material weight per unit volume) and specific modulus (the Young modulus divided by weight per unit volume). This graph shows these values for carbon fibres plotted on a grid together with typical values for other materials.

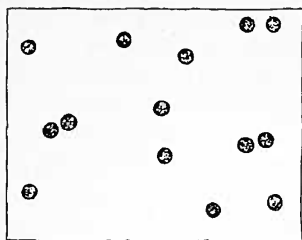
By courtesy of Science Journal.

extremely sensitive to surface damage and can have their strength catastrophically reduced even by being rubbed together by hand, carbon fibres can be roughly handled or cut with scissors without suffering a deterioration in properties.

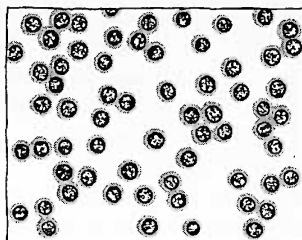
To make a useful product out of carbon fibre several routes may be followed to combine a large number of fibres physically with a suitable adhesive. Clearly, as the fibres themselves are made at white heat in a furnace they are well able to serve a structural purpose even at high temperatures, and a great deal of research is in hand to find adhesives that can bind the fibres together even when these are red hot or white hot. At the end of this account reference will be made to attempts that are being made to use metals as a matrix for reinforcement by carbon fibres, but at present the only binding agents in general use are various types of resin. Various types of epoxy and phenolic resins are being used in present-day carbon fibre composites, and, in an attempt to make a composite suitable for use in supersonic airliners at temperatures in excess of 200 °C, other resins such as polyphenylenes and polyimides have been used in experimental composites that have given very encouraging results.

How is a piece of composite actually made? As the starting point is a bundle of dry, springy fibres the first action is usually to 'wet' the fibres with dilute resin in a solvent such as acetone. Carbon fibres repel water but are immediately wetted by resins, when they become more pliable and lie together more closely. The docile wetted fibres could then be placed by hand into a mould, together with more resin.

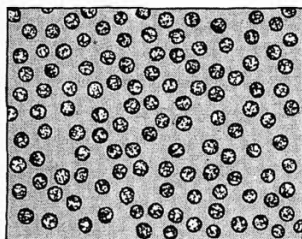
But this technique is not well suited to the manufacture of highly loaded precision engineering products, and the high cost of carbon fibres makes them unsuitable for use in any except such products, where their great strength and stiffness can be fully used. In any ordinary product the much cheaper glass fibres would do just as well. There are two precision methods at present in use for making true



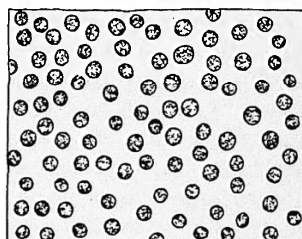
dry fibres



'wetted' fibres



composite with resin



composite with metal

Figure 37

Section cut through a bundle of raw carbon fibres emphasizes that these very springy filaments cannot be packed closely: the bundle is 'mostly empty air space'. If the fibres are 'wetted' with resin they become more docile, lie closer, and may stick together. When wetted fibres are pressed in a mould a resin composite results. If a metal matrix is to be used, however, the fibres must each be sealed within an inert coating, such as alumina or other ceramic.

By courtesy of Science Journal.

engineering products with carbon fibre composite. The most widely used is a two-stage process: first the carbon fibres are made up into a raw material in the form of rod, strip, tape, or sheet; then this is assembled to make the final products. To make the raw material, the fibres are first dipped in resin diluted with acetone and then carefully rolled by machine to make a sheet or tape of precise thickness and width. The resin is not cured, as it would be in making the final product, but the acetone is evaporated to leave the sheet in the form of something reminiscent of black veneer or thin card. The sheet

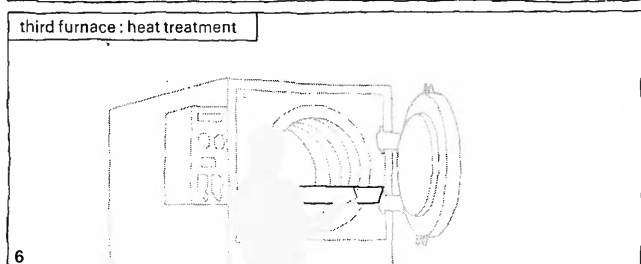
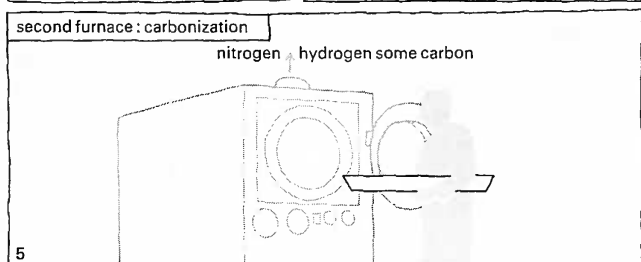
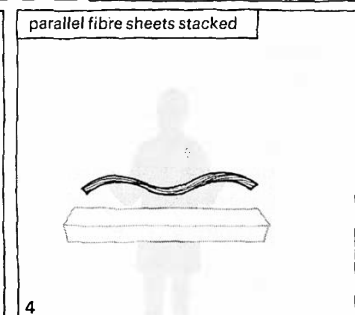
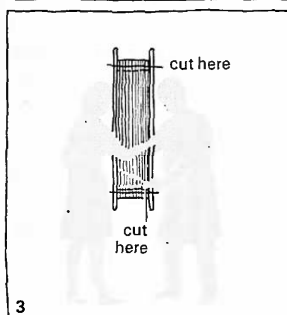
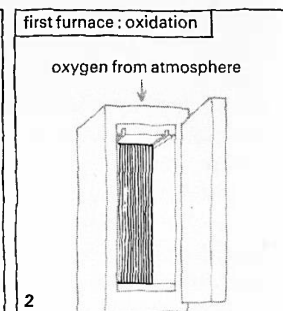
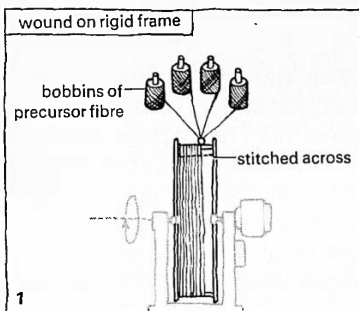
can be rapidly made in large quantities with a precise specification for dimensions and strength, and bought just like any other commercial product (whereas it would be difficult to buy raw fibre, which would have to be sold by weight and would be difficult to pack or store). It can be cut with scissors or by machines like high speed pastry-cutters, and the final product is made by assembling a lot of pieces of suitably shaped sheet to make a three-dimensional part. Again it is necessary to orientate the plies of the various laminations in carefully chosen directions to give the part the best performance when subjected to the loads it must bear. For example, the loads in the skins of an aircraft wing are mainly in a spanwise (tip to tip) direction, so if they were to be made of carbon fibre sheet, the plies would be arranged to run from tip to tip. If they were arranged across the wing from leading to trailing edge the wing would have poor strength in its most important load-bearing direction. This need to think of the direction of the fibres may cause trouble to workshops used only to metal fabrications, but it comes naturally to anyone used to making things out of glass fibre or wood. After all, nobody would make a flagpole or chair leg with the grain running across the section, because it would have little strength; and the same holds true for design in carbon fibre.

The second main way of making an engineering part from carbon fibre composite is by the technique known as filament winding. This is just what a spider does in making a web. A filament of carbon fibre, typically containing 10000 individual fibres, is wrapped round and round the part, starting with a hollow mandrel if the part is to be hollow, until the final shape is reached. The method is reminiscent of winding a ball of wool, or winding thread onto a spool; but it has an important difference in that the direction in which the thread is wound may change dramatically in different areas of the part. The technique of filament winding was first turned into a modern engineering process in the U.S. aerospace industry where it was used, initially with glass fibre, to make very large cases for solid propellant rocket motors. It was soon found that the mathematics of determining exactly how best to wind the filament was so complex that the whole job had to be

controlled by a computer. In the case of a rocket motor case a hollow drum-shaped mandrel is overlaid with thousands of layers of filament wrapped tightly round and round and from end to end, to give a finished cylindrical case with integral end closures having extremely high bursting strength and rigidity, yet weighing very much less than any equivalent metal case. Now carbon fibre can be used to make cases even stiffer, yet lighter. But filament winding is a slow business, typically taking several days to make a large product; and the need for computer control over such a long period means that costs are very high.

In the first production application for carbon fibres, dating from 1967, the first route has been adopted; and the same technique has been used in about 98 per cent of all the applications which have followed. The first real use of these fibres had long been foreseen by Rolls-Royce, who knew that very strong and stiff fibres could lead to a new generation of aircraft engines lighter yet stiffer than their predecessors. Although they had done much research on their own methods of making carbon fibres, the Royal Aircraft Establishment's method was superior, so Rolls-Royce adopted the physics and chemistry of the Farnborough process and obtained a licence to make the fibre in quantity. The Rolls-Royce engineers made a great contribution in scaling up a laboratory process into a large-scale industrial operation.

Rolls-Royce use various resins to turn their fibre into a composite material they call Hyfil. The use proposed for Hyfil was to make the huge fan on the front of the RB 211 engine selected as the standard power plant of the Lockheed 1011 TriStar, a very big three-engined airliner.



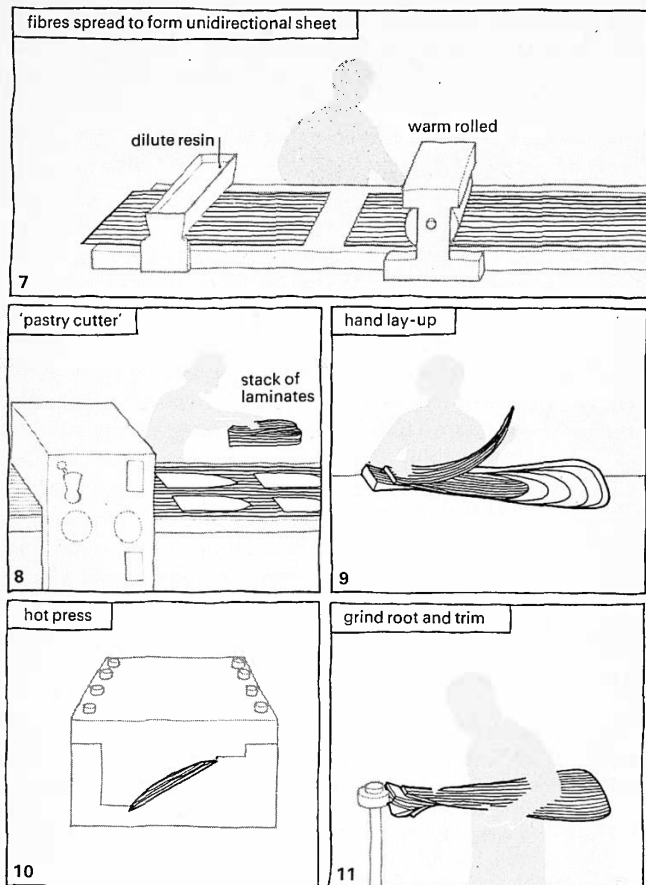
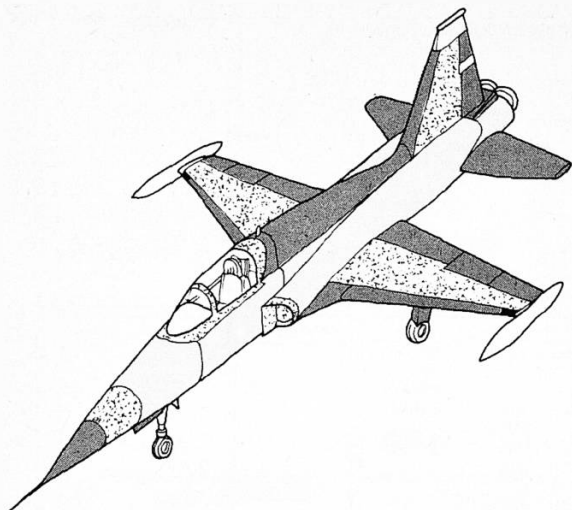


Figure 38

Batch process for making carbon fibres is depicted here, carried right through to the finished composite part. The product in this illustration is the fan blade for a Rolls-Royce aero engine but these sketches portray a generalized operation.

By courtesy of Science Journal.







-  flown in 1968, weight reduction 27 per cent
-  flown in 1970, weight reduction 25 per cent
-  to fly in 1971 with weight reduction of 15–20 per cent and the following year with advanced form of structure achieving 30–35 per cent
-  to fly in 1974 with advanced structure saving 20–30 per cent

Figure 39

F-5 Fighter aircraft is being progressively modified by Northrop Corporation in a joint programme with other firms and the U.S. Air Force to introduce advanced forms of composite structure. In the summer of 1967 it flew with wing tip leading edges filament-wound from Thornel 50 carbon fibre in resin. Landing gear doors in boron fibre followed in 1968 and later a carbon composite wing spar and other items were introduced on an experimental basis. Similar experience is being gained with other U.S. aircraft.

By courtesy of Science Journal.

Each fan blade in such an engine is really a miniature wing, with a streamlined profile which incorporates camber and twist, and the outer end is particularly thin. The tip moves faster than sound when the engine is running at high power. When it is rotated at such an immense speed the central force on each blade is extremely high, in addition to which the work of compressing the air imposes a huge aerodynamic (lift) load in a forwards direction. A shape of this kind subjected to very large mechanical loads is exactly the kind of application carbon fibres are suited for.

From the start of development of the RB 211 engine, Rolls-Royce considered the greatest problems would be those of making the Hyfil material at the exposed leading edges of the fan blades stand up to prolonged erosion by grit, rain, and hail and to severe bird impact. As a prudent 'back up', a parallel development was undertaken of a titanium fan blade and by mid-1970 almost half the total RB 211 running time had been on the metal blades. At the time of preparing this book, these difficulties remain and, for other reasons, the future of the RB 211 is in doubt. The making of radical innovations in technology is, and always will be, a high risk enterprise.

In the case of so complex and sophisticated a product, the use of carbon fibre instead of titanium, the second-best choice, does not make much difference to the selling price. But if carbon fibre were to be used to make a strong and stiff car body, the price would inevitably be high. There is, however, one crude way of using carbon fibre in a car body that has already been demonstrated to be worth while. In racing cars it is essential to keep the weight down to obtain high acceleration, yet the body must be very stiff to resist aerodynamic flutter loads and structural resonance. Aluminium bodies, steel bodies, and glass fibre bodies all have good and bad points, and none could claim to be ideal.

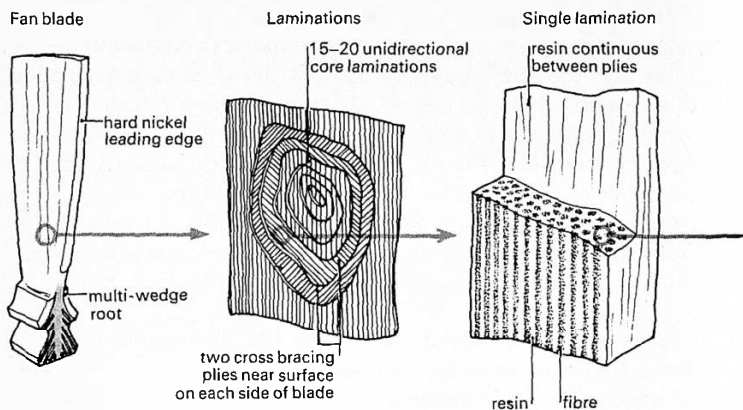


Figure 40

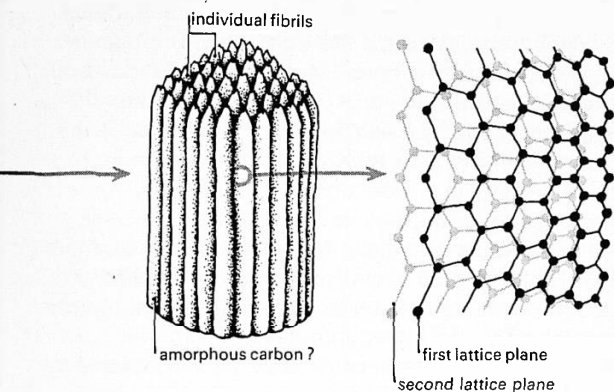
Structure of a carbon fibre composite part is suggested by successive magnifications of a prototype RB 211 fan blade. The blade itself is made up of numerous layers of pre-impregnated material, each consisting of carbon fibres and resin. Most of the laminations have the fibres running direct from the root to tip but two plies near the surface on each side have them orientated at 45° to make the blade stiffer against torsional loads. If a single fibre is examined it is found to consist of many distinct 'fibrils' of crystalline carbon (the fourth sketch shows a typical fibre end broken in tension), each of which is made up of a number of hexagonal lattice planes of atoms.

By courtesy of Science Journal.

In 1968 a small British firm, Glass Fibre Engineering of Farnham, obtained some lengths of carbon fibre, roughly marked out a criss-cross pattern on a thin body of glass fibre scrim, bonded the fibres onto the pattern with resin, and then put a second thin layer of scrim on to make a sort of 'tartan sandwich'. The result was a great success, at quite modest cost. The body, much lighter yet stiffer than any alternative construction, was fitted to a Ford car which won the Le Mans 24 hour race and then the World Manufacturers' Championship. Many other racing car teams are now looking not only at carbon fibre reinforced bodies but also at carbon fibre suspensions, connecting rods, and other important parts which must be both strong and light.

Single fibre

Crystalline structure



However, the carbon fibre composite body for the family car seems very unlikely at present. I.C.I., who are extremely well versed in the art of calculating the future, conducted a very detailed survey of the world market for carbon fibre in 1969, and investigated the likely selling price for mass-produced fibre made by the best foreseeable method in 1975–1980. They were not interested merely in becoming another firm making a few tonnes a year; they were anxious to discover whether it could be manufactured for about £6 per kilogramme or for an even lower price. Their studies showed that if manufacture for this sort of cost were possible, carbon fibre would break into all forms of transport, building construction, furniture, and a thousand other markets, replacing not only glass fibre but also steel, concrete, and very many other materials. Reluctantly, I.C.I. formed the conclusion that carbon fibre cannot be made for this level of cost. The best that one can hope for, when large-scale manufacturing plants are constructed, appears to be about £20 per kilogramme, so carbon fibre is never going to become a run-of-the-mill product. It will always be used in true engineering applications where stiffness and strength, and possibly light weight, are definitely called for.

But this does not mean the market for carbon fibre is limited. Nor does it mean that items made of carbon fibre reinforced composite material will always be much more costly than their counterparts in steel, light alloy, or titanium. In fact, one of the pioneer laboratories that worked on carbon fibre with the original Royal Aircraft Establishment team, the Atomic Energy Research Establishment at Harwell, has found several applications for carbon fibre where the change in material actually results in a reduction in cost. Rapidly rotating discs used to 'chop' beams of neutrons in nuclear physics used to be spark-machined from special high-strength steel and cost well over £50 each. Now they are moulded in carbon fibre composite and cost less, besides being stiffer and lighter. The small containers used in nuclear reactor experiments – called 'rabbits' because they are put down a hole – are another item where carbon fibre actually reduces cost. Indeed, carbon fibres look very attractive as reinforcing fibres for the reactor pressure vessels themselves.

An accompanying list (pages 90–92) shows some of the diverse items that can be made, or are already being made, using carbon fibre reinforcement. All these items are based on the use of a composite material where the matrix is resin. The use of special resins extends the upper limit of temperature to about 400 °C but even this is low enough to cut out many of the most important uses for which the fibres themselves would be entirely suitable. So considerable research effort is being made to use carbon fibres to reinforce a matrix not of resin but of metal. Unfortunately, there are considerable difficulties because the fibre often tends to go into solution in the metal or make a carbide. But many fibre/metal systems have been made to perform satisfactorily in the laboratory, and other research teams have even used carbon fibres to reinforce glass.

In designing parts in carbon fibre composites it is essential to remember that the fibres are the component of the material that has the strength and that they have their highest strength in tension. The problem is very much like designing a structural part in wood. Backyard shops experienced in glass

fibre construction take to carbon fibre like a duck to water, but most engineering firms have grown up using only metals and they take months to get used to a two-component composite material that has a pronounced 'grain' and highly anisotropic properties. And even the most experienced carbon fibre workers, such as those in the British and U.S. aerospace industries, still find great difficulty in joining carbon fibre composite parts to metal parts efficiently without losing strength.

At the time of writing this article, carbon fibre composite structures have been played with in the laboratory for four years and the Rolls-Royce fan blades have been on trial for two. Perhaps a thousand different things have been made in ones and twos, ranging from golf clubs and yacht masts to prostheses (such as false arms), dental plates, pieces of rifles, airline seat frames, gearwheels for Diesel locomotives, and fishing rods. In the United States a big and rapidly growing market is centred around the aerospace industry where carbon fibre imported from two British firms (Courtaulds, the makers of the Courtelle yarn, and Morganite Modmor, a special fibre subsidiary of a renowned carbon producer) have already been used to make a wide range of steadily more ambitious structures and parts. Now U.S. licensees and joint-venture companies of the two British producer firms are building plants to make tens, and later hundreds, of tonnes of fibre a year. One tonne of fibre, almost 2000 km of it, when mixed with at least a tonne of resin, can be used to make a very large number of small items. Precise cost figures for the U.S. plants have not been disclosed, but they will probably sell fibre for about \$80–100 per kilogramme. This means the composite material will cost just over \$40 per kilogramme, which is about 50 per cent more expensive than the cheapest titanium. But practically every part made from titanium has about half its weight machined away or in some other way unused, so the final cost of a titanium part (not including manufacturing cost) is about \$11.0 per kilogramme. The carbon composite part, on the other hand, costs very little to mould and wastes virtually nothing, so it may well turn out to be cheaper.

At present Britain is the source of the best carbon fibre in the world, while every other advanced country is either making fibres under licence, or trying to make it without a licence (or to 'invent' a similar fibre that might sidestep the need for a licence) or is merely importing small research quantities while wondering what to do. New materials of this calibre appear only very rarely. High strength fibres are the first of man's creations capable of replacing metals, and in applications where they can genuinely prove worth while they can enable a structure to be built weighing only about one quarter as much as the lightest structure that could be designed in steel or concrete.

Some carbon composite applications

Aerospace. The first production use is in aero engines where some of the largest and most critical parts are very well suited to carbon composite construction. In airframes for aircraft and spacecraft it is being introduced in highly stressed, carefully designed structures and also in 'harmless' places – such as airline furnishings and freight containers – to gain experience. The limits of aerospace use cannot yet be discerned.

Hydrospace. Deep sea submersibles of all kinds are regarded as ideal candidates in view of the very high mechanical strength and total indifference to water of good composites. First applications may be deep sea floats and instrument packages, followed later by manned hulls.

Bearings. Several kinds of bearing are likely to be among the first applications for carbon fibre composite to come to fruition. Some of the bearings needed for heavy rolling mills cannot be adequately made in today's materials but carbon composite should solve the problem. Addition of chopped carbon fibre to plastics is another early use seen in the bearing field, the composite having greater resistance to wear, lower friction, and other advantages.

Rotating parts. Included under this heading are such diverse items as large alternator rotors, helicopter rotor blades, aircraft and hovercraft propellers, hovercraft and other fans, marine propellers, and many other assemblies.

Tooling. All forms of plastics tooling may be expected to give way to carbon composites owing to the latter's greater dimensional stability, resistance to wear, near zero coefficient of expansion, and very much lighter weight.

Pressure vessels. All forms of gas bottles, rocket motor cases, road and rail tankers, nuclear reactors, and chemical plant are suitable, especially if they are made by filament winding.

Electric cables. Several organizations are studying carbon/metal systems as a route to much longer catenaries in electric grid transmission. The best answer seems to be a 50/50 composite of continuous carbon fibre in oxide free aluminium. This would have the strength of high tensile steel and better conductivity than today's steel/aluminium cables of equal section. Such a cable would enable the number of pylons per route to be markedly reduced.

Prostheses. Carbon composites are a 'natural', being much lighter than today's materials and having no reaction upon human skin.

Electronic aerials. Carbon composites are already being used for flush aerials on aircraft and for radar scanners and reflectors and appear very suitable for other aerials including radio telescopes.

Marine uses. In addition to propellers and submersibles carbon composites could lead to marine machinery one-third as heavy as today's while being magnetically inert and much quieter in operation; they are very suitable for hydrofoil foils, provided the surface is protected against erosion by impact and cavitation (also a factor with screws), and there is evidence that ship hulls in carbon could be much larger than the limit with glass, although economic considerations may lead to a glass/carbon reinforcement in the ratio 90:10.

Glassware. Addition of carbon fibre to glass opens up a range of material properties from brittle glass to materials which break gradually with considerable elongation. Carbonized glassware could be made unbreakable in ordinary household use and so attractive from the utilitarian viewpoint that black could become a preferred colour.

Sporting uses. Suggestions in this field include racing car bodies and yacht masts (both already in use), skis, fishing rods, oars, golf clubs, and similar structures.

Theories – true or not?

The following extract is by Karl Popper, who is a philosopher. He explains his view of scientific truth.

The way in which knowledge progresses, and especially our scientific knowledge, is by unjustified (and unjustifiable) anticipations, by guesses, by tentative solutions to our problems, by conjectures. These conjectures are controlled by criticism; that is, by attempted refutations, which include severely critical tests. They may survive these tests; but they can never be positively justified: they can neither be established as certainly true nor even as 'probable' (in the sense of the probability calculus). Criticism of our conjectures is of decisive importance: by bringing out our mistakes it makes us understand the difficulties of the problem which we are trying to solve. This is how we become better acquainted with our problem, and able to propose more mature solutions: the very refutation of a theory – that is, of any serious tentative solution to our problem – is always a step forward that takes us nearer to the truth. And this is how we can learn from our mistakes.

As we learn from our mistakes our knowledge grows, even though we may never know – that is, know for certain. Since our knowledge can grow, there can be no reason here for despair of reason. And since we can never know for certain, there can be no authority here for any claim to authority, for conceit over our knowledge, or for smugness.

From the preface by the author, K. R. Popper, to Conjectures and refutations (1963) Routledge & Kegan Paul.

Books for Unit 1

Strongly recommended for background reading

Bragg, Sir L. (1968) 'X-ray crystallography'. *Scientific American* Offprint No. 325.

Gordon, J. E. (1968) *The new science of strong materials: or why you don't fall through the floor*. Penguin.

Scientific American (1967) *Materials*. W. H. Freeman.

Textbooks for reference

Arons, A. B. (1965) *Development of concepts of physics*. Addison-Wesley.

Baez, A. V. (1967) *The new college physics: a spiral approach*. W. H. Freeman.

Bennet, G. A. G. (1968) *Electricity and modern physics*. MKS version. Edward Arnold.

Caro, D. E., McDonnell, J. A., and Spicer, B. M. (1962) *Modern physics*. Edward Arnold.

PSSC (1968) *College physics*. Raytheon.

PSSC (1965) *Physics*. 2nd edition. Heath.

Rogers, E. M. (1960) *Physics for the inquiring mind*. Oxford University Press.

Further reading

Bragg, Sir L. (1967) Nuffield O-level Chemistry Background Book *The start of X-ray analysis*. Longman/Penguin.

Fishlock, D. (1967) *The new materials*. Murray.

Frishmann, W. W. (1965) 'Tall buildings'. *Science Journal* reprint.*

Holden, A. and Singer, P. (1961) *Crystals and crystal growing*. Heinemann.

Kennedy, A. J. (1965) 'High temperature materials', *Science Journal* reprint.*

Loftas, A. A. and Gwynne, P. (1967) *Advances in materials science*. London University Press.

Morley, J. G. (1966) 'Fibre-reinforced metals', *Science Journal* reprint.*

Nuffield Advanced Chemistry (to be published in 1972) *Amount of substance: the mole concept and its use in solving problems*. Penguin.

Platts, C. V. (1967) Nuffield O-level Chemistry Background Book
The structure of substances. Longman/Penguin.

Walker, O. J. (1967) Nuffield O-level Chemistry Background Book
Plastics. Longman/Penguin.

* *Science Journal* reprints are no longer available. These articles will, however, appear in a collection of these reprints entitled *Physics and the engineer*, to be published in 1972 as part of the Nuffield Advanced Physics publications.

Terms and equations used in Unit 1

When a material is deformed, that is, squashed, stretched, bent, or twisted, the extent to which it is deformed is described by the *strain*, and the force or forces needed to deform it are described by the *stress*.

In the particular case of stretching:

$$\text{strain} = \text{extension/original length}$$

$$\text{stress} = \text{tension in specimen/cross-sectional area.}$$

Some, not all, materials deform so that the strain is directly proportional to the stress producing it, if the strain is not too large. Then the ratio stress/strain is constant.

$$\text{Young modulus} = \text{stress/strain}$$

Stiffness

A material that is bent only a little by a large force can reasonably be called *stiff*. Such a material will have a large Young modulus (in a bar bent into a curve, the material is stretched on the outside of the curve).

Strong

A material is *strong* if a large stress is needed to break it. The *breaking strength* (ultimate tensile stress) is the stress needed to break the material. A material can be stiff, but not strong, like a biscuit; quite strong but not very stiff, like nylon, or both strong and stiff, like steel.

Brittle

Glass, crockery, concrete, and similar materials snap cleanly when they break. Often the broken ends will fit together again (unless small fragments have been lost), showing that the material did not slide or flow before breaking. Such materials are said to be *brittle*. A material that is not brittle is called *tough*.

Ductile, plastic, soft

Many metals can be hammered or pressed into new shapes, or drawn through a die to form a wire. Such materials flow, slip, or slide internally long before they break, and are said to show *plastic* deformation. Plasticine is one of the first plastic materials that a child experiences.

Ductile materials can be drawn into wires (Latin *ducere*, to lead).

Malleable materials can be hammered into new shapes. Both properties require some degree of *plastic* behaviour. Hard materials are not plastic.

Elastic

A rubber band returns to its original length when it is pulled and then released. Other materials are elastic for small strains; steel wires will, for example, return to their original length after being stretched by a fraction of one per cent. (Steel springs do the same because the wire in them goes back to its original shape after being twisted a little as the spring is pulled out.)

In careful scientific usage, the word elastic is reserved for materials that behave in the same way on extension and relaxation. Rubber is perhaps not strictly elastic in behaviour, for when it relaxes after stretching the stress is often less at a certain strain on relaxation than it was upon extension.

You should know how to use the above words, and be able to understand what they mean when you meet them in scientific writing. You may also meet other terms such as creep, fatigue, dislocations, or work hardening. If you do, the following notes may help.

Creep

A material that is under continuous stress not great enough to break it may gradually extend more and more. Rubber bands show *creep*, as do materials like pitch and tarmac. Probably more materials show creep than we think, but the time

needed for an appreciable extension is very long. Raising the temperature usually increases creep, by reducing the time scale within which it happens appreciably.

Fatigue

Materials that are subjected to varying stresses, like railway wheels, car springs, or aircraft cabins (which are pressurized each time the aircraft flies) can fail after many stress variations (a million is typical) even though the stress was at no time big enough to break the material. The mechanism is not well understood, but depends on the formation of small cracks which enlarge each time the stress is applied.

Dislocation

A dislocation is a single defect in the otherwise perfect and regular arrangement of atoms in part of a crystal. There are several kinds of dislocation. In one kind a row of atoms stops, and meets two rows instead of continuing on as it would in a perfectly regular arrangement. In another kind, atoms form a rising spiral (like a spiral staircase) instead of lying in separate distinct layers. Defects such as an extra foreign atom in the crystal pattern, a simple hole where an atom is missing, or the boundaries between small crystals within the bulk material do not usually count as dislocations.

Work hardening

Dislocations can breed. When a material is stretched, bent, or hammered new dislocations can be produced. The presence of a few dislocations can make a material soft or plastic, because the dislocations can run through the crystal, resulting in slip. Paradoxically, the presence of many dislocations can make the material less plastic and harder, for a dislocation cannot then run far before it meets another and is stopped. A work-hardened material has been deformed enough to produce many new dislocations. In time, the dislocations can vanish again, especially if the material is kept hot, because dislocations of opposite types may come near each other and

allow the atoms to 'snap back' into a regular arrangement, or they may travel to the edge of the crystal leaving only a step on the surface. This process is called *annealing*.

X-ray diffraction

When a beam of X-rays, wavelength λ , falls with an angle θ between the beam and the plane of layers of atoms in a crystal, the X-rays scattered from each successive layer, the layers being distance d apart, can reinforce each other if the path differences between the successive scattered X-rays are right. The condition for a strong diffracted beam is

$$\lambda = 2d \sin \theta$$

This *Bragg equation* is named after Sir Lawrence Bragg.

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