Revision Guide for Chapter 5

Contents

Student's Checklist

Revision Notes

Summary Diagrams (OHTs)

Student's Checklist

Back to list of Contents

I can show my understanding of effects, ideas and relationships by describing and explaining:

the evidence we have for the sizes of atoms and molecules Revision Notes: Atomic microscopy	
the spacing and arrangement of atoms and molecules in solids and liquids Revision Notes: Crystals; Metals; Ceramics; Polymers; Glass; Composites	

I can interpret:

images produced by SEM (scanning electron microscopy), STM (scanning tunnelling microscopy), AFM (atomic force microscopy) and other images to obtain information about the structure of materials Revision Notes: Atomic microscopy Summary Diagrams: Looking inside wood; Looking inside metals and ceramics; Looking inside polymers; Looking inside glass	

I can calculate or make justified estimates of:

the size of a molecule or atom interatomic forces using the value of the Young modulus (e.g. in steel) Revision Notes: Estimating quantities on the atomic scale Summary Diagrams: Explaining stiffness and elasticity; Fracture energy and tensile strength;	

I can show understanding of materials and their applications by giving and explaining my own examples of:

how the properties of a material are linked to its structure and so affect its use Revision Notes: Metals; Ceramics; Polymers; Glass; Composites Summary Diagrams: Bonding and strength; Stopping cracks; Dislocations and slip;	

In carrying out a case study I have shown that I can:

use resources to gather, analyse and communicate information about the properties and uses of a material *e.g. textile fibres, building materials, designed materials, semiconductor materials, optical fibres* Refer to your own case study	

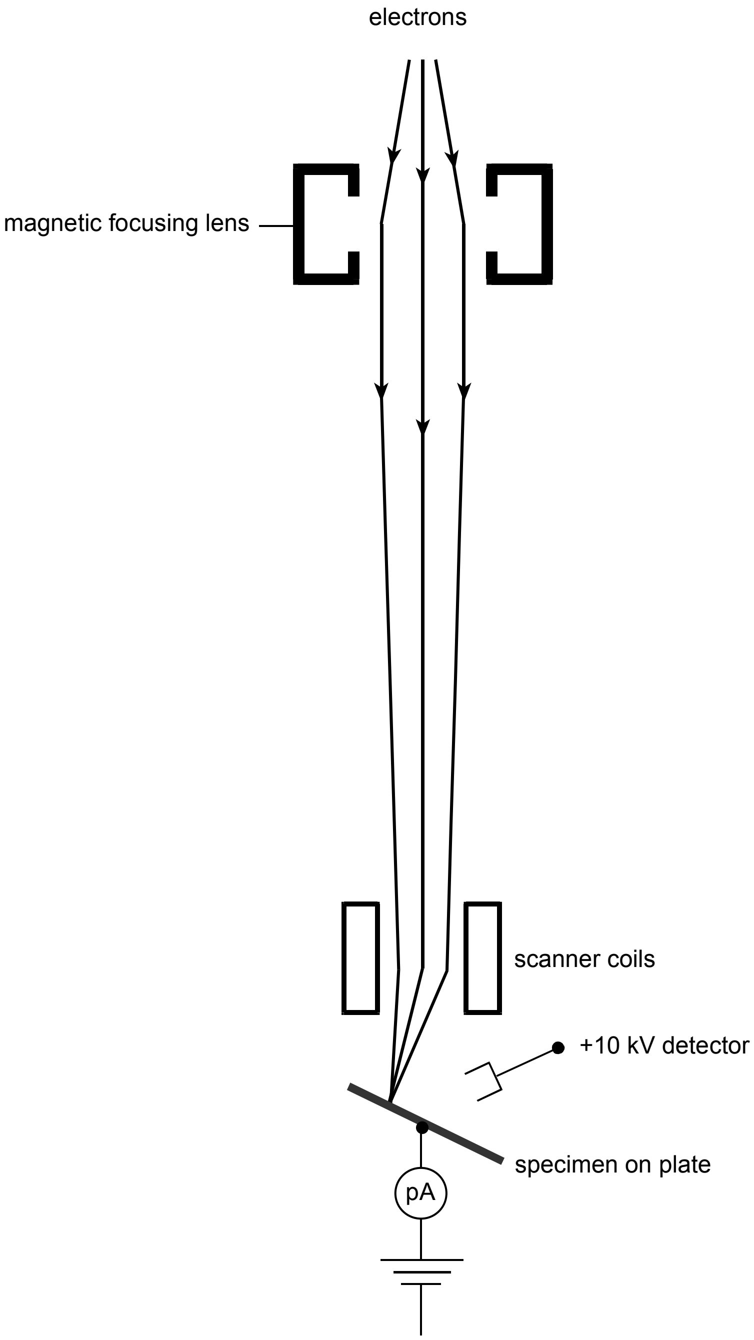
Revision Notes

Back to list of Contents

Atomic microscopy

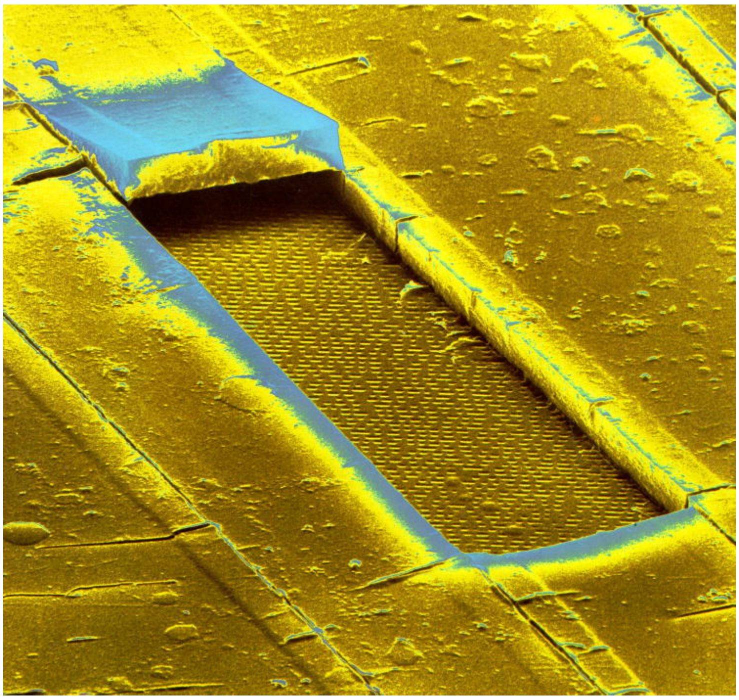
Modern evidence for the sizes, spacing and arrangement of atoms and molecules in materials comes from microscopes able to resolve very small objects.

The scanning electron microscope



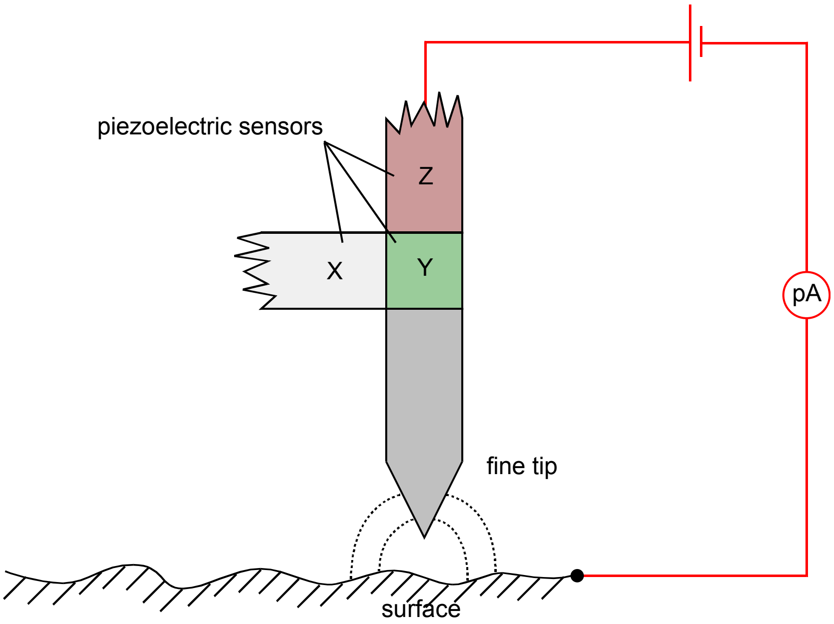
In a **scanning electron microscope** (SEM), the sample is coated with a conducting film and bombarded with a fine scanning electron beam which is focused onto the sample. Electrons are emitted from the impact point and collected by a detector. As the beam scans the surface, the detector current changes according to the number of electrons ejected from the surface. The detector current from the SEM is used to modulate the brightness of a cathode ray tube display, thus re-creating the surface scanned in the SEM.

Surface of a CD-ROM, imaged by scanning electron microscope



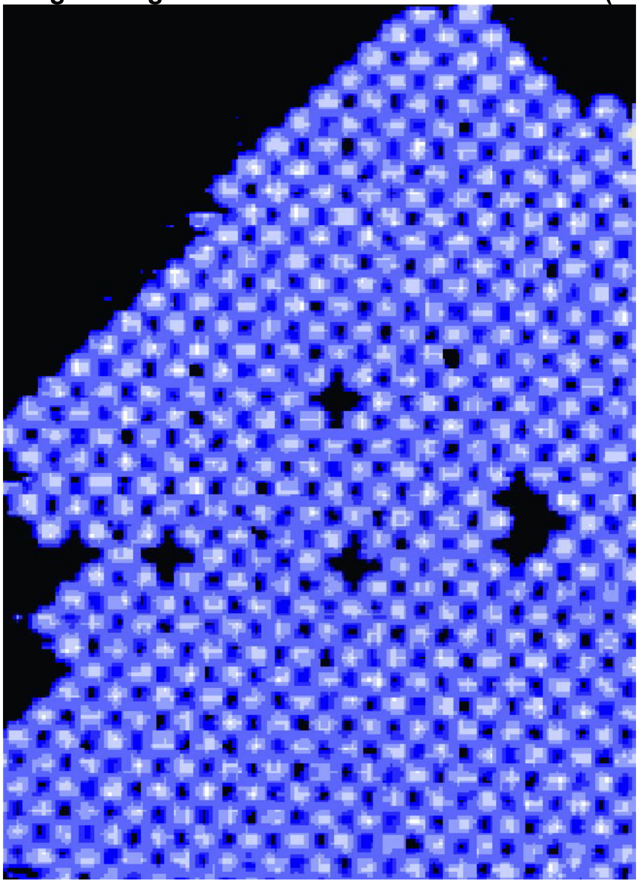
The **scanning tunnelling microscope** (STM) was invented in 1981 by Gerd Binnig and Heinrich Rohrer. Electrons tunnel across a gap between a surface and a fine conducting tip above the surface. This is a quantum-mechanical effect.

The scanning tunnelling microscope

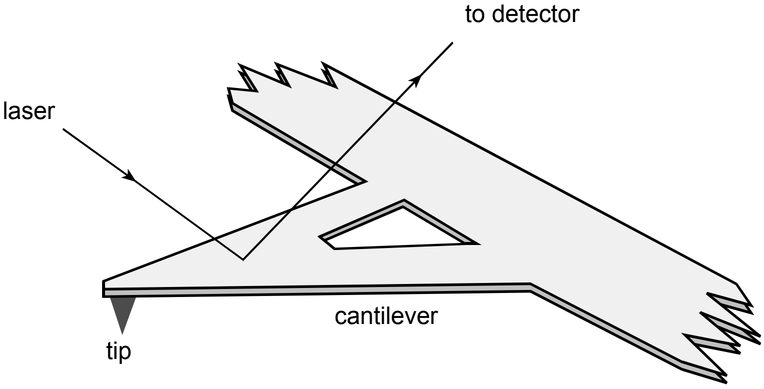


The tunnelling current is very sensitive to the gap width, and so may be used to determine the shape of the surface and to form an image of the surface on a display screen. Surface structures as small as individual atoms can be seen in STM images.

Image of organic molecules on a silver surface (scanning tunnelling microscope)



The atomic force microscope

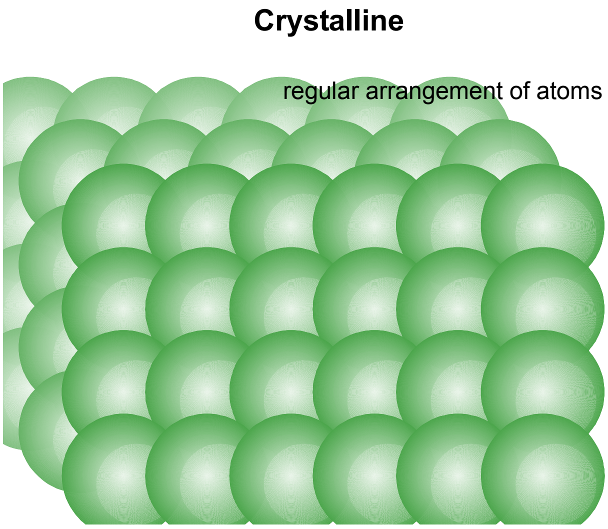


The **atomic force microscope** (AFM) also uses a probe tip, but detects interatomic forces which pull the tip towards or push it away from the surface. The tip is at the end of a tiny lever which bends as the tip moves. A laser beam reflected from the lever detects this movement.

Back to Student's Checklist

Crystals

Crystals include materials such as sodium chloride and diamond, in which atoms or ions are arranged in a large-scale regular lattice. Sodium chloride is an ionic crystal, in which positive and negative ions are held together by electrical forces between the ions. Diamond is a covalently bonded crystal in which electrons are shared between neighbouring atoms.



Back to Student’s Checklist

Metals

Metals are usually shiny, can be worked into shape, are relatively strong and conduct heat and electricity well. The atoms in a metal are ionised, freeing electrons which move throughout the whole material. The positive ions form a crystalline lattice, 'glued together' by this 'sea' of electrons surrounding them. This is the nature of the metallic bond: strong but non-directional.

Generally, metals are **polycrystalline**, composed of tiny crystal grains. The atoms in each grain are arranged regularly in rows in a lattice.

Stress in a metal causes planes of atoms to slip. Slip is made easier by the presence of **dislocations**; faults in the crystal lattice. This is what makes metals ductile and malleable. Slip also makes metals tough, because cracks are blunted by slip, and do not propagate well.

Metals are good conductors of electricity because of the presence of conduction electrons. The conduction electrons also increase the thermal conductivity of metals. But note that insulators such as marble (and notably diamond) can be excellent thermal conductors.

Back to Student’s Checklist

Ceramics

Ceramics are materials such as bricks, tiles, plates and cups. All these materials are strong and stiff but are brittle.

Ceramic materials consist of lots of tiny crystals or grains locked together in a glassy cement. This structure is usually achieved by high-temperature firing. Thus a ceramic is a material in which tiny ionic crystals are embedded in an amorphous glass.

Ceramics are opaque. The internal crystal boundaries scatter light falling on the material, so that the light does not penetrate the material.

Ceramics are stiff and strong because the ionic bonding of the crystals is both strong and directional. The crystals are hard to deform. The combination of small irregularly arranged crystals and glassy material binding them together makes the ceramic equally strong and stiff in all directions.

Ceramics are useful because they are resistant to chemicals and to high temperatures.

A major drawback of a ceramic is its brittleness. Cracks propagate rather easily in ceramics. If a crack forms in a ceramic under tension, the stress at the tip of the crack is large because of the small area of the tip. The tip opens up, and the crack propagates. Typically a fractured ceramic or glass shows a clean break. Tiles or sheet glass are cut to size by scribing a crack on the surface, and then bending the material so that the crack runs right through it.

Back to Student's Checklist

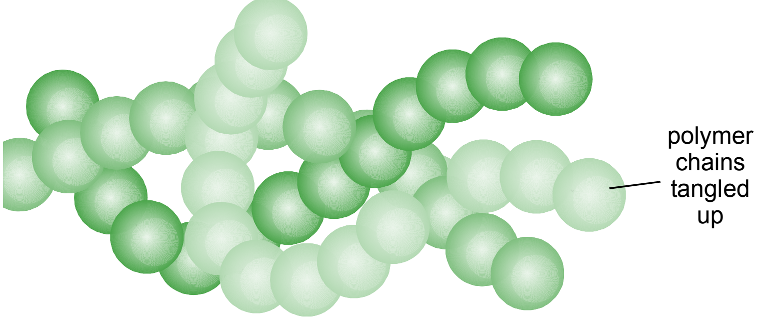
Polymers

Polymers are materials composed of long-chain molecules. Each molecule is a long chain of (usually) carbon atoms joined to each other by covalent bonds with other atoms joined to the carbon atoms at regular spacings along the molecule.

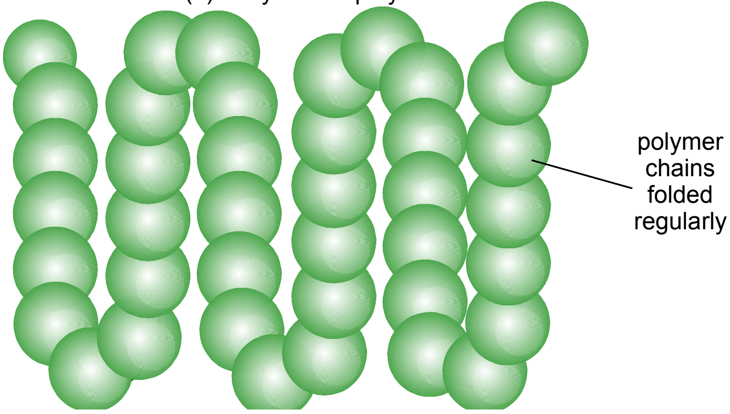
In solid polymers, the molecules are either tangled together as an amorphous structure or folded in a regular arrangement as a crystalline structure. Bonds form between polymer molecules that hold them in place relative to each other.

In a polymer

(a) An amorphous polymer



(b) A crystalline polymer



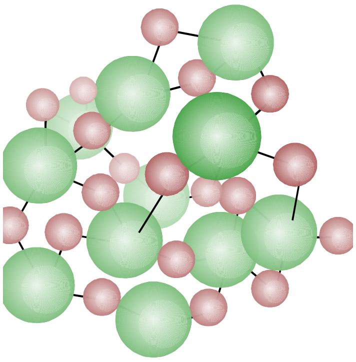
When a polymer such as rubber or polythene is stretched, its molecules become straighter. Before stretching, the molecules are tangled together. The elastic limit of polymers such as polythene can be quite small, so that materials made of it can easily be permanently deformed. This is the origin of the term 'plastic' applied to them.

Back to Student's Checklist

Glass

A glass is essentially a liquid with the liquid structure 'frozen' in place. A glass is therefore an amorphous solid. The silicate groups in glass form strong bonds with one another to make up a rigid structure without any regularity. The bonds are directional so the atoms are unable to slip past each other.

Structure of glass



red : oxygen
green : silicon

Other substances that can exist in a glassy state include the glazes on pottery or china, clear toffee and rubber at the temperature of liquid nitrogen.

Glass is brittle. When subjected to stress minute surface cracks concentrate stress at the tip of a crack. The crack widens and travels through the glass, as the tip of the crack fractures, forming a fresh tip where the process repeats. This behaviour is used when cutting glass.

Back to Student's Checklist

Composites

A composite material is a combination of two or more materials which enhances the desirable properties of each of the component materials.

Consider the desirable features of bone, wood, paper, leather, glass fibre and concrete.

Bone is stiff, strong and relatively light-weight compared with steel.
Wood is a little more flexible but is nevertheless very strong and even less dense than bone.
Glass fibre panels are strong, reasonably stiff and much less dense than steel panels.
Concrete is stiff as well as being strong in compression, capable of supporting large loads.

These properties derive from the structure of the composites. For example:

Wood consists of cellulose fibres cemented together by a natural resin called lignin. The fibres provide tensile strength. Because the fibres are intertwined and glued together by the lignin, stresses are shared amongst the fibres, and the wood is reasonably stiff and strong. It is also tough, because if one fibre fails, the extra stress is shared out by the lignin amongst other fibres.

Concrete is a composite of stones held together by cement. Concrete is used extensively in the building and construction industry because it can be moulded into any desired shape and set on site. Concrete is strong in compression because of the presence of the stones which press against each other. Concrete is weak in tension, because cracks easily propagate through the cement. This problem is avoided by using steel reinforcing rods.

Back to Student's Checklist

Estimating quantities on the atomic scale

Atomic dimensions

The size and spacing of atoms can be obtained directly from atomic level microscopy (the most accurate values come from x-ray diffraction). From this information, the Avogadro constant, the number of particles in one mole, can be found.

The calculation can be done in reverse. For example, given the Avogadro constant $N_A = 6.0\times10^{23}\ \text{mol}^{-1}$, you can estimate the size of an atom of aluminium, knowing that the density of aluminium is 2700 kg m^{-3} and that its molar mass is 27 g mol^{-1}.

One mole of aluminium atoms, mass 0.027 kg, has a volume of $\dfrac{0.027\ \text{kg}}{2700\ \text{kg m}^{-3}} = 10^{-5}\ \text{m}^3$

This volume contains 6.0×10^{23} atoms. The volume occupied by one atom is thus

$$\frac{10^{-5}\ \text{m}^3}{6.0\times10^{23}} = 17\times10^{-30}\ \text{m}^3.$$

This is the volume of a cube of dimensions 2.5×10^{-10} m. If the atoms in the solid touch one another, you could estimate their dimensions as about 0.25 nm.

Forces on atoms

The Young modulus of aluminium is 7×10^{10} Pa. Thus the tension in a bar 10 mm square at a strain of 0.1% will be:

area × *Young modulus* × *strain* = $10^{-4}\ \text{m}^2 \times 7\times10^{10}\ \text{Pa} \times 0.1/100 = 7000\ \text{N}$.

This force is shared out over all the atoms in the cross-section of the bar. If each atom occupies an area of dimensions 0.25 nm, then in an area 10 mm square there will be 1.6×10^{15} atoms. This gives an estimate of the force per atom as 4×10^{-12} N.

Back to Student's Checklist

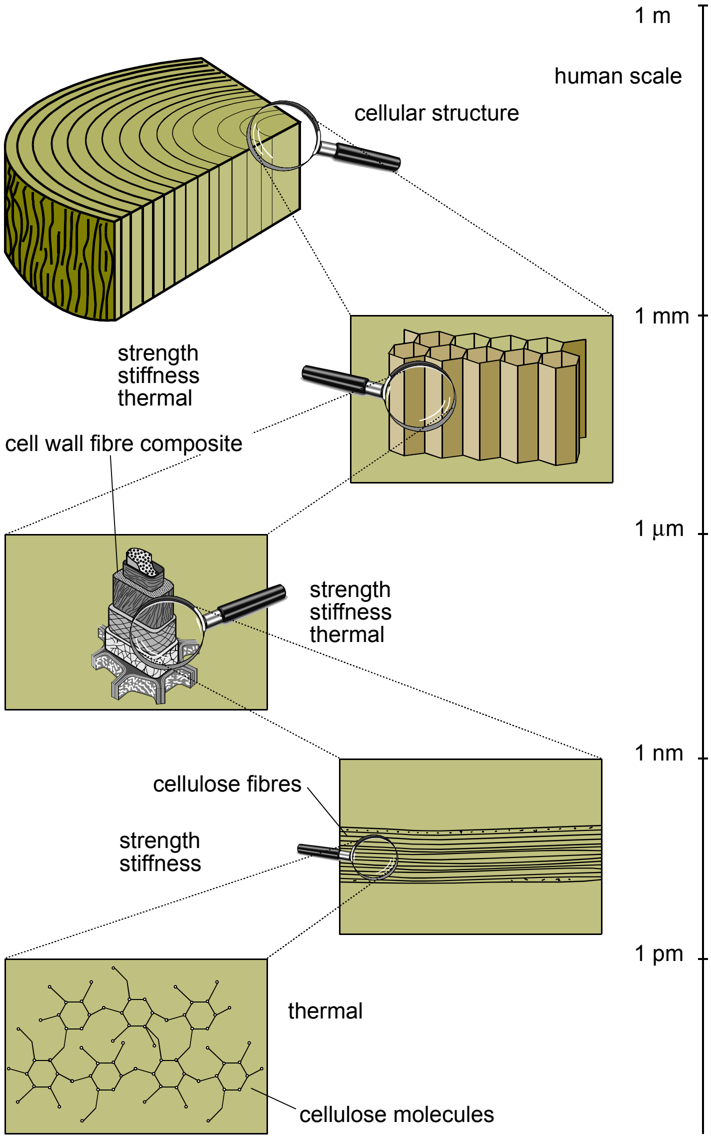
Summary Diagrams (OHTs)

Back to list of Contents

Looking inside wood

Here are the important structural features at each length scale, and the properties with each level of detail.

Looking inside woods



Source: MF Ashby and HR Shercliff, Cambridge University Engineering Department.

Back to Student's Checklist

Looking inside metals and ceramics

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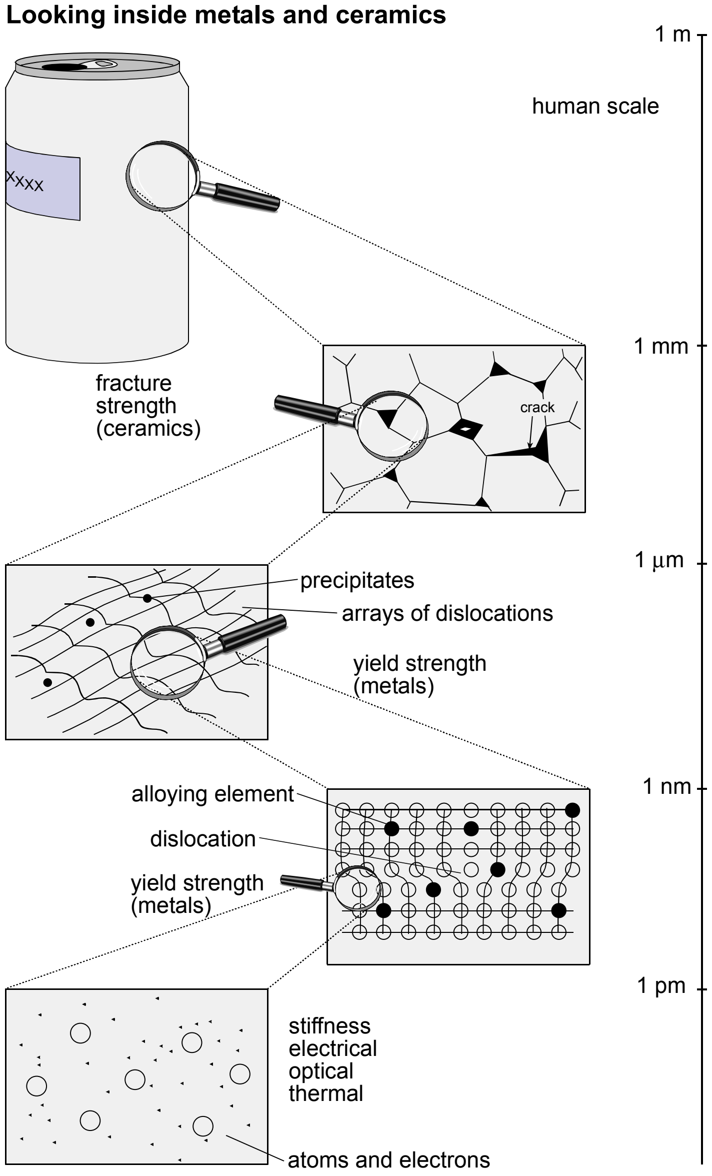

Looking inside metals and ceramics

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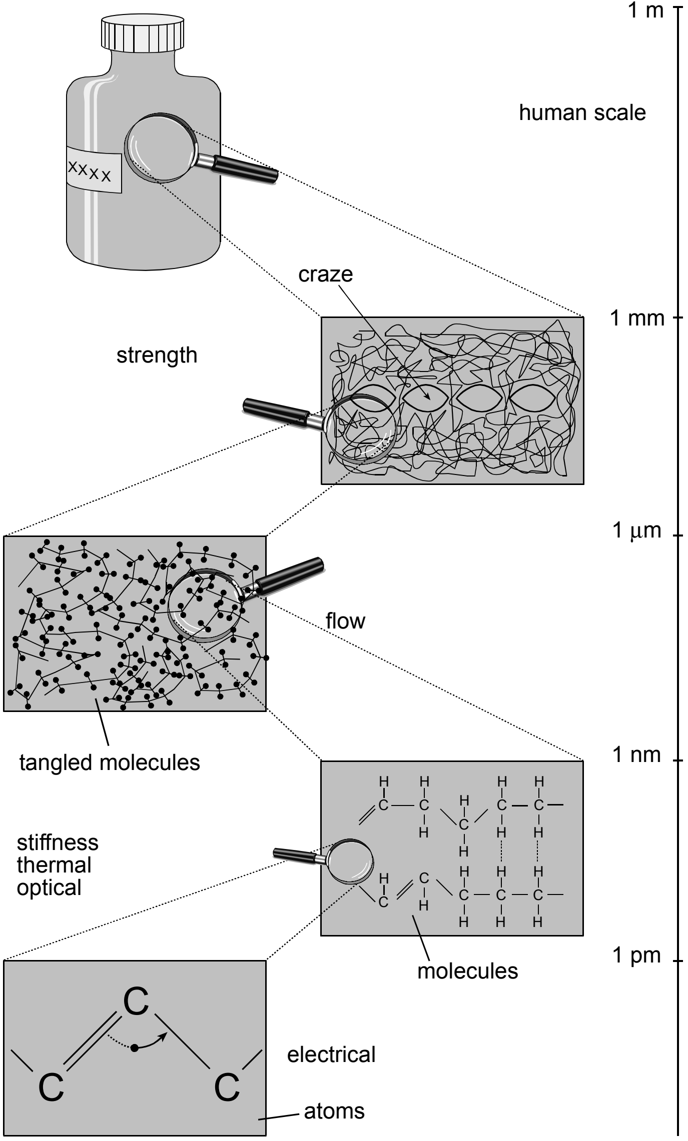
Back to Student's Checklist

Looking inside polymers

Here are the important structural features at each length scale, and the properties with each level of detail.

Looking inside polymers



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Back to Student’s Checklist

Looking inside glass

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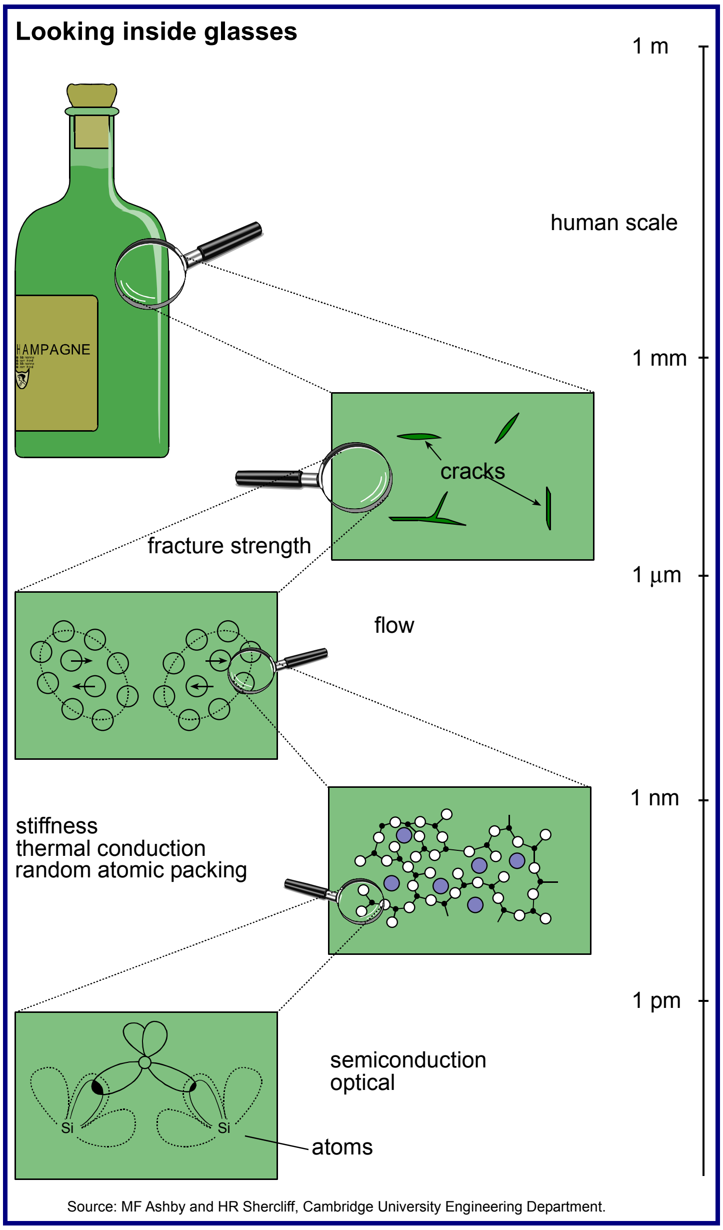

Looking inside glasses

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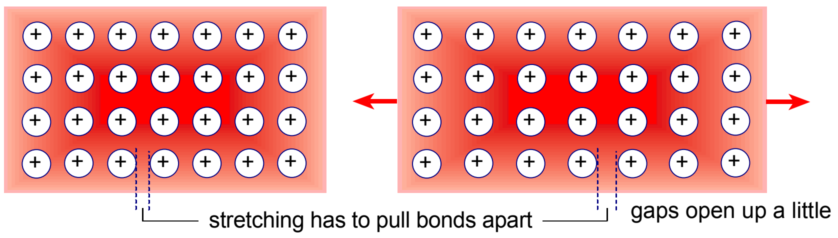
Back to Student’s Checklist

Explaining stiffness and elasticity

Explaining stiffness and elasticity

Metals



a metal is an array of positive ions bonded by negative electron 'glue'

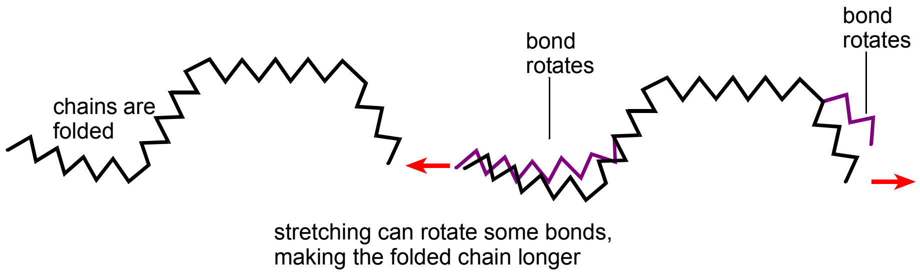
Elastic extensibility ~ 0.1%

Young modulus
~10^{11} — 10^{12} Pa

Stretching a metal stretches bonds — but not much.

Explaining stiffness and elasticity

Polythene



polythene is a long flexible chain molecule which folds up

Elastic extensibility ~ 1%

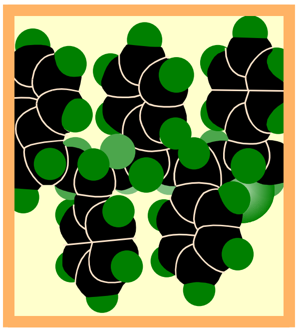
Young modulus
~10^{8} — 10^{9} Pa

Stretching polythene rotates bonds

Explaining stiffness and elasticity

Stiffer polymers

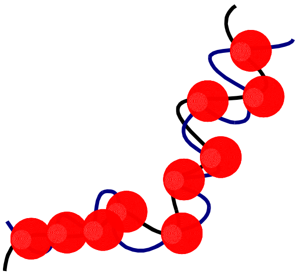
Polystyrene



Polystyrene has benzene rings sticking out sideways. They make chain rotations difficult.

Young modulus
~10^9 — 10^{10} Pa

Bakelite – a thermoset



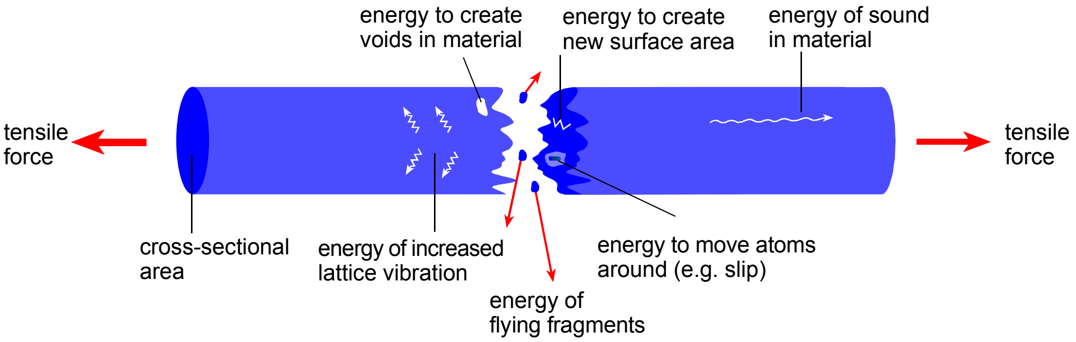
Bakelite has massively cross-linked chains. The cross-links stop the chains from unfolding.

Young modulus
~10^{10} Pa

Back to Student's Checklist

Fracture energy and tensile strength

Fracture energy and tensile strength



$$\text{fracture energy} = \frac{\text{total energy used to fracture}}{\text{specimen cross-sectional area}}$$

$$\text{tensile strength} = \frac{\text{breaking force}}{\text{specimen cross-sectional area}}$$

Large fracture energy = tough

Large tensile strength = strong

Back to Student’s Checklist

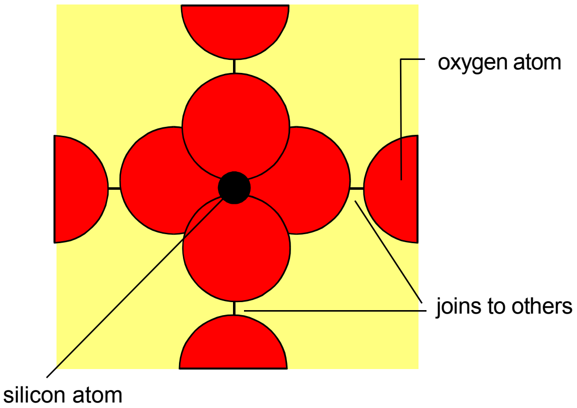
Bonding and strength

Ceramics

Ceramics have rigid structures

Covalent structures

example: silica (also diamond, carborundum)



Covalent bonds share electrons between neighbour atoms. These bonds are directional: they lock atoms in place, like scaffolding.

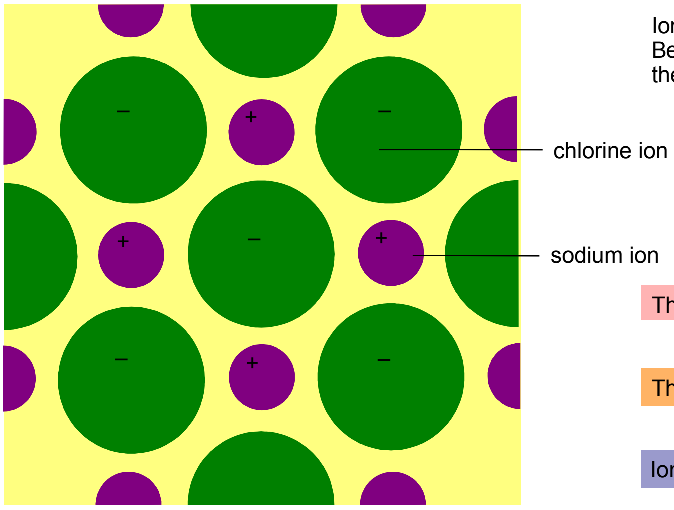
The bonds are strong: silica is stiff

The atoms cannot slip: silica is hard and brittle

Atoms are linked in a rigid giant structure

Ionic structures

example: common salt



Ionic bonds pass electrons from one atom to another. Because like charges repel and unlike charges attract, the charged ions hold each other in place.

The bonds are strong: salt crystals are stiff

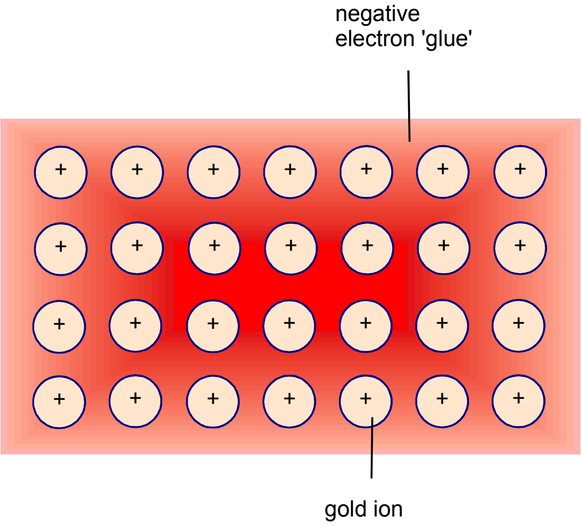
The ions cannot slip: salt crystals are hard and brittle

Ions are linked in a rigid giant structure

Metals have non-directional bonds

Metallic structures

example: gold



Atoms in metals are ionised. The free electrons move between the ions. The negative charge of the electrons 'glues' the ions together. But the ions can easily change places.

The bonds are strong: metals are stiff

The ions can slip: metals are ductile and tough

Ions are held together, but can move

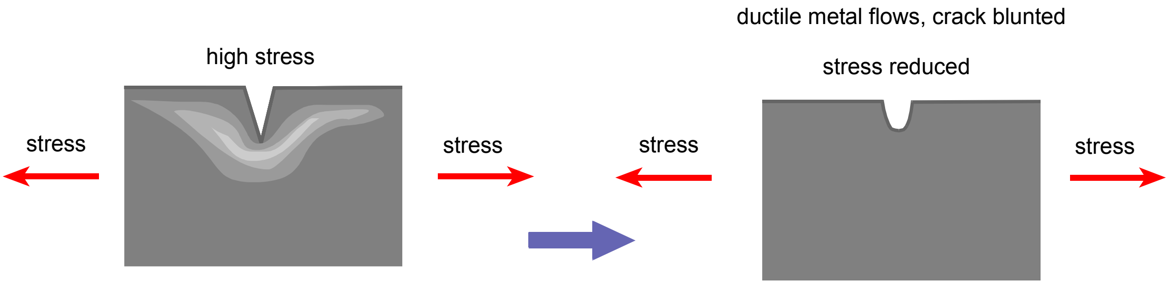
Back to Student’s Checklist

Stopping cracks

Metals are tough because they are ductile

Stopping cracks propagating

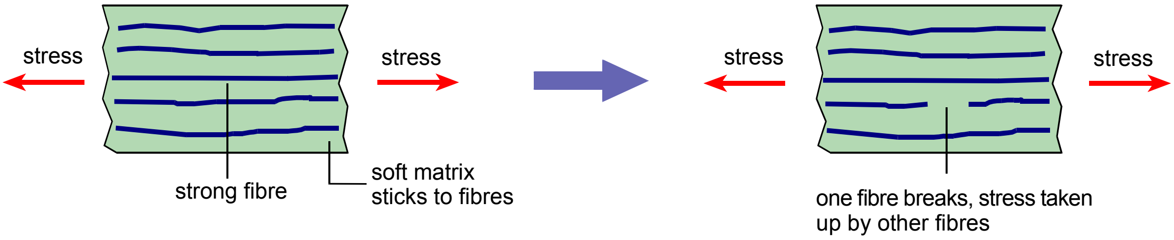
Metals



Metals resist cracking because they are ductile. Cracks are broadened and blunted. They do not propagate.

Fibre-reinforced materials are tough because cracks can't propagate through the soft matrix

Fibre-reinforcement



Fibre-reinforced materials use a matrix to share stress amongst many strong fibres. The matrix also protects the fibres from cracks forming.

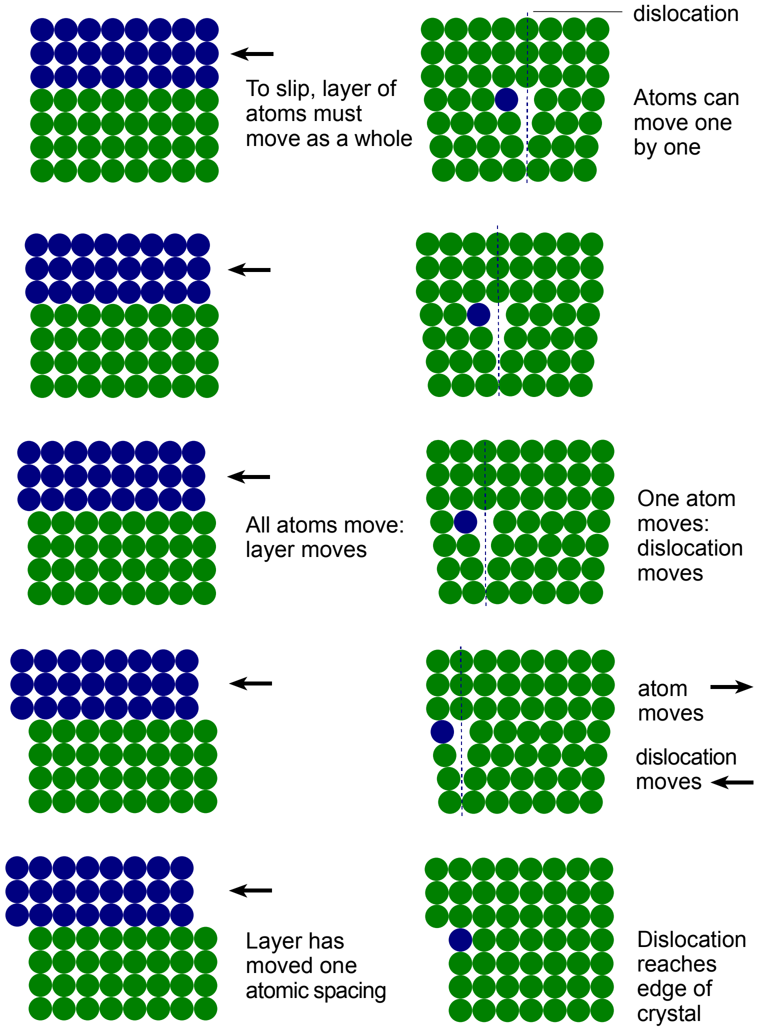
Back to Student's Checklist

Dislocations and slip

Dislocations make it easier for atoms in a metal to slip.

Shaping and slipping

Atoms in gold are in a regular array: a crystal lattice. To shape the metal, one layer must be made to slide over another.



in both a layer has slipped by one atomic spacing

Back to Student’s Checklist