

A-level Physics Tutor Guides

A-level Physics  
COURSE NOTES

**MATTER**

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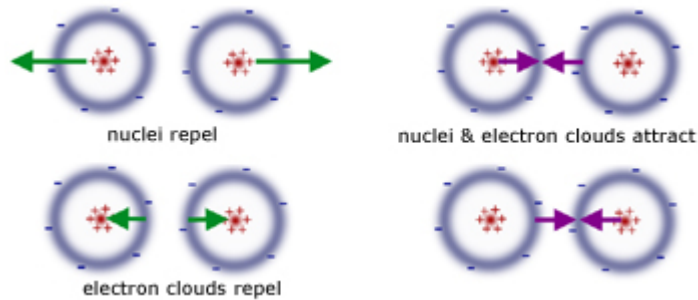
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## Intermolecular Force & P.E.

Molecules and atoms (considered the same)

While the kinetic theory of matter considers the motion of molecules to be free and random, there are forces between molecules.

The force acting between molecules is an electrostatic force. If we consider two molecules, the force is:



**repulsive** between opposite electron clouds

**repulsive** between opposite nuclei

**attractive** between one electron cloud and the opposing nucleus

As molecules have forces between them they must have potential energy.

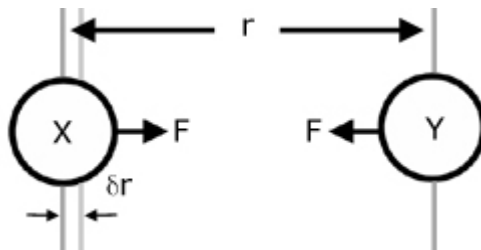
It is convenient to think of two molecules as having zero P.E. at infinite distance, where the attractive force between them is also zero.

Work is done when two attracting molecules are separated. So their P.E. must increase when they are parted.

However, since molecules at infinite distance have zero P.E., those at intermediary distances have negative P.E. relative to this level.

Conversely, repelling molecules have positive P.E. . Repulsive forces do work to move

Relation between force (F) and P.E. change ( $\delta E$  - delta E)



Consider two attracting molecules(X & Y). The force of attraction **F** of Y on X moves X a small distance  $\delta r$  (delta 'r') towards Y.

The distance  $\delta r$  is so small that the force **F** may be considered constant.

The work done  $\mathbf{W}$  in moving the force  $\mathbf{F}$  a distance  $\delta\mathbf{r}$  is given by: (remember work = force x distance force moves)

$$\delta W = F \delta r$$

If the change in the P.E. of X is  $\delta E$  (delta E), then:

$$\delta E = -\delta W$$

Note the minus sign signifies the decrease in P.E. of X as it is attracted towards Y.

Eliminating  $\delta W$  from the first two equations:

$$\delta E = -F \delta r$$

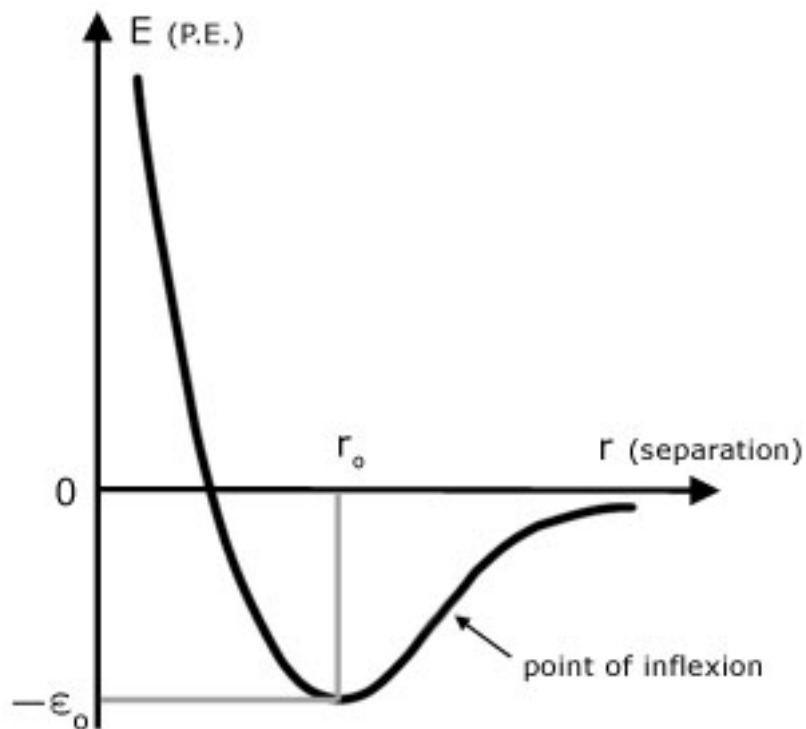
in the limit, as  $\delta E$  and  $\delta r$  tend to zero,

$$F = -\frac{dE}{dr}$$

This means that the negative of the gradient of an E-r graph equals the force F acting.

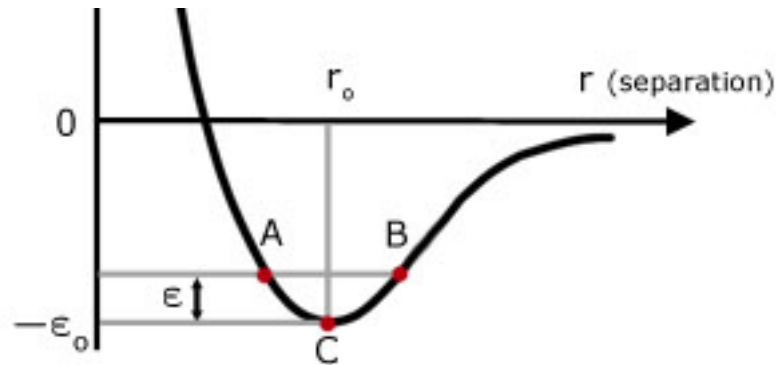
#### Curve of molecular P.E. (E) vs molecular separation (r)

The value of the equilibrium separation  $r_0$  depends on the solid and temperature. An approximate value is  $3 \times 10^{-10}$  m.



The point of inflexion is where the gradient is maximum on the right hand side of the graph.

P.E. and K.E. changes between molecules



If two molecules in a solid are at absolute zero, they have no kinetic energy and their separation is  $r_0$ . Now consider the two molecules at a higher temperature, with a shared kinetic energy  $\epsilon$ . This energy creates an imbalance between the attractive and repulsive forces.

**B**  $r$  maximum molecules attracted PE max, KE zero

**BC** PE converted into KE

**C**  $r = r_0$  equilibrium position PE min KE max

**CA** KE converted into PE

**A**  $r$  minimum molecules repelled PE max, KE zero

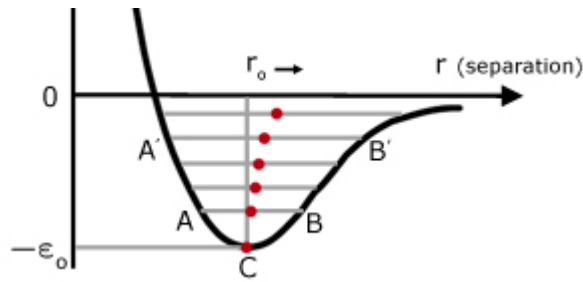
**AC** PE converted into KE

**C**  $r = r_0$  equilibrium position PE min KE max

**CB** KE converted into PE

In solids molecules can only vibrate small distances about fixed positions. The reason is that the kinetic energy  $\epsilon$  is much smaller than the potential energy  $\epsilon_0$  (approx. 10%). Hence a solid has a fixed shape and volume.

Effect of temperature on equilibrium position



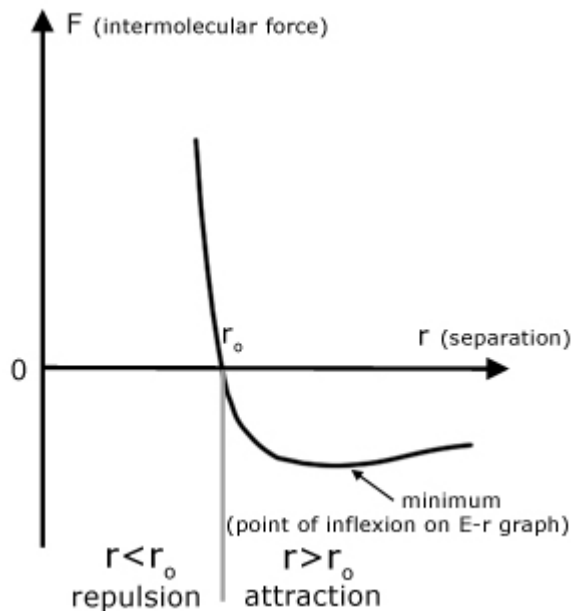
**C** represents the equilibrium position  $r_0$  at absolute zero. In this state the molecules have no kinetic energy and consequently do not oscillate.

Consider a low temperature P.E. level at **AB**. The mid-point of **AB** moves  $r_0$  to the right.

At a higher P.E. level **A'B'** corresponding to a higher temperature. The mid-point **A'B'** moves  $r_0$  even further to the right.

So as the temperature rises,  $r_0$  increases. The molecules move apart and the solid is observed to expand.

Curve of intermolecular force (F) vs molecular separation (r)



Force is the negative of the gradient of the E-r graph.

When F is **positive**, the force is **repulsive**.

When F is **negative**, the force is **attractive**.

## Properties & Definitions

### Breaking stress ( or ultimate tensile stress)

This is the maximum tensile stress that produces fracture.

### Brittleness

Brittle materials cannot be permanently stretched. They break after the elastic limit is exceeded.

### Creep

Creep occurs when a material is under **constant stress over time**. Strain gradually increases, causing eventual fracture.

### Dislocation

A dislocation is the **movement of a broken bond** through a crystal. The broken bond creates a small void between molecules. When a force is applied to the crystal, the void moves across lattices in the **opposite** direction to the force.

### Ductility

This is the property a material has whereby it can be **permanently stretched**.

### Elastic limit

This is the maximum force a body can endure and still regain its original shape and size, when the force is removed.

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### Elasticity

Elasticity is the property a material has whereby it regains its original size and shape when a deforming force is removed.

### Fatigue

Fatigue is the weakness induced in a material by it **repeatedly being stressed** in opposite directions. It can also occur when a material is repeatedly stressed and the stress being removed.

### Hooke's law

The extension of a stretched spring(or wire) is directly proportional to the extending force, provided the limit of proportionality is not exceeded.

### Stiffness

The stiffness of a body is the a measure of its resistance to changes in size and/or shape.

### Strain

Strain is a the ratio of change in length to original length. It can also be considered as the extension per unit length. Strain has no dimensions.

### Strength

Strength is the maximum force applied to a body before it breaks.

### Stress

Stress is the applied force divided by the cross-sectional area it operates over. It is the force per unit area of cross-section. Units of stress are  $\text{Nm}^{-2}$  (also Pascals Pa).

### Yield point

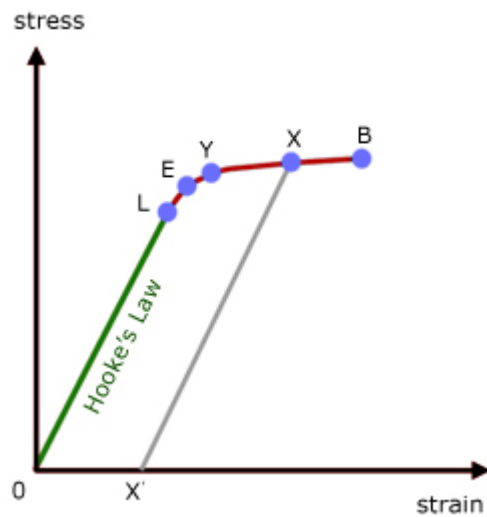
For a body being extended by an applied force, the yield point is when a large extension is produced for a very small increase in force. The material of the body is said to show '**plastic**' behaviour.



## Elasticity

### Young's Modulus

This is a typical stress-strain curve of a ductile material. A brittle material would have a much smaller strain value before breaking (making EB shorter).



- L - limit of proportionality
- E - elastic limit
- Y - yield point
- X - stress removed here, body has permanent strain  $OX'$
- B - breaking stress

For a given material, by definition, Young's Modulus ( $E$ ) is the ratio of stress\* to strain\*, provided the limit of proportionality is not exceeded.

\* sometimes referred to as stress  $\sigma$  (sigma), strain  $\epsilon$  (epsilon)

$$\begin{aligned}\text{strain} &= \frac{\text{extension(m)}}{\text{original length(m)}} \\ &= \frac{x}{l}\end{aligned}$$

$$\begin{aligned}\text{stress} &= \frac{\text{applied force(N)}}{\text{cross-sectional area(m}^2\text{)}} \\ &= \frac{F}{A}\end{aligned}$$

$$\text{Young's Modulus, } E = \frac{\text{stress}}{\text{strain}}$$

$$\begin{aligned}E &= \frac{\frac{F}{A}}{\frac{x}{l}} \\ &= \frac{F l}{A x}\end{aligned}$$

$$\underline{E = \frac{F l}{A x}}$$

The gradient at any point on a stress - strain graph is the Young's Modulus (E).

### Hooke's Law and molecular separation

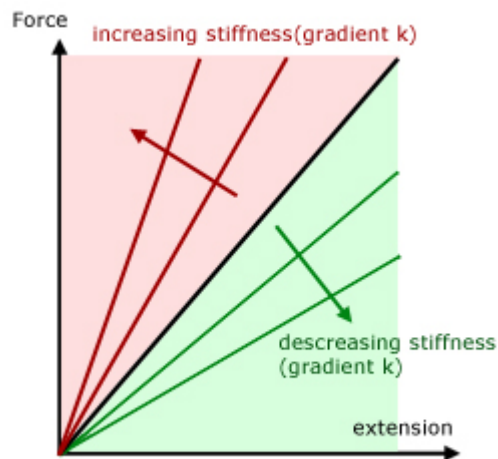
Hooke's Law states that the extension( $x$ ) of a spiral spring(or other elongated body) is proportional to the applied force( $F$ ), provided the limit of proportionality is not exceeded.

$$x \propto F$$

$$F = kx$$

$k$  is the constant of proportionality(a measure of 'stiffness')

So force-extension curves of different materials are straight lines through the origin, with gradient  $k$ .



On a stress-strain graph the Young's Modulus is constant for the portion of the graph where Hooke's Law applies. This can be easily shown by substituting for  $k=F/x$  into the equation for  $E$ .

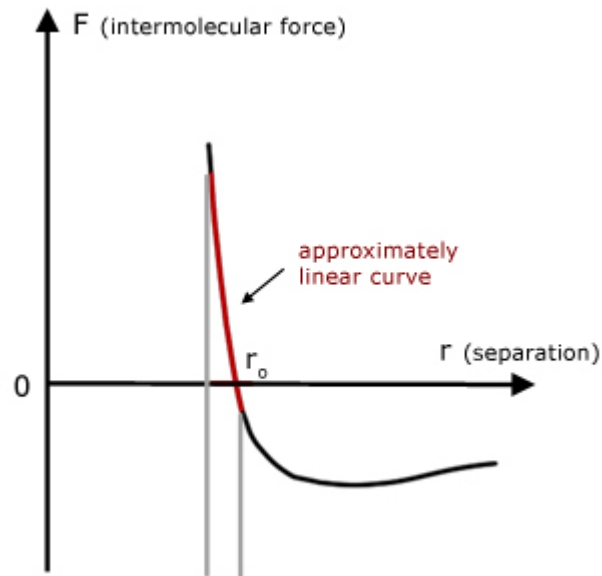
$$E = \frac{Fl}{Ax}$$

$$= \left(\frac{F}{x}\right) \frac{l}{A}$$

$$= k \frac{l}{A}$$

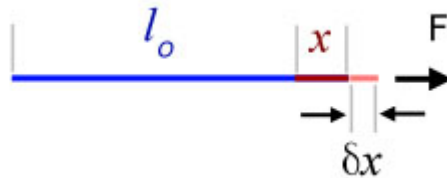
$E$  is a constant because  $l$ ,  $A$  and  $k$  are all constant.

The force  $F$  between molecules is directly proportional to small displacements either side of the equilibrium position  $r_0$ . This translates in the *bigger picture* to applied force being proportional to extension.



### Strain Energy

To obtain an expression for the strain energy (work done) in stretching a wire, consider a wire of original length  $l_0$  where a force  $F$  produces an extension  $x$ . It is assumed that the wire obeys Hooke's Law.



Now, let the force  $F$  cause a further extension  $\delta x$ , where  $\delta x$  is so small that  $F$  may be considered constant.

Since

work done = force  $\times$  distance force moves

$$\delta W = F \delta x$$

The total work done when the wire is stretched from 0 to  $x$  is the area under the  $F$ - $x$  curve between these two limits.

$$W = \int_0^x F dx$$

Since the wire obeys Hooke's Law,

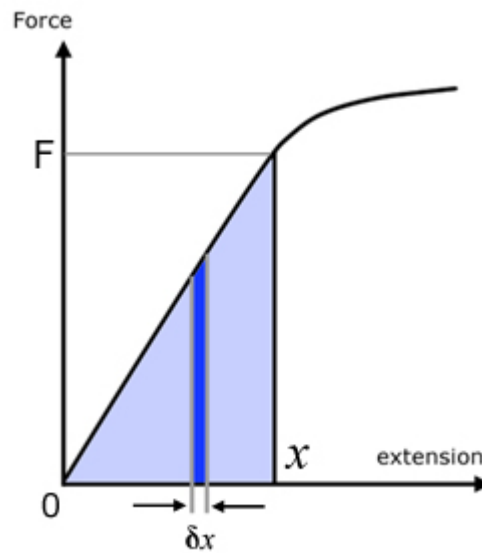
$$F = kx$$

Substituting for  $F$  in the integral expression(above):

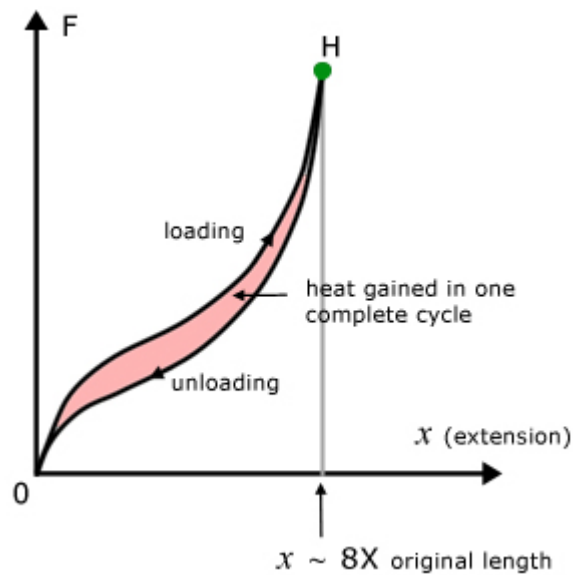
$$W = \int_0^x kx \, dx$$

$$W = \frac{1}{2} kx^2$$

$$F = kx, \quad k = \frac{F}{x}$$



As can be seen from the graph, the area under the curve is half the product of  $F$  and  $x$ .

Elastic Hysteresis

The graph illustrates how for a given force, the extension is greater for unloading than loading.

Looking at this another way, for a given extension the loading force is greater than the unloading force.

The stretching produces an increase in temperature (loading), but when the strain is reduced (unloading) the temperature drops. However, some heat is retained to keep the material above its initial temperature.

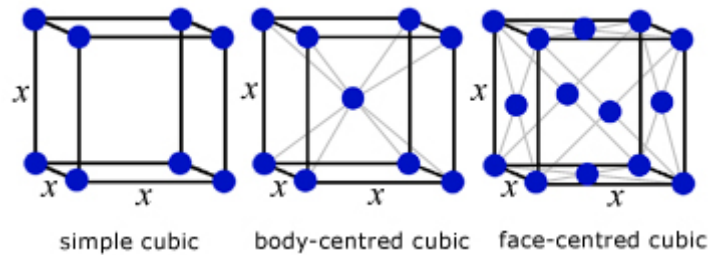
For a complete cycle, the increase in heat energy is the area of the hysteresis loop. The graph is for rubber, but metals also exhibit this property, though the effect is considerably smaller.

## Types of Solid

### Crystalline Solids

A crystal is a regular 3D arrangement of atoms, ions or molecules. All crystals are made from identical sub units called **cells**.

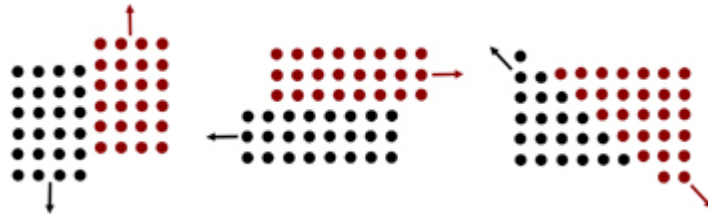
examples of cubic cells:



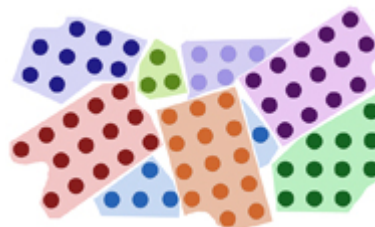
The physical properties of solids are governed to a large extent by their crystal structure(eg graphite & diamond).

It is a basic rule of physics that systems tend towards the lowest level of P.E. . Such is the case with crystals, where regular arrangements of atoms have a lower P.E. than the same atoms all jumbled up, with no structure.

In a large single crystal similar planes of atoms are parallel to each other. So the crystal can be cleanly cut or **cleaved** along these planes.



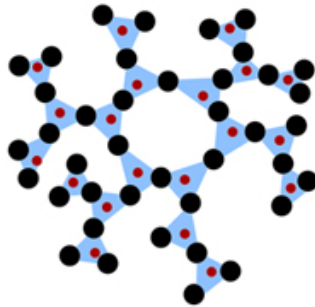
This is not the case with polycrystalline solids. In this case, a solid consists of many small crystals called **crystallites**(or **grains**).



large single crystals display a property called **anisotropy**. This means that physical properties(eg resistivity, linear expansion) are different for different directions along **crystal axes**.

### Amorphous Solids

Unlike crystals, amorphous solids have no definite structure. Further, they melt not at one temperature, like crystals, but over a range of temperatures.



Examples of amorphous solids:

wax, glass, ice, toffee, polythene

Amorphous solids behave more like liquids with high viscosities. For example, over time, a vertical pane of glass is observed to be thicker at the bottom than at the top.

### Glasses

Glasses are electrical insulators and transmit I.R. radiation. Manufacture is by melting mixtures of their components and cooling so that an amorphous solid is produced.

Types of glass:

#### Soda-Lime

Soda-lime glass is the commonest type of glass and is made from a mixture of silica  $\text{SiO}_2$ , calcium oxide  $\text{CaO}$  and sodium oxide  $\text{Na}_2\text{O}$ . Its main uses are window panes and bottles.

#### Lead Crystal

Lead crystal glass has a high refractive index and a relatively soft surface that can be easily cut. For these reasons it is used for wine glasses, decanters, flower vases, bowls etc.

In the manufacture of lead crystal, lead oxide  $\text{PbO}$  is used instead of calcium oxide  $\text{CaO}$  and potassium oxide  $\text{K}_2\text{O}$  is used instead of sodium oxide  $\text{Na}_2\text{O}$ .

#### Borosilicate

Borosilicate glass is heat-resisting and has many uses in the kitchen, laboratory and in industry. It familiarly known under its trade name **Pyrex**.

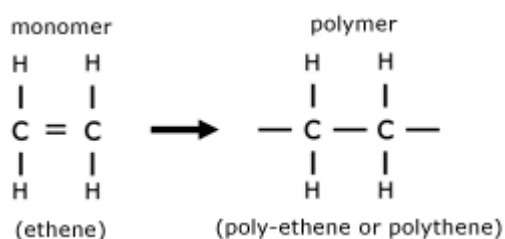
#### Fused Quartz



Fused quartz is manufactured by melting pure quartz crystals at temperatures around 2000 °C. It transmits U.V. and has low expansivity. Applications include: optics(lenses & mirrors), halogen lamps, optic fibre, acid glassware, high temperature industrial use.

## Polymers

Polymers are long chain molecules made from smaller units called monomers. The simplest polymer is polythene. This is made by the process called **polymerization**, whereby a monomer double bond is opened out to make a polymer, with side bonds.

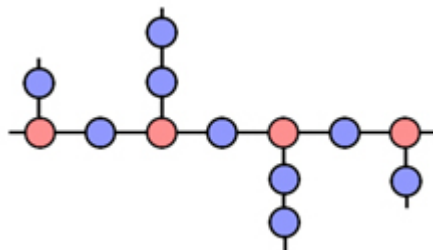


Polymer chain molecules fall into three distinct types:

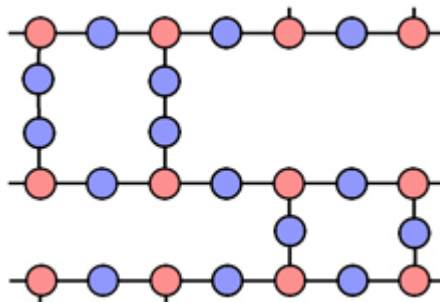
Linear - have flexibility (molecules slide past one another)



Branched - increased rigidity, lower density, m.p. & strength (molecules cannot easily pack together)



Cross-Linked - very rigid (no molecular sliding)



The bonds in polymers are mostly covalent. As a result, polymers have low thermal and electrical conductivities.

Their densities are quite low compared to metals and ceramics.

They have low melting points and can be adversely affected by sunlight. While polymers are cheap to produce and are resistant to water and acids, they do degrade when exposed to organic solvents.

The properties of polymers can be enhanced by the addition of certain chemicals:

lead is added to PVC to stabilise it against decomposition by sunlight

mica is added to thermosetting plastics to increase electrical resistance

glass fibre is added to resins to improve strength

Thermoplastics (eg polystyrene, acrylic, PTFE, PVC)

These become pliable on slight heating, becoming rigid again on cooling. The molecules are only weakly bound to each other. So chains are able to move with some freedom, taking up the shape of the mould.

Thermosetting plastics (eg bakelite, ebonite, epoxy resins)

Unlike thermoplastics, thermosetting plastics do not become pliable on heating. The moulding process takes place before polymerization is complete. After further heating the plastic sets, its shape becoming permanent.

As a result of the strong bonding between adjacent chains, thermosetting plastics can withstand considerable heating before decomposing.

Elastomers (eg raw & vulcanized rubber, neoprene)

Elastomers can produce very large extensions before returning to their original length, when the extending force is removed.

The elastic properties of elastomers are primarily a result of cross-links between adjacent sliding molecules. The large extensions produced by these materials is explained by tangled molecules becoming untangled in the large spaces between chains.