

SEP

Science Enhancement Programme

FANTASTIC PLASTIC



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The Science Enhancement Programme is a part of Gatsby Technical Education Projects. It is developing curriculum resources to support effective learning in science, and providing courses and professional development opportunities for science teachers. This booklet is part of the series 'Innovations in practical work', exploring ways in which low-cost and novel resources can be used in secondary science.



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HEALTH AND SAFETY

For practical activities, the Science Enhancement Programme has tried to ensure that the experiments are healthy and safe to use in schools and colleges, and that any recognised hazards have been indicated together with appropriate control measures (safety precautions). It is assumed that these experiments will be undertaken in suitable laboratories or work areas and that good laboratory practices will be observed. Teachers should consult their employers' risk assessments for each practical before use, and consider whether any modification is necessary for the particular circumstances of their own class/school. If necessary, CLEAPSS members can obtain further advice by contacting the Helpline on 01895 251496 or e-mail science@cleapss.org.uk.

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What's in this booklet?



Fantastic plastic in the classroom

An 'illustrated overview' of the topic with ideas for practical activities



Student activities

Photocopiable activity sheets for students with detailed teachers' notes



Curriculum links



References and further reading



Background science

Further Resources

DOWNLOADING DIGITAL RESOURCES FROM THE SEP WEBSITE

www.sep.org.uk



ORDERING PRACTICAL RESOURCES FROM MUTR

www.mutr.co.uk



See pages 54-55 for further details

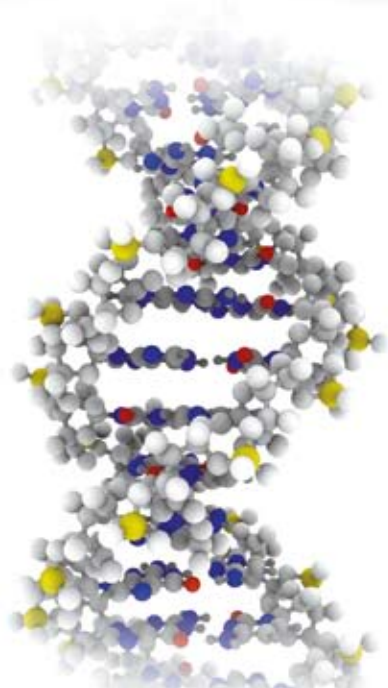


INTRODUCTION

Plastics – or polymers as they are more correctly called – look set to be the material of the future. Think of any product and it is likely that it consists, at least in some part, of a polymer: a car, food packaging, building materials, toys, clothing, and even food which contains polymers in the form of sugars and proteins. Every person in the world is created from DNA, a well-known long chain molecule – also a polymer.

As we progress through the 21st century, newly developed polymers will play an increasing role in our lives – smart polymers in medicine, light-emitting polymers in entertainment, electrolytic polymers in the hydrogen fuel cells that are likely to power our cars and our homes.

The emphasis of this booklet is on providing teachers with an overview of polymers as they are today, together with ideas to demonstrate some of their more unusual properties and the vast range of uses to which they can be put. The activities are designed to support the requirements of GCSE science specifications, but could be adapted for KS3 work or for older students, including those studying A level technology courses. A range of low-cost practical resources to support the activities are available for purchase from Middlesex University Teaching Resources (MUTR).



CURRICULUM LINKS

The following table shows the main relevant sections for each of the current GCSE science specifications.

GCSE specification	Sections particularly related to polymers
AQA Unit Chemistry 1b Oils, Earth and Atmosphere	<p>Alkenes can be used to make polymers such as poly(ethene) and poly(propene). In these reactions, many small molecules (monomers) join together to form very large molecules (polymers) (12.4).</p> <p>Polymers have properties that depend on what they are made from and the conditions under which they are made. For example, slime with different viscosities can be made from poly(ethenol) (12.4).</p> <p>Polymers have many useful applications and new uses are being developed, for example: new packaging materials, waterproof coatings for fabrics, dental polymers, wound dressings, hydrogels, smart materials, including shape memory polymers (12.4).</p> <p>Many polymers are not biodegradable, so they are not broken down by microorganisms and this can lead to problems with waste disposal (12.4).</p>
Edexcel Module 5 Synthesis	<p>Recall that polymers are large molecules which can be formed by a combination of many smaller molecules (C2 5.14).</p> <p>Draw a section of an addition polymer given the monomer and vice versa (C2 5.15).</p> <p>Explain the similarities and differences in properties between thermosetting and thermoplastics in terms of their structure (C2 5.16).</p> <p>Understand that chemists use information about known reactions to make new chemicals and predict the products of a reaction given the reactants and products of similar reactions (C2 5.17).</p> <p>Explain how addition polymers are formed from unsaturated monomers (C2 5.18).</p> <p>Predict uses of polymers given appropriate information about their properties (C2 5.19).</p> <p>Explain how the properties of a plastic can be altered, depending on the starting materials, conditions of reaction, and additives (limited to plasticisers, preservatives and cross linking), and relate this to their structure and bonding (C2 5.20).</p> <p>Discuss the problems of disposing of some plastics, including non-biodegradability and breakdown to toxic products (C2 5.21).</p>
OCR 21st Century C2 Material Choices	<p>Interpret information about how solid materials can differ with respect to properties such as: melting points; strength (in tension or compression); stiffness; hardness; density (C2.1, 1).</p> <p>Relate properties to the uses of materials such as plastics, rubbers and fibres (C2.1, 2).</p> <p>Relate the effectiveness and durability of a product to the materials used to make it (C2.1, 3).</p> <p>Understand that some small molecules can join together to make very long molecules called polymers and that the process is called polymerisation (C2.2, 9).</p> <p>Understand that by using polymerisation, a wide range of materials may be produced (C2.2, 10).</p> <p>Recall an example of a material that has replaced an older material because of its superior properties (C2.2, 11).</p> <p>Understand how modifications in polymers produce changes to their properties to include modifications such as: increased chain length; cross-linking; the use of plasticizers; increased crystallinity (C2.3, 3).</p>
C3 Food Matters	<p>Recall that many chemicals in living things are natural polymers (limited to carbohydrates and proteins) (C3.1, 1).</p>

GCSE specification	Sections particularly related to polymers
<p>OCR Gateway Module C1 Carbon Chemistry Item C1e: Making polymers</p> <p>Module C1 Carbon Chemistry Item C1f: Designer polymers</p>	<p>Construct the formula of an addition polymer given the displayed formula of its monomer. Construct the formula of a monomer given the displayed formula of an addition polymer. Describe polymerisation as a process in which many monomer molecules react together to give a polymer which requires high pressure and a catalyst. Explain that addition polymerisation involves the reaction of many unsaturated monomer molecules (alkenes) to form a saturated polymer.</p> <p>Suggest the properties a polymer (plastic) should have in order to be used for a particular purpose. Explain why a polymer (plastic) is suitable for a particular use given the properties of the polymer. Describe that the atoms in plastics are held together by strong covalent bonds. Relate the properties of plastics to simple models of their structure:</p> <ul style="list-style-type: none"> Plastics that have weak intermolecular forces between polymer molecules have low melting points and can be stretched easily as the polymer molecules can slide over one another; Plastics that have strong forces between the polymer molecules (covalent bonds or cross-linking bridges) have high melting points, cannot be stretched and are rigid. <p>Explain why chemists are developing addition polymers that are biodegradable. Explain some of the environmental and economic issues related to the use of polymers:</p> <ul style="list-style-type: none"> landfill sites get filled quickly wasting valuable land; burning waste plastics makes toxic gases; disposal by burning or land-fill sites wastes a valuable resource; difficult to sort out different polymers so recycling is difficult.
<p>WJEC Additional Science Chemistry</p>	<p>Know how large saturated hydrocarbons (alkanes) can be cracked by heating in the presence of a catalyst to form smaller more useful hydrocarbon molecules including monomers (alkenes) for making polymers (6c). Know the process of addition polymerisation of ethene to produce polythene (6d). Be able to draw the repeating unit for the addition polymers, poly(ethene), poly(tetrafluoroethene) (PTFE) and polyvinyl chloride (PVC) (6e). Relate the uses of polythene, PVC and PTFE to their properties (6f). Relate the uses of thermoplastics and thermosets to their properties and structure (6g). Use given data to compare the properties and uses of polymers and traditional materials (6h). Evaluate the social, economic and environmental impact of the widespread use of plastic products, for individuals, communities and the environment. (6i).</p> <p>Know that the term smart material has been given to a range of modern materials whose properties change with a change in the surroundings, for example:</p> <ul style="list-style-type: none"> shape memory polymer, which has the ability to regain its original shape when heated; potential uses include biodegradable surgical sutures and self repairing car bodies; polymer gels, such as hydrogels, have a cross linked polymer structure inflated with a solvent, such as water; intended uses include artificial muscles, robot actuators, absorbers of toxic chemicals, etc. (7a). <p>Use given data to evaluate the social, economic and environmental impact of the use of smart materials (7b).</p>

FANTASTIC PLASTIC IN THE CLASSROOM: IDEAS AND SUGGESTIONS

Polymers are all around us. This is probably why we take them for granted and assume that the properties of polymers are typically fairly mundane and certainly are unlikely to develop. We couldn't be more wrong! Not only do present-day polymers exhibit a huge range of properties, but new polymers are being developed all the time with ever more impressive properties.

This section gives an 'illustrated overview' of how practical work on plastics can be undertaken in the classroom. In the margin, references are given to student activities – these resources and the accompanying teachers' notes can be found later in this booklet.

A HISTORY OF POLYMERS

The earliest polymers to be exploited by mankind were natural materials: wood for structural members, cotton for clothing, and so on. However, polymers have also been extracted from biological systems and their properties exploited for thousands of years. Locust bean gum is a member of the galactomannan family that can be extracted from the fruit of the carob tree, which has long been cultivated widely around the Mediterranean. Indeed, it was used in ancient Egypt as an adhesive in mummification.

Examples of natural materials that were the earliest polymers to be used by humans: wood (left) and cotton (right).



It is only the last 150 years or so that synthetic and semi-synthetic materials have been deliberately developed for commercial exploitation. The first commercial materials to be developed were derived from natural polymers, notably, natural rubber. Around 1840, it was discovered, independently by Hancock in the UK and Goodyear in the US, that reacting rubber with sulphur reduced its tackiness and improved its elastic properties. This was a cross-linking reaction that resulted in the formation of a molecular network. At around the same time, it was discovered that by reacting cellulose with nitric acid, it was possible to produce a material with numerous useful properties – cellulose nitrate. This material could be spun into fibres to form ‘artificial silk’ and its main application was as gun cotton. Cellulose nitrate is a low order explosive! However, for a short time, it was also used in billiard balls. The mild explosions that occasionally resulted from violent cannoning of the billiard balls were an undesirable side-effect.

One of the first commercial polymers developed was rubber in the mid-19th century and used for solid tyres on the earliest bicycles (left); the first truly synthetic polymer was Bakelite in the early 20th century and was used for a number of domestic items such as this camera (right).



At the Great Exhibition in London in 1851 a medal for quality was awarded to Alexander Parkes for items made from a mixture of cellulose nitrate and castor oil as a plasticiser to make it more flexible. Based upon this John Hyatt created celluloid by using camphor instead of castor oil as the plasticiser added to cellulose nitrate to make it even softer. Probably the most influential application of this polymer resulted from its adoption in 1899 by Eastman Kodak as the base for its film products. However, it is extremely inflammable and degrades relatively rapidly releasing nitric acid, so that most early films have now been lost.

The first truly synthetic polymer was developed by Leo Baekeland around 1910, who reacted phenol and formaldehyde under controlled conditions to form the family of materials we know as Bakelite.

Things moved quickly and 1933 saw the birth of polyethylene by Gibson and Fawcett at ICI in the UK (Polythene is the Du Pont trade name), followed by Perspex (poly(methyl methacrylate) or PMMA), polystyrene, and poly(vinyl chloride) or PVC. Carothers’ work on polyamides around the same time led to the discovery of Nylon.

Developments on polymers in the 1930s led to many of the familiar plastics we use today: polyethylene milk bottle, polystyrene fast-food container, PVC pipe and nylon rope.



Although both the polyethylene and polyamide families are long chain molecules, they are formed by fundamentally different processes. Polyethylene requires a step-growth process whereas Carothers' initial work resulted in division of polymerisation reactions into two distinct types: condensation and addition reactions. For more information on the chemistry of these processes and the different physical properties they confer on the polymer, see the *Background science* section on page 48.

Despite all this technological advance, up until about 1930, there was no consensus about the molecular nature of this class of material. While it was accepted that they contained large structures, it was initially assumed that that these took the form of colloidal aggregates of smaller molecules, held together by secondary forces. However, the credit for establishing the real science of polymers can be given to Hermann Staudinger who, in the 1930's came up with the revolutionary idea that polymers were composed of long chains of smaller building blocks held together by covalent bonds making macromolecules. He was awarded the Nobel Prize in 1953.

WHERE ARE POLYMERS USED?

Polymeric materials now encompass a vast range of biological and synthetic materials that are used in a wide range of applications. The market for polymers involves many large commercial organisations that compete with one another in different market sectors. Thus, polymer nomenclature involves chemistry, from various eras, plus commercial trade names, all of which are used synonymously.

The vast majority of the items we call 'plastic' are made from one of five 'families':

1. **PE: polyethylene** (low density = LDPE, high density = HDPE), e.g. carrier bags.
2. **PP: polypropylene**, e.g. drinks cups, kettles, shampoo bottles
3. **PS: polystyrene and expanded polystyrene (EPS)**, e.g. insulating cups, packaging
4. **PVC: poly(vinyl chloride)**, e.g. window frames, insulation cables for domestic wiring.
5. **PET: poly(ethylene terephthalate)**, e.g. transparent water bottles.

The precise polymer chosen for any application depends upon the combination of properties required, such as its glass transition temperature (below which the polymer becomes brittle), its melting point, its toughness, its aging properties, whether it absorbs the chemicals it is to contain, how easily it can be moulded/ shaped and the cost.

The name of a polymer is derived from the monomer, for example propylene or ethylene terephthalate. If the monomer is a simple molecule such as 'propylene' then the name of the polymer is 'polypropylene' – with no brackets. If it is a combined molecule such as 'ethylene terephthalate' then the polymer is 'poly(ethylene terephthalate)' – with brackets.

Examples of commonly used trade names are Nylon™ (polyamide), Polythene™ (polyethylene), Kevlar™ (poly(paraphenylene terephthalamide), Teflon™ (polytetrafluoroethylene or PTFE) and Perspex™ (poly(methyl methacrylate) or PMMA).

Throughout this booklet reference will be made to a whole host of everyday plastic items we take for granted that can easily be used to demonstrate the range of polymer properties and how they can be exploited to create useful products including:

- Drinks can retainers (elasticity)
- Cosmetics / hair gels (gel consistency for spreading)
- Chewing gum (melts at body temperature)
- RFID tags (conducts electricity cheaply)
- Nappies (absorbs fluids)
- Solvent absorbing hydrogels (absorbent)
- Hot glue guns (thermoplastic)
- Post-it notes (sticky at room temperature)
- Police riot shields (tough yet lightweight)
- Medical e.g. sutures, valves, joints, possibly organs (inert in the body)
- Intelligent packaging (changes colour when in contact with deteriorating food)
- Heat insulation for houses, packaging (low thermal conductivity)
- Polystyrene shelters for disaster victims (lightweight and robust).

Polymers are now used extensively in a wide variety of familiar everyday items.



Despite the huge range of items made from plastic – the worldwide production of polymers is estimated at 245 million tonnes per year – it still consumes only 4% of the world production of oil.

Although plastic is seen by many as a modern evil, without plastic packaging the alternatives would weigh four times as much, increase transport costs with the greater amount of fuel needed to transport everything from household goods to food, cause the emission of twice as much greenhouse gas, and create more waste to be disposed of.

Plastic packaging in the food industry increases shelf life and reduces food waste – it is estimated that the plastic around a cucumber typically increases its life from 3 days to 14 days. And it's worth remembering that the amount of carbon dioxide used to produce meat is 100 times as much as the plastic film used to package it and prevent it going off too quickly.

Plastics as insulators are major components in our attempts to reduce energy consumption in the home in our fight against global warming.

Globally 50% of polymers are recovered when disposed of, either through recycling or through energy recovery. Some countries recover 100% of disposed polymers so they have totally eliminated plastics going to landfill – though the UK is one of the worst, recovering only 20%.

It is possible to recycle most of the commonly used polymers, for example, PET from plastic drinks bottles is often recycled as fibres in the 'stuffing' of jackets. Unfortunately the process for separating the various polymers before recycling is complex and expensive. Typically the polymers have to be ground down into pellets and then submerged in liquids in order to separate them by density. In most cases the process is, at present, economically unviable. Even if the process becomes more financially attractive PVC is unlikely to be recycled as it is usually filled with various colorants and fillers which would have to be removed before re-use.

WHAT IS A POLYMER?

Any long chain molecule is a polymer. Wood is a polymer too – cellulose is a polymer. In fact the human body is composed of long chain molecules – DNA, proteins – and so can quite reasonably be described as a self-replicating polymer.

Polymers are constructed by polymerizing or linking many 'monomers'. The term polymer is derived from the Greek *poly*, meaning many, and *meros*, meaning part and, as such, refers to materials in which the constituent molecules can be thought of as being made up of a sequence of many simpler units.

The majority of polymers are derived from oil products, through cracking to produce alkanes and alkenes, which then through polymerization form well-known polymers. Polyethylene is formed from the monomer ethene, and is used typically in carrier bags. Polypropylene, formed from the monomer propene, is a tougher material used for example in making crates. However, its low glass transition temperature means that if left out during cold weather it is likely to become brittle.

See Activity A1:

Can you cut a liquid?
(page 34)

A solution of polyox can be cut with a pair of scissors as it is being poured.

**Classroom activities**

An effective demonstration of evidence that polymers are composed of long chain molecules is to contrast what happens when you try to cut a liquid such as water (composed of separate molecules) with cutting a polymeric solution – of poly(ethylene oxide) or 'polyox'. This should be done as a teacher demonstration. Students can see the effect of the long chain nature of the polymer: when the solution is cut and the stress is suddenly released, the elasticity of the solution is dramatically demonstrated, as the liquid jumps back into the beaker.

Long polymer molecules intertwine or 'entangle' with each other, just like spaghetti on a plate. These physical entanglements allow polymer solutions to bear some mechanical stress. The molecules are usually coiled up, but when stress is imposed on them they can straighten out somewhat. When the stress is released, they coil up again. This coiling process gives a polymer its elasticity.

All long polymer molecules in a sufficiently concentrated solution will have physical entanglements that lead to viscoelastic behaviour. However, there is an additional factor at work in polyox. Water molecules can bridge two adjacent polymer molecules by forming hydrogen bonds. These bridges or 'cross-links' create a strong network of molecules. A three-dimensional network of molecules in a solution is referred to as a gel (see the section below 'How do you make a polymer?' for more about cross-linking).

This demonstration works because of the molecular chain length of the polyox. Greater molecular weight means longer chains. Their entanglement is greater, resulting in a more viscous liquid. The demonstration has to be done with a relatively high molecular weight polyox (i.e. long chain molecules). Lower molecular weight liquids are less viscous as the molecules are too short to entangle. The way that the molecular chains flow and tangle is described as 'reptation' from 'reptare' (to crawl in Latin) as the molecules are visualised as flowing and tangling like snakes.

Another simple demonstration of the long chain nature of polymers is to take standard plastic 'can retainers' (transparent plastic loops used to keep four drinks cans together for sale in supermarkets). Pulling on the side of one of the loops will gradually cause the plastic to stretch and also to separate into strands which can be seen very effectively if placed on an overhead projector and observed on the screen.

THERMOPLASTICS AND THERMOSETS

The two main classes of synthetic polymers are *thermoplastics*, which can be moulded since they are able to flow when heated but harden on cooling, and *thermosets*, which do not flow on heating – in fact they will decompose before there is any change in their mouldability. The difference lies in the way the molecules are bonded.

Thermoplastics, such as polystyrene (often used to make vending cups, the inserts in food packaging or the transparent packaging for Easter Eggs or toys), are formed of linear or branched molecules which are able to move past each other on heating.

Thermosets have been cured through a chemical reaction, to form a well-defined huge molecular network through 'cross-linking' (see pages 13-14 for more detail on this). An example is epoxy resin which is liquid when uncured but the addition of the 'hardener' results in a molecular network being formed creating a hard material – a reaction which cannot be reversed without further chemical reactions. N.B. For some thermosets the curing process (chemical reaction) can be induced by heating, but it is not a necessary element of the process, i.e. thermoset does not mean set through heat!

See Activity A2:

Food wrappers party tricks
(page 35)

Classroom activities

A high-powered hair dryer or hot air gun can be used in a teacher demonstration to shown the differences between thermoplastics and thermosets. Most shaped inserts for food packaging have been formed from thermoplastic materials. The initial flat sheet is heated and then moulded by vacuum compressing over a shaped mould then allowed to cool. Reheating the formed shape using a high-powered hair dryer or hot air gun allows it to revert to its original shape of an (almost) flat sheet. This also works with the transparent plastic front wrappers of Easter Eggs and toys as well as drinks cups.

All of the packaging shown here (left) is made of polystyrene; a plastic vending cup is also made of polystyrene and will flatten when heated.



A hot glue gun, often used in design and technology classes, is another good example of a thermoplastic. Anyone using a hot glue gun will be aware of the potentially annoying fine fibres of glue that are drawn. This, again, is evidence of the polymer being composed of long molecules tangled up.

A hot glue gun (left) heats the polymer used for the glue creating fine fibres (right) showing that this is a thermoplastic.



One of the practical activities described later in this booklet (Activity A5) involves the use of a polymer called polymorph – also a thermoplastic. In contrast, rubber (used in Activities A4, A5, A6 and A7) is a thermoset.

See Activity A3
What's that polymer?
(page 36)

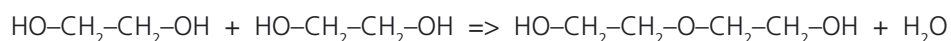
Polymer properties vary according to the way the polymer is processed and the fillers added, and students can explore this by looking at a number of items made from polystyrene with different properties that suit them for their job. The properties also depend on the molecular chain length of the polymer: longer chain lengths will produce a tougher more brittle material, and students can observe how the properties vary across a range of materials that have polymers with different chain lengths.

A variety of items made from polystyrene processed in different ways.

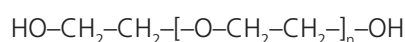


HOW DO YOU MAKE A POLYMER?

In a polymer, long-chain molecules are made by joining together the same molecular groups (or repeat units) to make a long chain. For example, the polyox or poly(ethylene oxide) described earlier in the section 'What is a polymer?' is produced from a reaction of ethylene glycol ($\text{HO}-\text{CH}_2-\text{CH}_2-\text{OH}$). Initially, two monomers join together with the elimination of a water molecule:



The addition of further monomers produces a long chain:



Note that the repeat unit for poly(ethylene oxide) is $[-\text{O}-\text{CH}_2-\text{CH}_2-]$. The scheme shows the complete structure of the polymer molecule – n represents the number of times the unit is repeated, and can typically be several thousand. Notice that there is an oxygen atom at every third atom along the chain. This oxygen readily forms hydrogen bonds with water, giving the polymer a very high solubility in water.

The process of creating a polymer from its monomers is polymerisation. The example above is a condensation polymerisation, so called because a simple molecule (in this case water) is eliminated during the reaction. Addition polymerization occurs when unsaturated monomers combine together without the elimination of simple molecules. Polyethylene is an example of an addition polymer.

Step-growth polymerization happens when any pair of monomers might react and begin to form short chains, which, in turn, can react. Nylon is step-growth. Making nylon is an interesting and well-known practical demonstration and details for this can readily be found from other sources (see *References and further reading* on page 53).

Cross-linking is a means by which a polymer's molecular structure can be changed in order to give the polymer different properties. Cross-linking results in the creation of networks of molecules linked to each other by covalent bonds. The degree of cross-linking determines the final properties of the material. Slime is a good example of a partially cross-linked material (details of how to make and test slime can be found in the SEP book 'Go with the Flow' – see *References and further reading* on page 53), as are cosmetic materials such as hair gel. Chewing gum and 'potty putty' are also partially cross-linked polymers. The property that people enjoy with potty putty (and chewing gum) is the fact it flows easily when pulled gently or left on the table, but will break when pulled hard. This demonstrates the fact that the molecules are able to flow past each other slowly when subjected to a gentle force, but are not able to flow quickly and will 'break' when subjected to a sudden force.

Some examples of materials that contain cross-linked polymers.



Once cross-linked, the material cannot easily be changed as the cross-linking is irreversible. Rubber in car tyres was traditionally cross-linked by vulcanization (a chemical process involving exposing the rubber to sulphur). As this cross-linking cannot be reversed, there are considerable challenges in disposing of car tyres at the end of their useful life since they cannot be degraded. Some use is made of them mixed with tarmac to coat roads with a sound-absorbing surface but we are still faced with huge mountains of car tyres.

The name 'rubber' is widely used to describe all synthetic elastomers. The name is believed to have been given to this material by Joseph Priestly in England in 1770, who discovered that dried rubber latex rubbed out pencil marks.

Natural rubber latex is the sap of a rubber tree *Hevea brasiliensis*. It is an elastic hydrocarbon polymer (i.e. it consists mainly of carbon and hydrogen). Essentially it is a polymer of isoprene units creating polyisoprene with a molecular weight of 100,000 to 1,000,000. Synthetic rubber can be made by deliberate polymerisation of a variety of monomers to produce polymers.

Classroom activities

Students can make their own solid rubber from liquid rubber latex. If rubber latex is mixed with a weak acid such as lemon juice or vinegar it will cross-link. By simply adding the acid to a small quantity of liquid rubber latex and stirring, a solid lump of rubber will be produced. The weak acid makes the rubber cross-link: this means that covalent bonds form linking one polymer chain to another, causing the liquid rubber latex to become solid. Thus the solid form, being composed of a huge molecular network created by cross-linking, is an example of a thermoset.

See Activity A4:
Making a rubber ball
(page 37)

Rubber can be made from liquid rubber latex and a weak acid such as lemon juice (1). After mixing the acid with the latex, solid rubber is formed (2), which can then be dropped in water and moulded into a ball shape (3), before drying it on a cloth (4).



See Extension X1:
Making your own rubber eraser (page 45)

Having made the rubber ball, students can carry out an investigation into its elasticity by seeing how far it will bounce (see the next section *The properties of rubber*). Using a similar procedure, students can also make their own rubber eraser, and test how good it is at removing pencil marks from paper.

THE PROPERTIES OF RUBBER

Natural rubber is an elastomer. The word elastomer comes from two terms, *elastic* (which describes the ability of a material to return to its original shape when a load is removed) and *mer* (from polymer).

When a rubber ball hits the floor it feels a strong force (or stress). The stress causes the rubber to deform on impact (it flattens). It is the covalent cross-linkages that ensure that the rubber will return to its original shape when the stress is removed so that the ball bounces.

The elasticity of a rubber ball can be tested by comparing the height from which it is dropped with its bounce height.

See Activity A5:
Testing bounce
(page 38)



Classroom activities

Students can use a rubber ball that they have made themselves (see previous section) to compare the 'bounciness' of rubber with another polymer called 'polymorph' which can also be easily moulded into the shape of a ball. They can drop the rubber ball from a given height and measure the bounce height, and can repeat this across a range of different heights.

Polymorph is a thermoplastic material that softens and can be moulded at a relatively low temperature. It is supplied in the form of granules – when these are added to water at about 60 – 65 °C. The granules soften and stick together in a clump which can then be moulded into a shape by hand. Care needs to be taken to avoid scalding by ensuring that the water is not too hot (it is advisable to use a thermometer to monitor the temperature) and by drying the polymorph before moulding by hand. Once it has cooled, the 'bounciness' of the polymorph ball can be compared with that of the rubber ball.

Making polymorph: the granules soften when put into warm water (1), and can then be removed as a clump (2) and moulded by hand (3).



See Activity A6:

Make your own rubber band (page 40)

The elasticity of rubber can also be tested by making a rubber band and then measuring its extension when a force is applied. To make the rubber band, students dip the end of a pencil (or wider item) into rubber, then into water and finally into lemon juice before gently rolling it off the end of the pencil to form a ring.

Making a rubber band: a pencil is dipped into rubber latex (1). After putting into weak acid to make the rubber cross-link, and then into water, the rubber can be rolled off the pencil (2) to form a ring (3).



Measuring the extension of the rubber band against force.



Students can now test the elasticity of the rubber band by adding slotted masses and measuring how far it stretches. They can find out whether the rubber band obeys Hooke's Law, i.e. whether its extension is proportional to the applied force.

Heating a stretched rubber strip makes it contract. This seems odd as most materials expand when you heat them. Whether a material expands or contracts when it is heated depends upon the material's entropy. The entropy of a material is a measure of the organization or orderliness of the molecules. For molecules that are arranged in an orderly way, the material has a low entropy and when the molecules are disordered, the entropy is high.

When a material is heated, its entropy increases because its molecules move about more and so become more disordered. Rubber contains very long chain molecules. When rubber is heated, sections of the molecules move about more energetically and pull on neighbouring parts. As the middle of the molecule moves more it tends to pull on the nodes of the molecular network (the link points), which then move closer together causing the rubber strip to get shorter.

This can easily be demonstrated by hanging approximately 1kg from a thick elastic band and then heating the band using a hot air gun. The length of the stretched band should be noted initially. It will shrink by around 1 cm quite quickly when heated.

A stretched rubber band contracts when heated.



See Activity A7:
Making and testing foam rubber (page 42)

If rubber is cross-linked while carbon dioxide is bubbling through it, the rubber forms a foam with the gas bubbles set into the rubber. These make foam rubber more compressible than the solid form. Foam rubber is easily made by using a weak acid to cross-link the rubber as for making a rubber ball, but adding sodium bicarbonate to the mixture. This reacts with the acid to produce carbon dioxide. By creating a foam rubber pad and a flat rubber pad, a comparison can be made between the two to see the effect on the compressibility of incorporating the gas.

Foam rubber can be made from rubber latex, citric acid and sodium bicarbonate (1); when mixed together bubbles of carbon dioxide are produced (2). The properties of the foam rubber produced can be compared to a similar piece of rubber which has been produced without foaming (3).



OTHER PROPERTIES OF POLYMERS

Polymers can be designed to have pretty much any property you wish including flexibility, elasticity, toughness, stickiness, temperature sensitivity, light sensitivity, chemical sensitivity, electrical insulation, electrical conductivity, thermal insulation, shape memory, selective absorption, melting temperature, glass transition temperature, solubility in water or other solvents, and degradability.

Electrical insulators Polymers are well-known as electrical insulators. Their lack of mobile charge carriers ensures that no charge can flow under normal circumstance – though even the best electrical insulators can ‘break down’ under extremely high fields. The insulators surrounding underground electrical cables have to be very rigorously tested for breakdown strength as, should the cable insulation break down, it would blow a huge hole in the ground as the high voltage shorted to earth.

A balloon can be electrically charged by friction because it is a good electrical insulator.



One simple demonstration of the electrical insulation properties of polymers is charging a polymer by friction. Any polymer, such as a balloon, can be charged by friction (in the case of a balloon, by rubbing on a woollen jumper). As the balloon is an insulator, the charge does not flow away but remains on the balloon's surface. Putting the balloon against a neutral wall will result in it sticking as the charged balloon is attracted to the induced charges in the wall.

Electrical conductors Polymers are now being developed that can conduct electricity. One such polymer is polyaniline; although it was discovered in 1862, it has only just been recognised as a conducting polymer, as no-one had previously checked its conductivity! Conducting polymers are leading to RFID tags (Radio Frequency Identification tags) being applied to a whole host of products for a range of purposes. Instead of barcodes on food wrappers, there will be RFID tags which will carry the same information that a barcode carries today (or perhaps more). This means that checkouts in supermarkets will not need lasers to read the barcode but will read the RFID tags electronically.

Smart polymers Polymers are now being developed with ‘smart’ properties. Some are able to change colour with temperature. These are used for simple thermometers which are applied to a child's head to determine whether they have a fever, or can be built into mugs or even clothes so that they change colour with the temperature of their contents. Other smart polymers can be moulded when warm (thermoplastic) but will revert to a predetermined shape when reheated. An example of this is ‘shape memory polymer’ (see *Obtaining the practical resources* on page 55).

A strip of shape memory polymer composite has been warmed, twisted into a new shape and left to cool (left). When warmed again by dipping in hot water, it reverts to its original shape (right).



See Activity X2:

Why do plastic bags sound different? (page 46)

Classroom activities

Polyethylene has a range of properties, depending on whether it is high density or low density. These properties can be investigated and include sound, density, and melting point. The best material to demonstrate this is ordinary plastic carrier bags. Students can try to classify plastic bags by whether they are 'crackly sounding' or 'quiet' and then to compare the density of the two groups. Bags made from high density polyethylene are more 'crackly' than those from low density, as it is more crystalline (see the *Background science* section on page 48 for more information about the forms of polyethylene).

POLYMER PROPERTIES RELATED TO THEIR USES

Some polymers are hydrophobic or 'water-fearing', which means that water will not spread on their surface and they will not dissolve in water. A common example is polytetrafluoroethylene or PTFE, known commercially as Teflon™. This consists of long chains of carbon with two fluorine atoms bonded to each carbon atom. Replacing the fluorine atoms with hydrogen atoms creates polyethylene, which is likewise hydrophobic. If PTFE is drawn out into fibres, the result is a material with networks and voids such that water vapour can pass through but water droplets cannot. This is now exploited as a breathable fabric under the trade name of Gortex.

Polymers that absorb and dissolve in water are known as hydrophilic or 'water-loving'. Most hydrophilic polymers contain –OH (hydroxyl) groups along the length of the molecule. These groups form hydrogen bonds with water and are attracted to polar molecules.

Sodium polyacrylate is a hydrophilic polymer, and is used in a material known as a 'hydrogel'. The electric charge on the polymer enables it to hold even more water than neutral hydrophilic polymers. When the sodium counter ion is dissolved in water it is surrounded by several water molecules, and other water molecules are able to create hydrogen bonds with the polymer. There is still an attraction between the positive sodium ions and the negative polymer, and this attraction can be thought to be holding the whole structure together.

There is another kind of polymer material that can absorb not water but oil. Rather than being hydrophilic, this type of material is 'lyophilic' or 'oil-loving'. The material is a polymer gel that can absorb up to half of its own weight in oil. The gel is spread on the oil spill and forms a thick 'carpet' which is then rolled up and taken away. The oil can later be removed by reversing the absorption process. Two additional uses of this material may be in transporting drugs around the body and as a replacement for the silicone oil used in present-day breast implants.

See Activity A8:
What is a hydrogel?
(page 44)

Classroom activities

Students can test the claim that a given mass of a hydrogel is able to absorb its own mass of water. (In fact it can absorb several times its own mass.) Hydrogels are used in disposable nappies, and students could compare the absorbency of nappies from different suppliers.



Hydrogel is put into a petri dish (1) and water added until it can absorb no more (2). Weighing before and after shows that it can absorb several times its own mass.



POLYMERS AND THE ENVIRONMENT

Increasing attention is being paid to degradable and biodegradable polymers. A biodegradable polymer is, technically, one that degrades due to naturally occurring organisms. Degradable is more correctly applied to polymers that break down often due to environmental conditions. Although biodegradable polymers were first attempted in 1960's by adding starch to polyethylene (a constituent of many bags and packaging materials), they met with little success. Now polyethylene can be made to degrade through the inclusion of additives which result in chain scission under the action of light, heat or mechanical stresses. This is the cause of carrier bags becoming fragile and, finally, flakey. Alternatively it can be co-polymerised with starch. The starch will be consumed by microorganisms leaving voids in the structure and giving it a much larger surface area. This means it is more permeable to oxygen, which will ultimately weaken it. However the material still requires additives to make it degrade completely.

The final products of degradation are water and carbon dioxide plus a small amount of residue. Thus degradable or biodegradable polymers should not be seen as a good solution to the litter problem as they are still producing harmful greenhouse gases as they degrade.

Poly lactide is naturally biodegradable and is derived from renewable sources such as maize. It also consumes carbon dioxide during production and is completely recyclable and compostable. It can be used in food packaging and in the medical industry. However it is much more costly than non-degradable polymers, and tends to be more brittle and less flexible, so companies tend to prefer more established polymers at the moment. However if cost implications can be overcome and the mechanical properties can be improved this would seem an excellent way forward.

DESIGNER POLYMERS – EXAMPLES OF RECENT AND FUTURE DEVELOPMENTS

Synthetic polymeric materials have only been used for the last 100 years or so but have already had a massive technological impact. Indeed, take a look around – what is it that you can see that is not a polymer? Polymer fibres are used in many clothing applications, polymers as the basis of paints and coatings, polymer adhesives hold together many artefacts, and the casings for the vast majority of electrical items are made from plastic. In the vast majority of these instances though, the polymers are serving a rather mundane role: they are important in that they are cheap and adaptable and, thus far, that has been their major advantage.

However, this situation is changing. In the future, plastics won't just be the passive boxes that hold all the clever stuff in your computer display – they will be doing all the clever internal stuff as well. The rate of change in this area since the late 1970s has been enormous, and it is not possible at present to be certain of the future or to provide a comprehensive overview of current developments. Here though are some examples to illustrate how polymers are evolving from worthy engineering material to exciting stars that will make a whole new generation of technology possible.

Semiconducting or light-emitting polymers Recent developments in conducting polymers have led to semiconducting polymers, and light-emitting polymers (OLEDs). Flat screen televisions measuring only 3 mm in thickness, and even screens that are flexible and can be rolled up, are being developed using this technology. There are also proposals to replace all light bulbs with light-emitting polymers in homes and offices. These will be more efficient than low-energy light bulbs and will rarely need replacing.

Electro-active polymers (shape memory/actuators) More polymers are being developed that have an additional property – that of changing shape when an electric field is applied. The aim is to develop these as replacement muscles, particularly in prosthetic limbs or hands, so that amputees can control their limbs. Another polymer, poly(vinylidene fluoride) or PVF₂, is a piezoelectric material, generating a field across it when under pressure (or vice versa). It is being used in ultrasound transducers, microphones and sonar transducers.

Electret fibres for dusters and toys Electret fibres are polymeric fibres that can be woven into products such as carpets, dusters, and even stuffed toys. The charges on the fibres are unevenly distributed so that different parts of the fibre will attract small charged particles – such as dust! For a duster, this makes it more able to pick up and retain dust. For a carpet or a stuffed toy, the fibres trap and hold dust and allergens such as house dust mite, so that children with asthma are less likely to be affected by dust in the air.

Medical applications Polymers have a huge, and growing, range of uses in the medical field. Presently we use replacement plastic joints, veins, skin (for burns victims), lenses (for cataract sufferers) and heart valves. Slow-release drugs are impregnated in degradable polymers, while recently a fully functioning bladder was ‘grown’ from cells impregnated into a polymeric matrix for transplant. The vision for the future is to be able to grow fully functioning replacement livers and kidneys to remove the need for live donor organs. There is even the possibility of artificial blood to supplement real blood during transfusions.

Polystyrene shelters for disaster victims When a natural disaster causes people to lose their homes, one of the biggest problems is to provide cheap, quickly erected but robust shelters. A recent development has been to use expanded polystyrene shelters – these are easy to ship to refugees and simple to erect, and are robust and warm. Later, the polystyrene frame can be used as a base onto which concrete is applied to make the shelters longer lasting until proper housing can be created.

With this range of properties, the potential for new polymers remains unimaginable. Who knows what new polymers are just around the corner?

STUDENT ACTIVITIES

FANTASTIC PLASTIC

Teachers' notes

The student materials consist of a series of practical activities intended for use at KS4. The key ideas are:

- Polymers are composed of long chain molecules.
- Polymers can be divided into two groups: *thermoplastics* which deform when heated due the intermolecular bonds being relatively weak, and *thermosets* which do not change when heated due to being formed of a molecular network of much stronger covalent intermolecular bonds.
- Heating a thermoplastic provides the energy that allows it to change shape or flow.
- Polymers are composed of monomers that are then joined into long chain molecules by a process of polymerisation.
- Polymers in liquid form can be cross-linked to create a solid by the formation of covalent bonds, creating a huge molecular network or what is, in effect, one giant molecule.
- Natural rubber is an elastomer. The word elastomer comes from two terms, *elastic* (which describes the ability of a material to return to its original shape when a load is removed) and *mer* (from polymer).
- When a rubber ball hits the floor it feels a strong force (or stress). The stress causes the rubber to deform on impact (it flattens). Relaxation of the rubber to its natural shape results in thermal energy of the material being converted to kinetic energy.
- It is the covalent cross-linkages that ensure that the rubber will return to its original shape when the stress is removed so that the ball bounces.
- Adding gas to a polymer as it cross-links can incorporate bubbles into the structure which gives it the property of being compressible due to the spaces in the rubber.
- Different polymers have different properties, for example different densities of the same polymer will have different properties. This is what determines its potential uses.

Visit the SEP website www.sep.org.uk for supporting resources including image files and editable versions of the student sheets. See page 55 for information on obtaining the practical resources.

An overview of the activities

The activities are:

- **Activity A1** Can you cut a liquid?
- **Activity A2** Food wrappers party tricks
- **Activity A3** What's that polymer?
- **Activity A4** Making a rubber ball
- **Activity A5** Testing bounce
- **Activity A6** Make your own rubber band
- **Activity A7** Making and testing foam rubber
- **Activity A8** What is a hydrogel?

There are two extension activities:

- **Extension X1** Making your own rubber eraser
- **Extension X2** Why do plastic bags sound different?

Notes on the activities

Activity A1: Can you cut a liquid?

This activity is a teacher demonstration that introduces the idea of long chain molecules (see also page 9 of this booklet 'What is a polymer?').

LEARNING OBJECTIVES

Students will:

- observe how a polymer solution can be 'cut' when poured
- interpret the behaviour of the polymer in terms of its composition of long chain molecules.

NOTES

This is a useful demonstration that polymers are made of long chain molecules. Contrast the behaviour of this viscoelastic polymer liquid with a more typical liquid composed of small, individual molecules that can easily move past each other.

The polyox solution should be made up in advance. It is not recommended that students make up the solution themselves – or that they try cutting the liquid. This should be done as a demonstration by the teacher.

Only try to cut the liquid with the upper beaker held almost upright (not more than 30° to the vertical) and not leaning over as gravity will make it continue to pour and create a mess on the scissors. Pour the liquid from the side of the beaker (not the lip) to get a reasonable flow, return the beaker to an almost upright position then cut liquid sharply around 1 cm below the edge of the beaker. The liquid will visibly jump back in to the beaker. This takes practice!

N.B. This polymer is extremely slippery and great care should be taken when handling beakers if liquid has been spilled on the outside.

As an additional demonstration of long chain molecules, you could use drinks cans retainers (the type used to hold 4 cans together). Pull one 'loop' slowly by hand and note that the materials 'shreds' into strands. This can be seen easily by eye or can be placed on an old-fashioned OHP and projected. The shredding demonstrates the orientation of the molecules and that polymers are made of long chain molecules. The 'strings' that are drawn from the glue in a hot glue gun are also evidence of the long chain nature of polymers, as are the long strings that you can pull from chewing gum and from potty putty.

RESOURCES NEEDED

For the teacher demonstration:

- Approx 100 cm³ of polyox solution in 250 cm³ beaker
- Empty 250 cm³ beaker
- Scissors.

MAKING UP THE SOLUTION

The solution should be made in advance.

- 25 cm³ propan-2-ol (or other anhydrous alcohol, e.g. ethanol)
- 3 – 4 grams polyox [high molecular weight poly(ethylene oxide)]
- Stirring rod
- 2 x 600 cm³ beakers
- Colouring e.g. food colouring or fluorescein (optional but fun!).

Mix 25 cm³ alcohol with 3 – 4 grams polyox in a clean dry beaker. This is to disperse the powder, not to dissolve it. Add 350 – 400 cm³ tap water in one quick pour (as quickly as you can!) and stir until the polyox powder has dissolved. As you stir, the viscosity of the polymer solution will increase. Add colouring if required – food colouring or fluorescein.

The gel, once made, can be kept for many months in a watertight container. It will become thin after a while. Simply sprinkle some polyox powder onto the surface of the liquid, shake to disperse and wait 24 hours for it to dissolve and your liquid will be thick enough to cut again.

HEALTH AND SAFETY

Polyox: Avoid inhalation of dust and eye contact. Wear eye protection. If polyox powder enters the eye, immediately flush with water, continue washing for several minutes, and obtain medical attention.

Propan-2-ol: HIGHLY FLAMMABLE (keep well away from naked flames) and IRRITANT/HARMFUL (it is irritating to the eyes, and the vapour may cause drowsiness or dizziness).

There is no hazard from skin contact with polyox solid or the solution; if it comes into contact with hands (it feels very slippery) they should be washed with soap and water.

Activity A2: Food wrappers party tricks

This activity is a teacher demonstration that introduces the idea of thermoplastics compared with thermosets (see also page 11 of this booklet 'Thermoplastics and thermosets').

LEARNING OBJECTIVES

Students will:

- recognise that polymers can be divided into two groups: thermoplastics and thermosets
- explain how thermoplastics can deform (flow) when heated because of the relatively weak intermolecular bonds
- explain why thermosets do not change when heated due to being formed of a molecular network with much stronger covalent intermolecular bonds.

NOTES

This demonstrates that not all plastics shrivel up when heated as most students will predict. 'Moulded' plastic packaging (thermoplastics) such as that in a box of chocolates, around an Easter egg, holding items in place in a box, etc. has been thermoplastically formed by heating and stretching. Heating will cause the plastic to revert to its original form of a flat plastic sheet. Conversely thermosets do not react like this when heated.

CAUTION: Care should be taken when using a hot air gun - the gun and the plastics become very hot. Wear eye protection. If a hair drier or hot air gun is brought from home it will need to be electrically tested and its use in a school will not be indemnified by the manufacturer.

Thermoplastics:

Take any thermo-formed plastic packaging, put it in a clamp and heat using a high-power hair drier or hot air gun (paint stripper). The sheet will not shrivel but will flatten.

Alternatively take a plastic vending cup marked with PS on the bottom (polystyrene), put it in a clamp and direct the air from a hair drier or hot air gun into the cup. It will revert to its original flattened form.

Thermosets:

To demonstrate this, the only way is to show nothing happens when it is heated. For example, take a polythene rod, heat it with a hair drier or hot air gun to soften and bend it by hanging weights on the end. Allow it to cool to set it – it is a thermoplastic. Do the same with epoxy rod – nothing happens. It does not soften or bend.

RESOURCES NEEDED

For the teacher demonstration:

- Collection of 'vacuum formed' plastic packaging (sometime called blister packaging)
- Polystyrene cup (not expanded polystyrene)
- Polythene rod
- Epoxy rod
- High-power hair drier or hot air gun
- Clamp stand, bosshead and clamp to hold objects
- Set of slotted masses.

Activity A3: What's that polymer?

Students look at a number of objects made from polymers that illustrates the range of properties (see also page 9 of this booklet 'What is a polymer?').

LEARNING OBJECTIVE

Students will:

- recognise that polymers can have a range of properties and that these are related to their uses.

NOTES

Polystyrene has a range of properties depending upon the way it is processed. In Task A students will observe the properties and how they relate to the uses of the product.

The properties of different polymers are related to the length of the constituent hydrocarbon chain – for example the range from candle wax to Tupperware to gas mains pipe. In Task B students will observe how these items differ.

RESOURCES NEEDED

TASK A

Students need access to a range of objects made from polystyrene:

- Ceiling tile
- Drinking cup – expanded polystyrene
- Plastic drinking cup marked PS on bottom
- Clear plastic box (e.g. Ferrero Rocher)
- Egg carton
- Packaging pieces (to pack around fragile items)
- Any other item marked with PS on the bottom.

TASK B

Students need access to a range of objects made from polymers of different chain lengths:

- Candle
- Tupperware container
- Gas mains pipe.

Activity A4: Making a rubber ball

Students use liquid rubber latex to see how simple cross-linking of liquid polymers can create a solid (see also page 13 of this booklet 'How do you make a polymer?').

LEARNING OBJECTIVES

Students will:

- carry out a procedure to create a solid rubber object from liquid rubber latex
- interpret the change in terms of cross-linking of the polymer in liquid form to produce a solid by the formation of covalent bonds, creating a huge molecular network

NOTES

Students should wear vinyl gloves when handling wet rubber latex and making the round ball shape. See the section on 'Health and Safety' for this activity. Note that the technique used for rolling plasticine into a ball doesn't work for the rubber ball – it has to be *squeezed*. After forming the ball and dropping into water, it should be dried using a fabric cloth (paper towels will stick to the rubber ball).

HEALTH AND SAFETY

Rubber latex solution may cause a skin allergy for some students, so skin contact should be avoided; eye protection and vinyl gloves should be worn when handling it. Once fully cross-linked it is unlikely that there will be an allergic response, so the solidified rubber can be handled normally unless a student is particularly sensitive to latex.

The rubber latex solution contains approximately 0.5% ammonia (similar to the proportion in Copydex), and care should be taken not to inhale the fumes. In case of contact with eyes, flush with copious clean water. If swallowed, drink plenty of water. In both cases immediate medical attention should be sought to ensure no ill after effects.

RESOURCES NEEDED

Each group will need:

- Rubber latex solution
- Lemon juice or vinegar
- Small container (plastic vending cup size)
- Stirrer – ideally wooden or metal, not glass
- Vinyl protective gloves – 1 per student is sufficient
- Eye protection
- Cotton cloth to dry ball
- Access to a large bowl of cold water in which to rinse the ball (groups of 6 can share).

Activity A5: Testing bounce

Students use balls made of different materials to explore the elastic behaviour of different polymers (see also page 15 of this booklet 'The properties of rubber').

LEARNING OBJECTIVES

Students will:

- recognise that natural rubber is an elastomer
- plan a test to measure the elastic behaviour of a rubber ball
- compare a rubber ball with another ball made from a less elastic material.

NOTES

In Task A, students will need to use the balls that they have made in Activity A4. It uses the well-established technique of dropping the ball from a measured height and noting the height to which it bounces. (Note that it may be difficult to control where the ball bounces as it may not be very round.) There is added interest as students may compete to see whose ball bounces best!

In Task B, students make a ball from polymorph. This is moulded by hand after warming in hot water (temperature about 62 °C). Care has to be taken that students do not handle the polymorph when it is too hot. See the section on 'Health and Safety' for this activity. Polymorph can be moulded into many shapes after heating (it doesn't have to remain above 62 °C). Ask students to mould it into a ball of the same size as their rubber ball and test it in the same way. It will not bounce as readily as the rubber.

In Tasks C and D, students compare the bounce of the polymorph ball with the rubber ball. Students could go on to calculate percentage efficiency of bounce at each of the different drop heights.

RESOURCES NEEDED

Each group will need:

- Rubber ball from Activity A4
- Metre rule
- Clamp stand, bosshead and clamp
- Beaker of hot water (approx. 65 °C)
- Polymorph crystals
- Tongs
- Fabric towel.

HEALTH AND SAFETY

Polymorph should be heated using water in the range 60 – 65 °C, and it is recommended that the water temperature is monitored with a thermometer. Water at this temperature can cause scalding, and using water above this temperature will present an even greater scalding hazard. Polymorph is very warm when removed from the hot water so care should be taken when handling. To avoid direct contact with the hot polymorph and water, it should be dried on a fabric towel before moulding.

Activity A6: Make your own rubber band

Students make a rubber band from liquid rubber latex to investigate its elastic behaviour (see also page 13 of this booklet 'How do you make a polymer?').

LEARNING OBJECTIVES

Students will:

- carry out a procedure to create a rubber band from liquid rubber latex
- interpret the change in terms of cross-linking of the polymer
- plan a test to measure how the extension of the rubber band varies with the force applied.

NOTES

This is similar to making the rubber ball in Activity A4, but allows the band to be tested afterwards to demonstrate Hooke's Law or simply the concept of elasticity.

The procedure for making the rubber band is relatively quick, so the beakers of materials could be shared by several groups.

Students could also remove masses one by one and record and plot extension for each load back to zero. The activity can also be extended by testing rubber bands made of different diameters by using wider supports such as the neck of glass bottles.

RESOURCES NEEDED

Each group will need:

- Round pencil (pencils with angular shapes do not coat well)
- Metre rule
- Clamp stand, boss head and clamp
- Set of slotted masses (10 g).

Each group will need access to:

- Beaker of rubber latex solution 5 cm deep
- Beaker of citric acid solution (lemon juice) 5 cm deep
- Beaker of cold water more than 5 cm deep
- Large empty beaker to stand pencils in for drying.

HEALTH AND SAFETY

See the notes for Activity A4 for information on how to handle liquid rubber latex.

Activity A7: Making and testing foam rubber

Students make samples of foam rubber and compare their properties (see also page 15 of this booklet 'The properties of rubber').

LEARNING OBJECTIVES

Students will:

- carry out a procedure to make solid rubber and foam rubber from liquid rubber latex
- compare the different properties of foam rubber and solid rubber due to the air pockets in the foam.

NOTES

In this activity students make another kind of object from liquid rubber latex; the reaction between the citric acid and sodium bicarbonate in the mixture produces carbon dioxide which creates foam rubber. This is compared with a block rubber sheet. As an additional activity, students could vary the amount of citric acid and sodium bicarbonate to create sample with different properties.

RESOURCES NEEDED

Each group will need:

- Rubber latex solution
- Citric acid powder
- Sodium bicarbonate powder
- Stirrer
- 2 x small container (plastic vending cup size)
- Vinyl protective gloves.

HEALTH AND SAFETY

See the notes for Activity A4 for information on how to handle liquid rubber latex.

Activity A8: What is a hydrogel?

Students test the properties of a hydrogel (see also page 20 of this booklet 'Polymer properties related to their uses').

LEARNING OBJECTIVES

Students will:

- recognise that hydrogels are polymer gels that can absorb huge quantities of fluid
- find out how much water can be absorbed by a hydrogel.

NOTES

Students measure a specified quantity of hydrogel into a dish and then add water until it is no longer possible to get more water to be absorbed. Weighing the product and subtracting the initial mass will give the mass of water absorbed to test the claim that the gel can absorb its own mass of water. In fact it can absorb several times its own mass.

Hydrogel is safe to handle but students should wear eye protection and be asked to wash their hands as a matter of good practice after handling chemicals.

RESOURCES NEEDED

Each group will need:

- 2g hydrogel crystals
- 10 cm diameter petri dish
- Dropping pipette
- Access to scales.

Extension X1: Making your own rubber eraser

Students use liquid rubber latex to see how simple cross-linking of liquid polymers can create a solid (see also page 13 of this booklet 'How do you make a polymer?').

LEARNING OBJECTIVES

Students will:

- carry out a procedure to create a solid rubber object from liquid rubber latex
- interpret the change in terms of cross-linking of the polymer in liquid form to produce a solid by the formation of covalent bonds, creating a huge molecular network.

NOTES

This activity uses the same procedure as in Activity A4, but this time the rubber is moulded into a chosen shape for a pencil eraser. It should be left to cure until it is a dark yellow and totally dry, and can then be tested by rubbing out pencil marks.

RESOURCES NEEDED

The resources required are the same as those for Activity A4.

HEALTH AND SAFETY

See the notes for Activity A4 for information on how to handle liquid rubber latex.

Extension X2: Why do plastic bags sound different?

Students compare the properties of high density or low density polyethylene, and the activity provides a useful opportunity for student to devise their own procedures (see also page 20 of this booklet 'Polymer properties related to their uses').

LEARNING OBJECTIVE

Students will:

- recognise some of the differences in properties between low density and high density polythene.

NOTES

In Task A, students crumple the bags to see differences in the sound made and separate into 'crackly sounding' and 'quiet'. They then need to measure the density of samples from each to see if crackly is higher or lower density. There are two simple approaches that can be used:

- measure the volume and mass of bag directly and calculate
- measure volume by displacement of water (brings in some challenges!).

The exercise offers considerable challenge to obtain accurate results as densities range from 0.92 – 0.98 g/cm³.

Task B is a teacher demonstration of another difference in properties that density makes. Take a block of material, use a temperature probe and melt the polymer (until clear) on a hot plate. The melting point of low density polythene is 100 °C, whereas for high density it is 130 °C. (CAUTION: Heated polymer will melt.

Care should be taken when applying the tip of the thermometer, not to touch the melting polymer with your hands.)

RESOURCES NEEDED

Each group will need:

- Collection of plastic bags from different companies
- A means of measuring the volume of the bags – by actual measurement of dimensions or using a displacement can
- Scales.

STUDENT SHEETS

FANTASTIC PLASTIC

FANTASTIC PLASTIC: CAN YOU CUT A LIQUID?

Polymers can be in solid or liquid form. You will observe a solution of a polymer (called 'polyox') to see whether its properties are the same as other liquids.

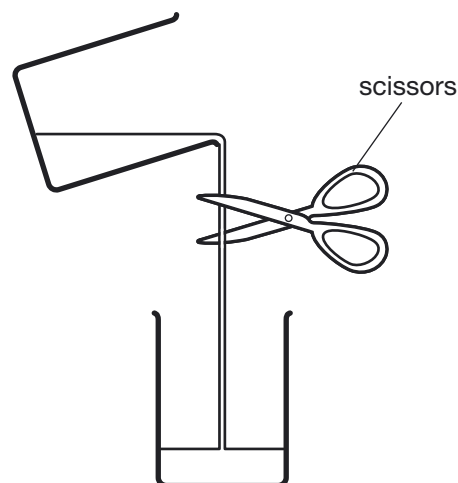
Teacher demonstration

Your teacher will demonstrate an experiment to show the difference between a polymer solution and other liquids. The polymer solution is poured from one beaker to another, and then scissors are used to try to 'cut' the solution.

1. What do you see happen when your teacher pours the polymer solution?
2. What do you see when your teacher uses the scissors?
3. What happens if you try to cut pouring water?
4. Why do you think you can't cut pouring water? Use the idea of a liquid being made of lots of separate molecules to help your explanation.
5. Why do you think the polymer solution behaves differently from water when you try to cut it? Use the idea of long chain molecules to help your explanation.



Wear eye protection. Avoid touching the polymer solution. If you get the solution onto your hands, wash them thoroughly.



FANTASTIC PLASTIC: FOOD WRAPPERS PARTY TRICKS

The inserts in boxes of chocolates that keep the chocolates in place are made of polymers. So are the inserts in other food packaging. Plastic vending cups are made of polystyrene, another polymer. These materials show a very unusual behaviour when heated.

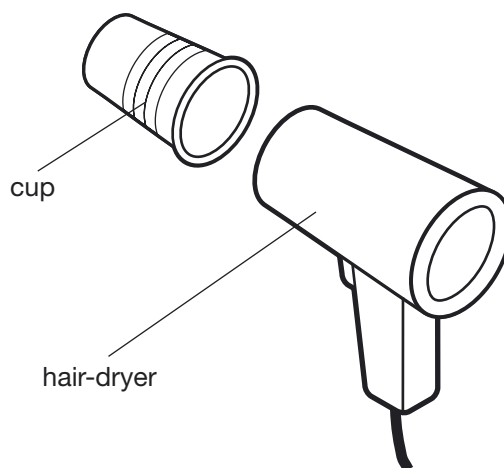
Teacher demonstration

Your teacher will demonstrate an experiment to show what happens when some polymers are heated.

1. What do you see happen when your teacher heats up the insert from a box of chocolates?
2. What do you see when your teacher heats up a vending cup?
3. What do you see happen when your teacher heats up the polyethene rod and the epoxy rod?
4. Some polymers are called thermoplastics. Which polymers have you seen in this experiment that are thermoplastics?
5. Polymers that don't react to heat like thermoplastics are called thermosets. Why do you think that thermosets behave differently from thermoplastics when they are heated? Use the idea of strong bonds between molecules to help your explanation.



Do not touch the hot air gun, the hot plate or the heated plastic.



FANTASTIC PLASTIC: WHAT'S THAT POLYMER?

Different polymers have different properties. And sometimes one polymer can have different properties depending on how it is processed. It is important that the right properties are chosen so that the object performs properly – imagine a cup that melts when you pour tea or coffee into it!

For this activity you will need to observe the materials in two different groups of objects.

Task A

Different ways of using polystyrene

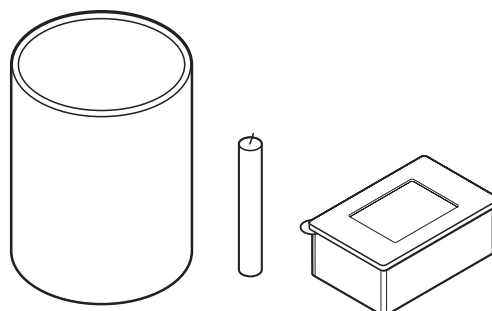
1. Look at each object in the first group in turn. Decide what it has to do and what properties the polymer has that makes it able to do the job.
2. Make a table that shows the job of the polymer and which properties are most important when choosing the polymer – for example melting point, hardness, brittleness, flexibility, insulation, density, cost, etc.

Task B

Properties and molecular chain length

To compare the properties of the materials, you will need to make each sample into a cylinder of approximately the same size.

3. Look at each object in the second group in turn. Decide how they are different from each other.
4. Try to use the idea of different molecular chain lengths to explain why these items have different properties.

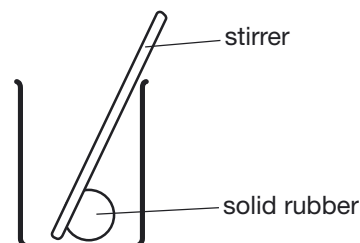
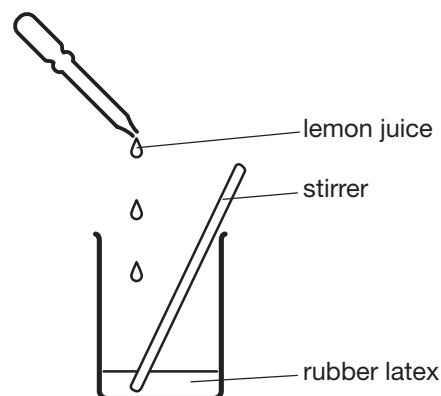


FANTASTIC PLASTIC: MAKING A RUBBER BALL

Rubber is a natural polymer – it is the sap of the rubber tree and it bleeds out of the tree as a white liquid when the bark of the tree is cut. This activity shows you how this simply natural polymer can be cross-linked to make it solid.



Some people have allergic reactions to liquid rubber latex. Wear protective gloves to avoid touching the liquid rubber, and wear eye protection. Do not inhale the fumes, which contain ammonia.



1. Pour 5 cm³ rubber latex solution into small container such as a plastic cup or a small beaker.
2. Add a squirt of lemon juice or vinegar.
3. Stir to mix.
4. Rubber will solidify and begin to stick to the stirrer. Add more lemon juice or vinegar if some liquid rubber remains in the container.
5. Keep stirring until the rubber has completely solidified and is completely stuck to the stirrer.
6. Drop the solid rubber into the water and squeeze with your gloved hand to make it into a round ball shape. This isn't easy and you have to do this quickly if you want a round ball.
7. Dry the ball using a fabric cloth (not a paper towel).
8. Check that the ball bounces. Keep the ball safe – you will need it for a later activity.
9. Why do you think that the liquid becomes solid when you add the weak acid?

FANTASTIC PLASTIC: TESTING BOUNCE

Many solid polymers are bouncy. Here you can test two different bouncy balls to see if they are the same. You will start by using the rubber ball you made in activity A4. Then you will make a ball from a different polymer called polymorph.

Task A

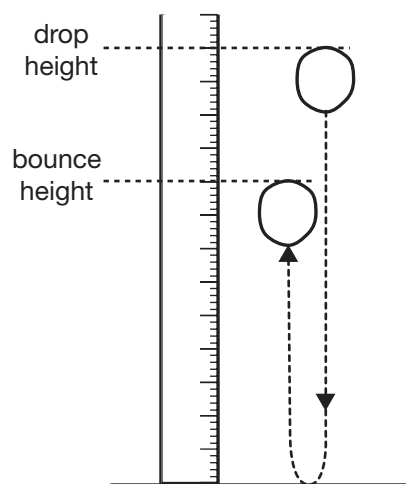
Testing your rubber ball – how high does it bounce?

1. Support a metre rule vertically on the floor using a clamp and retort stand.
2. Try dropping the ball and see how easy it is to measure the height to which it bounces.
3. Choose a sensible drop height and use the rule to measure the height from which you will drop the ball accurately.
4. Allow the ball to fall then note height to which it bounces. You may have problems with the balls not bouncing vertically. You need to think carefully how you will solve this problem. It will be difficult to measure the bounce height accurately and you may have to try several times before you get an accurate measurement.
5. Measure the bounce height accurately 3 times and take the average.

Task B

Making a ball from a different polymer (polymorph)

6. Make another ball using 'polymorph'. To do this, drop some polymorph beads into warm water (at about 62 °C).
7. The beads will begin to soften and stick together. Lift them out of the water using tongs, and dry with a fabric towel.
8. When the polymorph is cool enough to handle, mould it into a ball making it the same size as your rubber ball.



The polymorph will be very warm when it is first taken out of the hot water. Take care when you handle it. Do not handle until it is comfortable to hold it without feeling your hands are getting hot.

FANTASTIC PLASTIC: TESTING BOUNCE

Task C

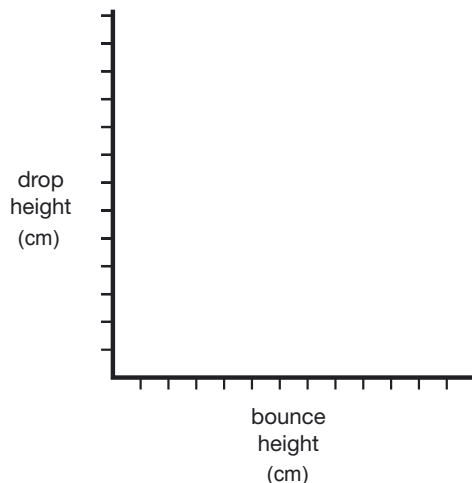
Comparing the two balls

9. Test the bounce of the polymorph ball in the same way as you tested your rubber ball.
10. Which ball bounces higher?
11. Why do you think one ball bounces higher than the other? Use the idea of energy transfers to help your explanation.

Task D

Going further

12. For each ball, change the drop height and measure the bounce height three times again. Take the average.
13. Repeat this until you have measured the bounce height for 5 different drop heights.
14. Draw a graph for each ball (on the same axes) to show the relationship between drop height and bounce height.
15. How do the two materials compare for bounciness? Is one material always better than the other for all drop heights?
16. Is polymorph a thermoset or a thermoplastic? How can you tell?
17. Is rubber a thermoset or a thermoplastic? How can you tell?



FANTASTIC PLASTIC: MAKE YOUR OWN RUBBER BAND

We take rubber bands for granted. In this activity you can make your own rubber band from liquid rubber and also test it for stretchiness.

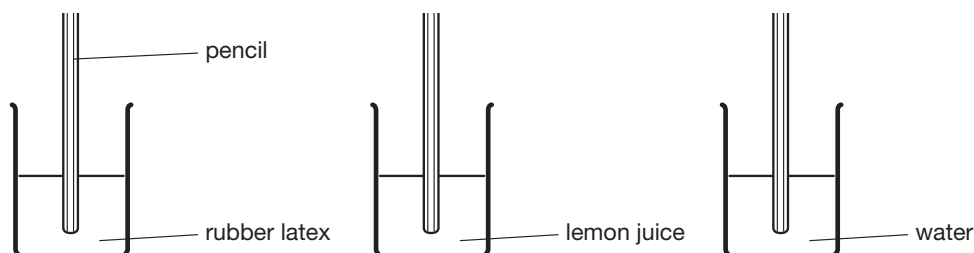


Some people have allergic reactions to liquid rubber latex. Wear protective gloves to avoid touching the liquid rubber, and wear eye protection. Do not inhale the fumes, which contain ammonia.

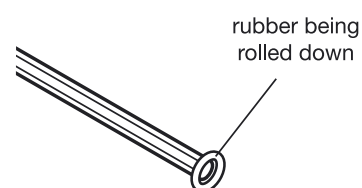
Task A

Making the rubber band

1. Dip the blunt end of your pencil into the rubber latex to a depth of 5 cm (no more!).

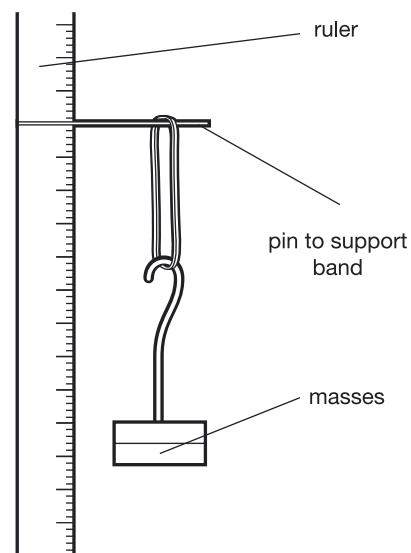


2. Remove your pencil – do not touch the rubber latex film.
3. Dip your pencil coated in rubber into lemon juice so that the rubber latex is covered.
4. Dip your pencil into cold water so that the rubber latex is covered.
5. Leave the rubber latex coating to dry for at least 10 minutes.
6. Roll the rubber coating off the pencil carefully forming a rubber ring – your rubber band. It's very easy to break the rubber band as you roll it off your pencil. You may have to practise this a few times before it works.
7. To make a larger diameter band, use a thicker cylinder, such as the neck of a glass bottle.



FANTASTIC PLASTIC:**MAKE YOUR OWN RUBBER BAND****Task B****Testing your rubber band**

8. Hang the rubber band from a retort stand.
9. Hang masses of a few grams onto the band and measure the extension.
10. Plot a graph of extension (mm) against weight (N).
11. Does the rubber band stretch uniformly?
12. Does a wide diameter rubber band hold more weight than a small diameter rubber band?
13. Does a longer rubber band stretch more than a shorter one?



FANTASTIC PLASTIC: MAKING AND TESTING FOAM RUBBER

Foam rubber is made by trapping bubbles of gas in the rubber as the rubber latex cross-links and becomes solid. Here you will make your own foam rubber and test it for 'squashiness' compared with ordinary rubber.

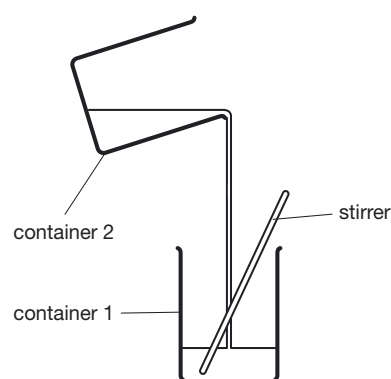
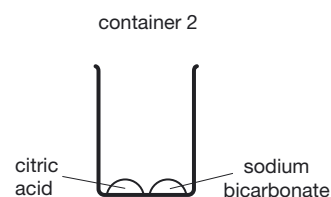
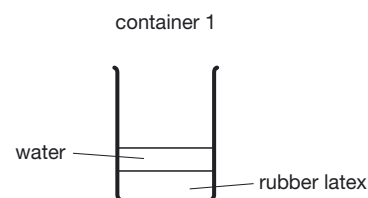
Task A

Making your foam rubber

1. Pour 10 cm³ rubber latex solution into a container such as a small beaker or plastic cup. Make sure the container has a small diameter base (less than 5 cm).
2. Add 10 cm³ water to the rubber latex solution.
3. In another container put 1 spatula of sodium bicarbonate powder.
4. Add 1 spatula of powdered citric acid to the sodium bicarbonate powder and mix well.
5. Pour the sodium bicarbonate powder/citric acid powder mix into rubber latex solution and stir quickly to mix then leave it to foam.
6. When it has finished foaming, drop the foam rubber cushion into water to wash it.
7. Leave the foam rubber cushion for 30 minutes to dry and harden before using it.



Some people have allergic reactions to liquid rubber latex. Wear protective gloves to avoid touching the liquid rubber, and wear eye protection. Do not inhale the fumes, which contain ammonia.



FANTASTIC PLASTIC:

MAKING AND TESTING FOAM RUBBER

Task B

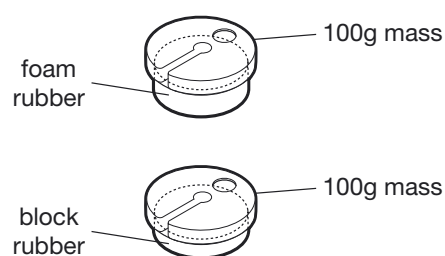
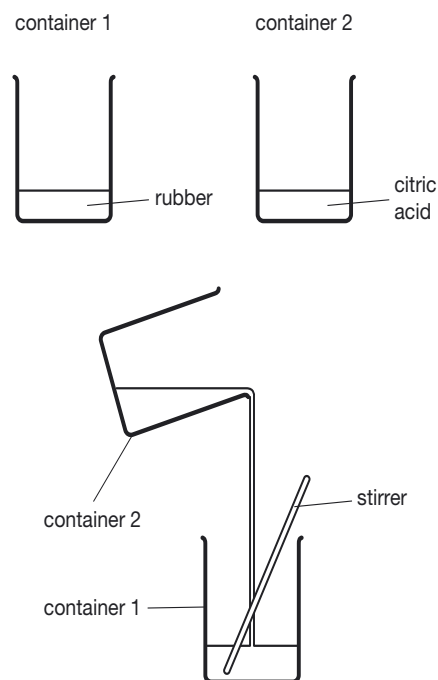
Making a block rubber sheet

8. Pour 10 cm³ rubber into the 5 cm diameter base container.
9. Mix 1 spatula citric acid powder with 10 cm³ water to make citric acid solution.
10. Pour the citric acid solution into the rubber latex solution and stir to mix. The rubber latex will cross-link and form a solid in the bottom of the container.
11. Wash the solid rubber in water and leave for 30 minutes to dry thoroughly before testing.

Task C

Comparing your rubber samples

12. Measure the thickness of the two samples.
13. Place a 100 g mass on the top of each sample and measure the thickness of the sample by measuring the distance between the bench and the 100 g mass.
14. Increase the mass and measure the thickness of the sample each time.
15. How much force does it require to squash the foam rubber to the same thickness as the solid rubber?



FANTASTIC PLASTIC: WHAT IS A HYDROGEL?

Hydrogels are special polymers that are supposed to be able to absorb more than their own mass of liquid. Here you will test if this is true and just how much they can absorb.



Wear eye protection. The hydrogel is safe to handle but wash your hands after handling and before eating.

1. Weigh 2 g hydrogel in a large petri dish.
2. Add water gently using a pipette, making sure it is totally absorbed by the polymer.
3. As you get to the limit of the polymer's absorption, you will find it takes longer and longer for the water to be absorbed.
4. When you are sure you are at the limit of the hydrogel's absorption, weigh the petri dish and its contents to work out how much water was absorbed.
5. Is it true that the hydrogel can absorb more than its own mass of water?

These hydrogels are used in disposable baby's nappies to keep the baby dry. There are also hydrogels designed to absorb oil when an oil tanker crashes and spills its oil into the sea. And there are hydrogels that absorb toxic chemicals that can be spilt onto the road if there's an accident with a truck carrying chemicals on the motorway.

FANTASTIC PLASTIC: MAKING YOUR OWN RUBBER ERASER

We use rubber erasers all the time but don't stop to think how they are made or how they work. Here you will make your own eraser and test it.

1. Put 10 cm³ rubber latex into a cup.
2. Add a squirt of lemon juice and stir.
3. Drop the solid rubber into clean water and mould into the shape you want for your eraser.
4. Dry using a towel.
5. Allow to dry thoroughly by leaving it for at least 30 minutes in a warm place. It may be a good idea to leave it to dry overnight. You will know that it is thoroughly dry as it will appear a much darker yellow than when it is newly made.
6. Test your new eraser by making some pencil marks on paper and trying to rub them out.
7. What do you notice about the way that an eraser removes the pencil marks? A pencil mark is a line of graphite sticking to the paper. Where does it go when you rub it out?



Some people have allergic reactions to liquid rubber latex. Wear protective gloves to avoid touching the liquid rubber, and wear eye protection. Do not inhale the fumes, which contain ammonia.



FANTASTIC PLASTIC: WHY DO PLASTIC BAGS SOUND DIFFERENT?

We use thousands of plastic bags each day. Most of them are made of a polymer called polyethylene.

Here you will find out why some plastic bags seem different from others, even though they are made from the same material.

Task A

Sorting out the plastic bags

1. Take a range of plastic bags from different companies. Crumple them to see the different sounds they make. Separate them into two groups – the 'crackly' ones and the 'quiet' ones.
2. Some bags are made out of high density polyethylene. Others are made out of low density polyethylene. High density polyethylene has very different properties from low density polyethylene.
3. Work out how to measure the density of two very different plastic bags to see if high density polyethylene makes bags that are crackly or quiet.
4. How can you be sure your method was accurate? What can you do to make it more accurate?

Task B

Teacher demonstration: melting polythene

5. Your teacher will use a high density polyethylene sample and a low density polyethylene sample, heat each one up on a hot plate and take the temperature when it melts.
6. Which one do you think will melt at the lower temperature?



Do not get close to the hot plate to avoid burns to the skin.

BACKGROUND SCIENCE

FANTASTIC PLASTIC

BACKGROUND SCIENCE

This section gives further information about the nature of polymers, their molecular structure and macroscopic properties, and their future development and applications.

NATURE OF POLYMERS

Chemically, the building blocks, or *monomers*, from which polymers are made can be extremely simple, and possibly the most simple of all is polyethylene, where the repeat unit in the idealised chain is just $-\text{CH}_2-\text{CH}_2-$. Since all the repeat units are the same, such a material is termed a *homopolymer*.

Most synthetic polymers are relatively simple molecules. Indeed, many important materials are simple variants on the polyethylene structure and can be thought of simply as $-\text{CH}_2-\text{CHR}-$; that is, where one of the hydrogen atoms has been replaced by a chemical group designated R. When $\text{R} = \text{CH}_3$ then the resulting polymer is polypropylene, currently the second most important bulk commodity polymer after polyethylene.

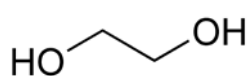
Copolymerisation is a widely used method for producing materials with desirable properties from existing monomers. If a molecule contains two repeating units, A and B, with the molecular backbone consisting of a simple random sequence of A and B units, then the resulting polymer will be a *random copolymer*.

Alternatively, the A and B units may be arranged in blocks; a block of A units followed by a block of B units would be termed a *diblock copolymer* while a block of A followed by a block of B followed by a block of A is a *triblock copolymer*. Both of these molecular architectures would be linear molecules.

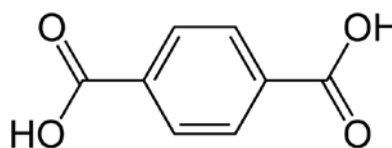
Another structure is where short A blocks are attached to a long backbone of B units to give a *graft copolymer*; in this case, the molecule would be a highly branched structure. Finally, the A and B units could alternate along each molecule to give an *alternating copolymer*. Such a structure can also be thought of a homopolymer in which the repeat unit takes the form AB. Although this may appear as mere semantics, many technologically important materials are prepared by reacting together two different chemicals in exactly this way to produce long chain molecules. Poly(ethylene terephthalate) (PET) is produced by a reaction between ethylene glycol and terephthalic acid to produce a polymer which is widely used in packaging applications, such as drinks bottles, and as fibres.

Synthesis

The preceding section has described a range of different molecular forms as being polymeric but what is it that they all have in common? PET constitutes a good example of the concept of *functionality*: the ethylene glycol molecule contains an hydroxyl group at each end, both of which are capable of reacting; the terephthalic acid molecule contains a carboxylic acid group at each end, both of which are, again, capable of reacting. Thus, when a molecule of ethylene glycol reacts with a molecule of terephthalic acid, the product still contains reactive sites at both ends and can go on to react further. In this case, each constituent contains two reactive sites or functional groups, such that they are termed *bifunctional*.



ethylene glycol



terephthalic acid

If such reactions were to continue the result would be a long linear structure. If, however, we were to introduce just a few addition species that contained three rather than two functional groups then the result would be branched, rather than purely linear molecules. As we increase the average functionality of the monomers, so the tendency for branching increases until at some point the result will be a network. An example of this type of reaction, which involves many *polyfunctional* monomers, is the curing reaction of an epoxy resin – once the network has formed the initially liquid resin becomes solid.

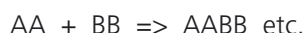
How many is ‘many’?

This question is difficult since there is no absolute answer. Rather, it depends on what property or characteristic is of interest. For example, one of the important characteristics that defines the behaviour of a molten polymer is the tendency for molecules to become entangled with one another, a phenomenon that dramatically affects the flow characteristics, or mechanical properties of the melt. Below a critical point, termed the *entanglement molecular weight*, the viscosity of the material only increases slowly as the molecules get longer; above this critical threshold, the viscosity increases dramatically as the system becomes increasingly entangled as the molecules get longer.

The most important ‘bulk commodity’ polymers – polyethylene and polypropylene – are both materials that include a significant crystalline fraction (40-90%). These crystals contain molecules which, in the ideal case, repeatedly fold back upon themselves. This is characteristic of polymers and, therefore, one can argue this tendency to fold defines a polymer; in polyethylene, the onset of *chainfolding* occurs for chains containing more than about 150 carbon atoms. Systems which do not exhibit polymeric characteristics such as those examples described above are commonly termed *oligomers*.

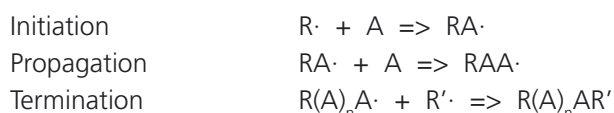
Condensation reactions and addition reactions

Condensation or, more correctly, *step-growth polymerisation reactions*, are characterized by the random reaction of functional groups within the system. Such reactions are exploited in the formation of, for example, polyamides (e.g. Nylon), which are produced by reacting equal molar quantities of a diamine and a dicarboxylic acid, that is two bifunctional monomers. This can be represented:



where A and B represent the functional groups on each of the molecules. Initially all the molecules in the system will either be AA or BB but, after the first reaction occurs, there will, additionally, be just one AABB molecule. The probability will therefore be that the next reaction will be as shown above. In other words, it will probably not involve AABB. Thus this type of process does not tend to result in the early production of long molecules. After the reaction is complete there will be a distribution of molecules that vary statistically with respect to their length. As discussed above, polymeric characteristics are strongly dependent on molecular length. Will the resulting material behave like a polymer? This will depend on the precise nature of the length distribution we have produced.

Addition reactions involve three distinct steps and, as such, differ fundamentally from the process described above in which all functional groups are equivalent. Addition reactions progress as additional monomers attach themselves to the existing polymer chain. The initial creation of polyethylene (an addition polymer) at ICI on 27th March 1933 was followed by much activity attempting to reproduce this feat, but with limited success. The key to the process was the inclusion of the correct amount of oxygen in the reaction vessel: at the high pressures and high temperatures initially used, oxygen serves as an initiator for a rapid chain reaction between ethylene monomers involving *free radicals* (i.e. a neutral species containing unpaired electrons – effectively, half of a covalent bond). This continues until the radical is destroyed or transferred to some other molecule.



Because each propagation step occurs rapidly, this process results in the rapid growth of long molecules, but the termination process is still a random event and, therefore, the result is again a material that contains a range of molecular lengths.

Attempts to control the polymerisation process more closely resulted in the development of alternative approaches. In the 1950s Ziegler, Natta and others developed catalysts that enabled many other polymer types to be produced. In the late 1980s so called metallocene catalysts were developed which offer far greater control of molecular architectures than was possible previously. The full implication and possibilities of this are, as yet, not fully explored.

Variations in structure

Polymer molecules are structurally complex beasts. In general, a sample of polymer will contain a variety of molecular forms which may differ from one another in terms of:

- molecular length
- number of branches or side groups
- length of branches
- distance between branches or side groups
- average number of branches or side groups per molecule.

All of these can apply even to one single material – say, polyethylene. Therefore it is critically important when thinking of polyethylene that this variability is remembered. Polyethylene A and polyethylene B may both be labelled polyethylene, in the same way that both Edam and Gorgonzola will both be found under ‘cheese’ in the supermarket. Edam and Gorgonzola are very different; polyethylene A and polyethylene B may also be!

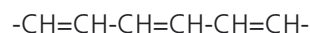
MOLECULAR STRUCTURE AND MACROSCOPIC PROPERTIES

The macroscopic properties of engineering plastics depend upon many factors. However, of these, the most important are:

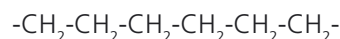
- the physical and chemical properties of the constituent monomers
- the way in which the monomers are joined together.

Monomer chemistry

Many of the fundamental characteristics of a material are determined at the monomer level. For example poly(vinyl acetate) is soluble in water because the acetate groups give considerable scope for hydrogen bonding. Polyacetylene is produced by the polymerisation of $\text{CH}\equiv\text{CH}$ and has a molecular structure that, in one dimension, can be represented:



That is, the molecular backbone contains alternating carbon-carbon double and single bonds. However, in practice, the extra electrons in the double bonds are not confined as shown in the above diagram but rather, are delocalised along the complete chain. Consequently, this material is a good conductor of electricity and, when suitably processed, can exhibit electrical conductivities comparable with the best metallic conductors, such as copper and silver. Conversely, the polyethylene backbone is composed of a simple sequence of carbon-carbon single bonds and, therefore, does not have the extra electrons in the backbone to render it conducting; these electrons are involved instead in bonding with the extra hydrogen atoms.



Molecular architecture

The properties of polymers are not just determined by the monomer units; properties can be 'engineered in' by controlling the molecular architecture. For example, an idealised polyethylene molecule is a linear sequence of ethylene units and constitutes a highly regular structure that crystallizes readily and exhibits a melting temperature of the order of 130 °C. When in crystalline form, the molecules are packed together more densely than in less ordered structures and therefore have a slightly higher density. Such materials are therefore referred to as high density polyethylene (HDPE). In practice, a few branches are in fact deliberately introduced into HDPE since this has been found to result in better overall properties. Introducing more and more branches ultimately results in a copolymer that is termed linear low density polyethylene (LLDPE). These materials contain more branches and are therefore less crystalline than HDPE: they soften at a lower temperature, and exhibit lower mechanical moduli and reduced tensile strength. However, LLDPEs have greatly improved resistance to environmental stress cracking – e.g. utensils made from LLDPEs are 'dishwasher proof'.

Cross-linking

Historically, cross-linking constitutes one of the first means by which the properties of a polymer were modified to make it more suitable for use in a particular application (Goodyear's vulcanised natural rubber). Cross-linking is now widely used to produce artefacts from many thermosetting systems. As the density of cross-links increases so the material becomes increasingly stiff and, therefore, by controlling the cross-link density it is possible to produce materials of the desired stiffness.

The characteristic bounce of rubber results from the deformation of a network that springs back when the force is released: this occurs because all the deformed molecular conformations between the cross-links or nodes relax back to their equilibrium conformations. These elastomeric properties stem from the presence of a network, and such a network would indicate a thermoset – the term 'thermoplastic elastomer' therefore appears to be an oxymoron. However, by clever control of the molecular architecture of block copolymers, it is possible to achieve just this effect.

Consider, for example, a triblock copolymer in which the two terminal blocks are composed of monomers of a material that, at the temperature at which the product will be used, is a tough crystalline solid. Now, if the central block is composed of a monomer which confers soft elastic properties then we will be able to form our object by heating the block copolymer to a temperature at which the end blocks melt and then cooling it down. If the monomers in the terminal and mid-blocks are thermodynamically immiscible, then we can form a wide variety of different structures by varying their relative length but, under all conditions, the end-blocks will crystallize with other end-blocks leaving the stretchy mid-blocks grouped together in between.

Thus, we have replaced our molecular nodes in a conventional elastomer with crystalline aggregates of a different chemical composition. The overall properties of this material will not only be a reflection of the elastic mid-block, it will also reflect the presence of the tough end-blocks. Why would this be useful? Consider the sole of a sports shoe - it needs to be flexible (provided by the mid-block) but also durable (provided by the end-blocks).

THE FUTURE

While the vast bulk of polymers produced today are electrical insulators, some polymers conduct electricity very well indeed. These materials are generally referred to as conducting polymers. The process by which this happens has much in common with conventional semiconductors in that it requires the introduction of dopant ions. Silicon can equally well be doped to make it n-type (conduction primarily by electrons) or p-type (conduction primarily by holes), though a given conducting polymer tends to conduct either by electrons or by holes.

All the possibilities of current microelectronics can, theoretically, be replicated using combinations of electron transport polymers and hole transport polymers, except that silicon does it all so much better. In which case, why bother with polymers at all? Single crystal silicon is expensive to produce, inflexible and can only be produced in small sizes. Polymers are cheap to produce, flexible and can be processed in whatever size you want. For example, a 'use-once-then-throw-away' RFID (radio frequency identification) tag to replace the bar code on an item of shopping doesn't need the processing power of a PC microprocessor, but it does need to be cheap.

By creating a suitable junction between a hole-conducting polymer and an electron-conducting polymer, and applying a voltage across the device, charges will move in opposite directions until they meet at the junction where they combine and give out light. This is the basis of a polymeric organic light-emitting diode (OLED) and the potential applications for such a device are enormous. Again, this can all be done at present using inorganic semiconductors so why bother? Current LED traffic lights are certainly bright, but this is achieved by bringing together lots and lots of individual LEDs, because you cannot cheaply produce large area inorganic LEDs. Since many conducting polymers are soluble, you could just 'paint' them where you need them, easily producing large-area devices. Getting a good colour balance is not straightforward though, and research on this continues.

For display applications, OLEDs have considerable benefits over existing LCDs in that they can be viewed from almost any angle, have improved clarity and brightness and, whereas conventional LCDs require a backlight and effectively act as a shutter, OLEDs generate light only when and where required. Although devices containing OLED displays are already available, in reality these constitute a hybrid technology in that, while the active light-emitting layer is organic, the drive circuitry that controls the display is based on conventional rigid inorganic materials. The real benefits of this technology will therefore come when organic display elements are combined with organic drive circuitry to produce fully flexible devices. Although the concept has already been proven by major electronics companies, such as Sony, at present the number of pixels is limited.

If it is possible to create lighting from electricity then what about the other way round? While inorganic semiconductor photovoltaic cells are quite efficient, again, large areas are required and this is economically unattractive. Polymer-based photovoltaic cells have been produced but, currently, the efficiency is very low. Nevertheless, a lot of work is going on to solve this problem, and approaches such as the inclusion of fullerene derivatives are showing promise. The possibility of cheap photovoltaic cells capable of efficiently using energy from the Sun could have significant implications.

REFERENCES AND FURTHER READING

Websites

Additional resources can be found on the SEP website (see page 54). Links to other particularly relevant websites are also listed on the SEP website. Some examples are given below.

Royal Society of Chemistry (www.rsc.org)

There is a great deal of useful and accessible information on this site, including experimental instructions on making nylon.

Practical Chemistry (www.practicalchemistry.org)

This website contains a growing collection of chemistry experiments, including a useful section on polymers.

Wikipedia (<http://en.wikipedia.org>)

The section 'Polymer' provides a reliable explanation of polymer properties and history with useful links.

Science is fun in the lab of Shakhshiri (<http://scifun.chem.wisc.edu/>)

This website of the University of Wisconsin-Madison has a 'Chemical of the Week' – the section on polymers gives a good explanation of the various common polymers with details of recycling.

BBC Bitesize (<http://www.bbc.co.uk/schools/gcsebitesize/>)

The section on useful products from oil is relatively low level but is good for basic information.

Books

Go with the flow: investigating bouncy fluids and other strange materials

Hollamby P (2005) Publisher: Gatsby Science Enhancement Programme (ISBN 978-0750641326).

This booklet includes information on some interesting and unusual polymer materials, including details of how to make and test slime.

Introduction to polymers

Young R J and Lovell P (1991) Publisher: International Thomson Computer Press (ISBN 978-0748757404).

A good overall textbook that covers the underlying physical principles of polymeric materials.

Polymer physics

Gedde U (1995) Publisher: Kluwer Academic Publishers (ISBN 978-0412626401).

Also a good textbook for the underlying physical principles.

Polymers: Chemistry and Physics of Modern Material

Cowie J M G and Arrighi V (2007) Publisher: CRC Press Inc. (ISBN 978-0849398131).

Similar to the two above but a general textbook with a more chemical emphasis.

Plastics materials

Brydson J A (1999) Publisher: Butterworth-Heinemann (ISBN 978-0750641326).

Very different from those listed above – focuses instead on different classes of polymers so has more of an engineering feel to it.

An introduction to the mechanical properties of solid polymers

Ward I M and Sweeney J (2004) Publisher: John Wiley & Sons (ISBN 978-0471496267).

A good introduction that discusses the mechanical aspects of polymers.

SOURCES

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SEP produces a range of digital resources to accompany each of its publications. These are available from the 'SEP Associates' area of the website (www.sep.org.uk).

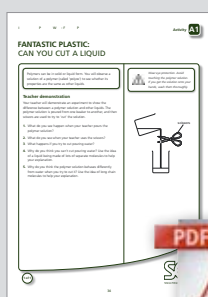
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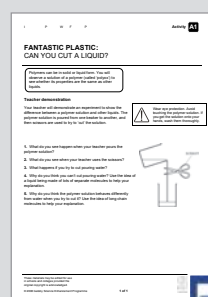
PDF file of booklet

On the SEP website there is a downloadable PDF file of the whole booklet that can be printed or viewed on screen.



PDF files of student sheets

In addition to the whole booklet, the student activities are available as separate PDF files.



Word files of student sheets

Each student sheet also exists as a Word file. These files can be edited in order to adapt the activities to suit individual circumstances.



PowerPoint presentations

These contain the photographs and drawings shown in this booklet. They can be used to create custom-made presentations.



Links to other sites

The SEP website provides links to other useful websites on this topic.

OBTAINING THE PRACTICAL RESOURCES



SEP works in close partnership with Middlesex University Teaching Resources (MUTR) in identifying and developing low-cost practical resources to accompany its publications. Many other resources for school science and technology can also be purchased from MUTR.

The latest prices of the products shown below and further information can be obtained from www.mutr.co.uk, or by requesting their latest catalogue. Orders can be made by post, telephone, fax or email by providing an official school order number or by credit card.



Polyox **233-004**

A solution of polyox (polyethylene oxide) behaves as an 'elastic liquid', i.e. it 'self-siphons'.



Rubber latex **211-019**

Adding a weak acid to liquid rubber latex creates cross-links between the molecules, producing solid rubber.



Polymorph **PL1 004A**

A tough 'engineering' material, but which can be softened and moulded at a relatively low temperature.



Hydrogel **233-003A**

This white power can absorb many times its own weight in water producing a gel.



Shape memory polymer **234-100**

When heated, shaped and cooled it will retain its new shape; when heated again it will revert to a flat sheet.



Slime **SEP 002**

This pack contains the ingredients for making green slime (PVA, borax and fluorescein).



Smart putty **SEP 011**

When pulled slowly smart putty will stretch, but when pulled quickly it will snap.



Smart gum **SEP 012**

Smart gum is similar to smart putty, but has a lower viscosity and flows more easily.

There are many other novel and interesting polymer materials available from MUTR, such as magic snow and liquid polymorph, as well as a range of conventional plastics such as polypropylene, acrylic and polystyrene sheets.

You can download the written materials in this booklet, and find further information from: Science Enhancement Programme www.sep.org.uk

The Science Enhancement Programme (SEP) is part of Gatsby Technical Education Projects. It undertakes a range of activities concerned with the development of curriculum resources and with teacher education.



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You can order a range of plastics materials and other practical resources from Middlesex University Teaching Resources.

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