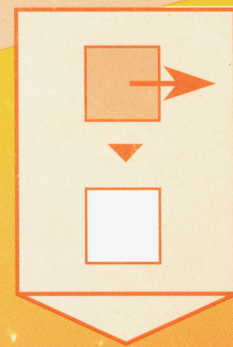
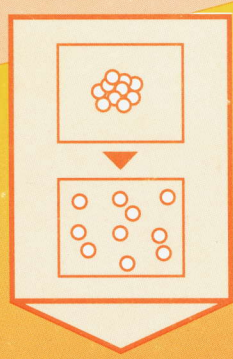


# ENERGY AND CHANGE

*Introducing  
a new approach*

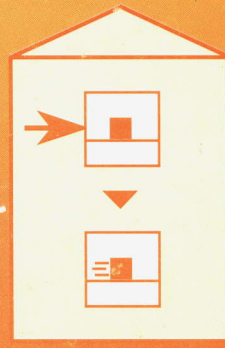
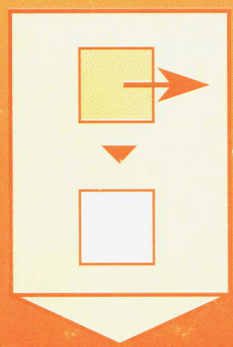
**Richard  
Boohan**

**Jon  
Ogborn**



*The key ideas  
behind the  
materials:*

*• Differences  
drive change*



*• Pictures help  
understanding*



The  
Association  
for Science  
Education

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# **Energy and change**

**Introducing a new approach**

**Richard Boohan**

**Jon Ogborn**

**A PROJECT SPONSORED BY THE NUFFIELD FOUNDATION**

## Preface

### About the approach

Increasing emphasis in science education has been placed on making fundamental and everyday issues, from pollution to global warming, accessible to a wider range of pupils. The National Curriculum contains many such examples. Essentially, pupils are expected to make sense of *processes of change*. Despite being of central importance to science, teachers and textbooks lack a way of explaining change that makes sense for this purpose. Essentially, what is needed are simple, everyday and coherent ways of talking about thermodynamic ideas which are accessible to school pupils.

'Energy and change' is a set of three booklets outlining a new approach which starts from commonsense ways of explaining why things happen. In developing these materials we have had three important criteria in mind, namely, that the approach should be:

- intelligible to pupils
- useful to teachers
- scientifically consistent

So the approach is useful to *all* pupils in helping them to understand the world, while those who later specialise in science can build on the ideas in a natural way.

Our central idea is that change is caused by *differences*, for example, differences in temperature or in concentration. To make these ideas intelligible to pupils we have developed a range of *abstract pictures*, examples of which can be found throughout this booklet. Some of these pictures may appear somewhat daunting at first, but we have found that pupils are quickly able to become familiar with them, and are stimulated into a good level of discussion.

It is all too easy to offer advice about ways *not* to talk about energy and change, but this only leads to a feeling of paralysis. What we are hoping to do is to offer to teachers a new and constructive way of talking about these ideas with pupils.

### About this booklet

This booklet is for those who want to find out more about the general approach, the abstract pictures used and the scientific ideas behind the approach.

### Other booklets

*Activities in the classroom* - This booklet is for those who want to pick out some activities to use in the classroom, and to find out how the ideas can fit into the existing curriculum.

*Background stories for teachers* - This booklet is for those who want to read about some scientific topics and to see how they can be looked at in a new light.

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## Introduction

*"Shoe leather wears out because it rubs against the sidewalk and the little notches and bumps on the sidewalk grab pieces and pull them off. That is knowledge. To simply say, 'It is because of friction,' is sad, because it's not science."*

Richard Feynman (quoted in 'Genius' by James Gleick)

In this booklet, we address the fundamental question 'why do things change?', not simply by labelling phenomena with words to explain them away, but by looking at the essential nature of physical, chemical and biological changes. Our aim is to provide a coherent framework within which many important scientific concepts can be developed.

The key idea in our approach is to pay attention to the differences which drive change. For example, air in a balloon tends to leak out because of a *pressure difference* - it continues to spread out until the pressure difference disappears. Pollution spreads out and mixes with the air in the atmosphere because of a *concentration difference*. Eventually the concentration difference disappears. Hot coffee cools because of a *temperature difference*. Energy spreads out into the surroundings, as it goes from hot to cold, until eventually the temperature difference disappears. Thus, differences tend to disappear because matter or energy or both become more spread out. This essentially simple idea is also powerful. We can use it to make sense of a wide range of phenomena from a hot cup of tea cooling, to the direction of chemical reactions and even to the complexity of life.

Many differences are expensive to obtain and may be able to do something for us. A frozen ice cube has to be specially made and can cool a drink. Pure water has to be specially provided and is important for life. Differences must be maintained if they are to be useful, and this may be difficult - ice easily melts, water easily becomes polluted.

How can we make differences? The hot water for the coffee was made hot by a hotter flame. Pure water can be made by distilling it, using a hot flame. Behind this is the idea that it takes a (bigger) difference to make a difference. Fuels are valuable because they can create a difference which drives a desirable change, such as heating a house or driving an engine. A difference is being used up to create another difference.

Warm rooms, plants or animals are all kept as they are, far from balance with the environment, by a heater, by sunlight, or by food. They do it by continually consuming differences, so as to maintain themselves. By being away from equilibrium they themselves constitute a difference which can cause other changes, as when we run around or when a flame heats a kettle.

An understanding of why things change is clearly of fundamental importance in science. How is it currently taught in schools? 'Energy is what makes things happen' is a fairly typical statement which could be found in many school science textbooks. It sounds plausible, but it is wrong, and has led to much confusion. A flame heats a pan of water, not because the flame 'has a lot of energy', but because the energy in the flame is more concentrated than the energy in the water (i.e. it is hotter). It is this difference which drives the flow of energy.

In addition, the focus in most school textbooks has been on learning about 'forms of energy'. But to say that a car engine converts chemical energy in petrol to kinetic energy adds little to our understanding of the fundamental nature of the change (in the same way that saying friction makes shoes wear out attaches a word to the phenomenon but does not explain it). And while electric fires are said to 'convert electrical energy to heat energy', what do fridges do? We cannot say they convert electrical energy into 'cold energy'! A 'differences' approach accounts for such changes more easily - electric fires and fridges create temperature differences which do not arise by themselves, but are created by a difference being used up in a power station.

The National Curriculum does not refer to 'forms of energy' but instead talks in terms of 'energy transfer', in which the focus is on what happens to energy, where it is at the start and at the end, how it moves from one place to another, and so on. The terminology adopted by the National Curriculum is consistent with the idea of energy flows being driven by differences.

It should be clear from the above account that our approach to teaching about why things change is not something which can be confined to a topic called 'energy'. The activities we have developed can be used in many areas of the science curriculum. They form the basis of a consistent story about processes of change which can be developed across the whole age range. Here are a few examples of areas in which these ideas could be used:

dissolving	energy efficiency
pollution	weathering of buildings and rocks
evaporation	metal extraction and corrosion
separating and purifying mixtures	microbes and decay
chemical change in everyday materials	cost of energy used by domestic appliances
meaning of hot and cold	cycling of materials in ecosystems
energy transfers	energy transfers in ecosystems
weather and the water cycle	the atmosphere
burning fuel and the release of energy	maintaining the internal environment of plants and animals
energy resources	enzymes and the synthesis of biological molecules
photosynthesis	
respiration	

In understanding such a wide range of different kinds of processes, we will need to help pupils see that many changes are essentially similar, even though, superficially, they appear to be very different. Thus, dissolving is rather like evaporation in that particles spread out, though there are also important differences. Respiration is in some ways like burning. A human being can be understood as being a 'steady state system' rather like a central heating system. Making such abstractions is not easy, so we have developed a range of pictorial representations to help pupils to do this. In the next part of this booklet, 'Telling the story in pictures', we use abstract pictures to tell our story about 'differences', though it is told in a way aimed at teachers and not at pupils. The booklet 'Activities in the classroom' is concerned with relating the approach to the science curriculum, and the section 'Ideas and activities' tells a parallel story (using the same headings), showing how these ideas can be introduced to pupils.

## Telling the story in pictures

The story told in this booklet is concerned with one simple question - 'why do things change?'. Such a story needs to be of help in explaining a wide range of phenomena, for example:

a cup of tea cooling  
pollution spreading in the atmosphere  
heating water in a saucepan  
running a car engine  
a power station generating electricity  
a puddle of water evaporating

a car rusting  
a centrally heated room  
a hurricane  
a flame  
a human being  
an ecosystem

All of these changes appear superficially to be very different, though there are in fact fundamental similarities between many of them. One way of helping to make clearer these similarities is by using abstract pictures which represent the essential features of the changes. In telling the story here, we shall develop a 'picture language' which will help in answering the question about why things change.

### 1 Backwards and forwards

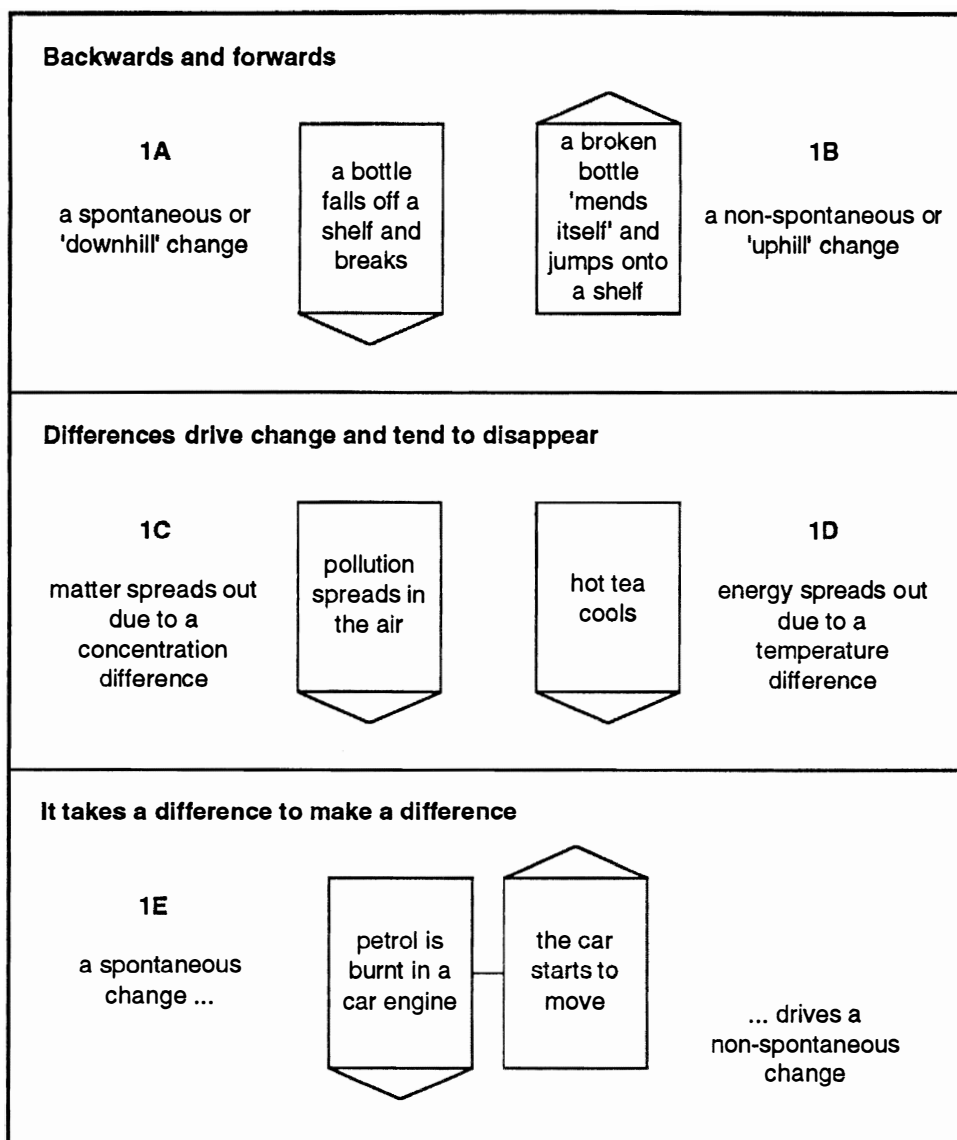
*Everything tends to go downhill.*

Why do things change? Fundamental to this question is why things tend to happen in *one direction* and *not the other*. A bottle falls off a shelf and breaks - this is not a very remarkable event. But a pile of broken fragments from a broken bottle assembling themselves into a bottle which jumps back up onto the shelf? If we saw this with our own eyes, we would suspect a conjuring trick, and if watching it on film we would think that it had been played backwards. Figures 1A and 1B show these two changes with arrows to represent whether the change is spontaneous or not. Spontaneous changes happen rather easily - like going downhill - so this has an arrow pointing down; the non-spontaneous change has an arrow pointing up.

Some things, though, do not look so crazy played backwards. If a very bouncy ball fell off a shelf, bounced on the ground and rose to the height of the shelf, this would look much the same played backwards. And we are familiar with seeing ice change into water or water changing into ice depending on the temperature - the conditions determine the direction in which some changes happen. Ultimately the conditions can be fixed so that any change could in some sense be reversed. A broken bottle cannot mend itself and jump on a shelf, but someone may fix the conditions such that the glass melts, is blown into the shape of a new bottle and is raised to the shelf. The question now is what makes the changes in a human being happen that are able to make other changes happen?

The story developed in this booklet is based on the simple yet powerful idea that *differences drive change*. Thus, changes are driven by differences such as those between hot and cold, or between concentrated and dilute. Differences tend to disappear because matter or energy or both become *more spread out*. Figures 1C and 1D give some examples of spontaneous changes. Pollution spreads in the atmosphere because of a concentration difference, until eventually the concentration difference





**Figure 1**

**Some changes happen spontaneously and others need to be driven**

disappears. Hot tea cools because of a temperature difference. Energy spreads out into the surroundings, and eventually the temperature difference disappears. When energy and matter are spread out or mixed as evenly as possible, there are no differences and equilibrium is reached.

There are many changes which *do* happen even though they are *not* spontaneous. How does this come about? Another important idea is that a spontaneous change can *drive* a change which is not spontaneous. It takes a difference to make a difference. For example, a car does not spontaneously start moving. It happens because it is *coupled* to another change happening in the engine. Figure 1E represents how one change can be used to drive another. When petrol starts to burn, you do not need to do anything to keep it burning - it does so spontaneously. (We shall see, in a later section, how we can think of petrol as a 'stored difference'.) We could simply let petrol burn in the open air and let the energy spread out, but by burning it in an engine we can arrange it so that a spontaneous change (burning of petrol) drives a non-spontaneous change (getting the car moving).

For us, on Earth, the most important spontaneous change is the spreading out of energy from the Sun into space. It is the temperature difference between the hot Sun and cold space which drives many changes on Earth. The energy would spread out from the Sun, even if it existed alone in empty space.

Because the Earth exists too, the spreading out of energy can drive other changes such as the synthesis of glucose in plants which in turn drives the muscles of human beings who are able to make bottles and put them on shelves.

## 2 Spreading and mixing of matter

*Matter tends to go from where there's a lot to where there's not.*

Imagine a Universe, much simpler than the one we live in, consisting of identical particles which move around at random with no tendency to stick to each other. Suppose too that when this Universe was created, some regions of it were quite densely packed with particles, while others were rather sparse. What would happen to such a Universe as it evolved? Because of the random movement of the particles, they would tend to spread out from the dense regions to where it was less dense. Differences in concentration of the particles would tend to disappear until eventually there were no differences left. Figure 2A represents this change, showing the states 'before' and 'after' the change (with time running 'down the page'). Notice that the large arrow on the bottom indicates that this is a spontaneous change - or a change that 'just happens by itself'.

Imagine a very slightly more complex Universe, in which there was not one, but two kinds of particle. Now, starting with differences concentrations in different regions, the two kinds of particles would tend to mix until they were both spread evenly. Figure 2B represents this - again this is a change that 'just happens by itself'.

But we do not have to exist in such a Universe to see similar phenomena in the everyday world around us. If you put a drop of ink into water, it will gradually spread out until all the water is the same colour. The ink spreads out until the concentration is the same throughout the water. It is now at *equilibrium*. *A difference drives this change, and the difference disappears.*

Differences in pressure are similar to differences in concentration, and can also make things spread out. If you release the valve of a bicycle tyre, the air will rush out. This is due to a difference in pressure between the air in the tyre and the atmosphere. If you evacuate a container, the pressure inside is now lower than the atmosphere, but again this difference can drive change.

We do not need to know anything about particles in order to observe that differences in concentration and pressure tend to disappear. But it is our knowledge of particles which helps us to explain why this happens.

The reverse processes - in which differences in concentration and pressure are created - are not spontaneous. Figures 2C and 2D show pictures representing matter becoming more concentrated or 'bunching together' and matter being separated or 'unmixing'. The 'up' arrow at the top of each box indicates that these are changes which do not 'just happen by themselves'. It is rather more difficult to create concentration differences than to allow them to disappear, and they are often valuable or useful to us. A bar of gold is worth more than traces of gold scattered throughout a mountain, and pure water is better to drink than salt water.

### Spreading and mixing of matter

Changes which 'just happen by themselves'

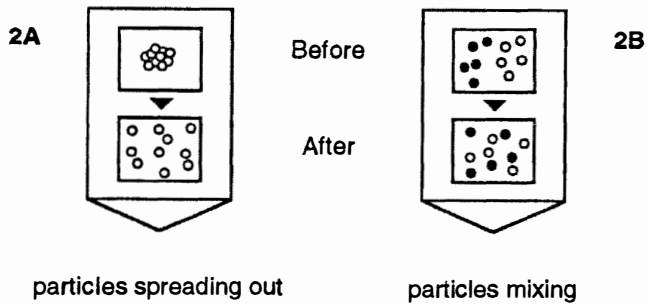
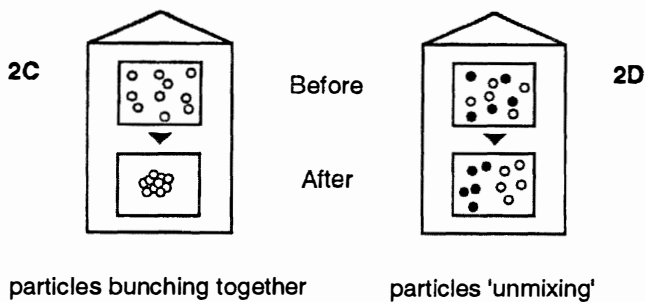


Figure 2

Particles spreading out and mixing are changes which 'just happen'

### Bunching together and 'unmixing'

Changes which do not 'just happen by themselves'



### Examples

Sugar dissolves in water.

Soapy water removes dirt from clothes.

The smell of perfume spreads through a room.

A puddle evaporates.

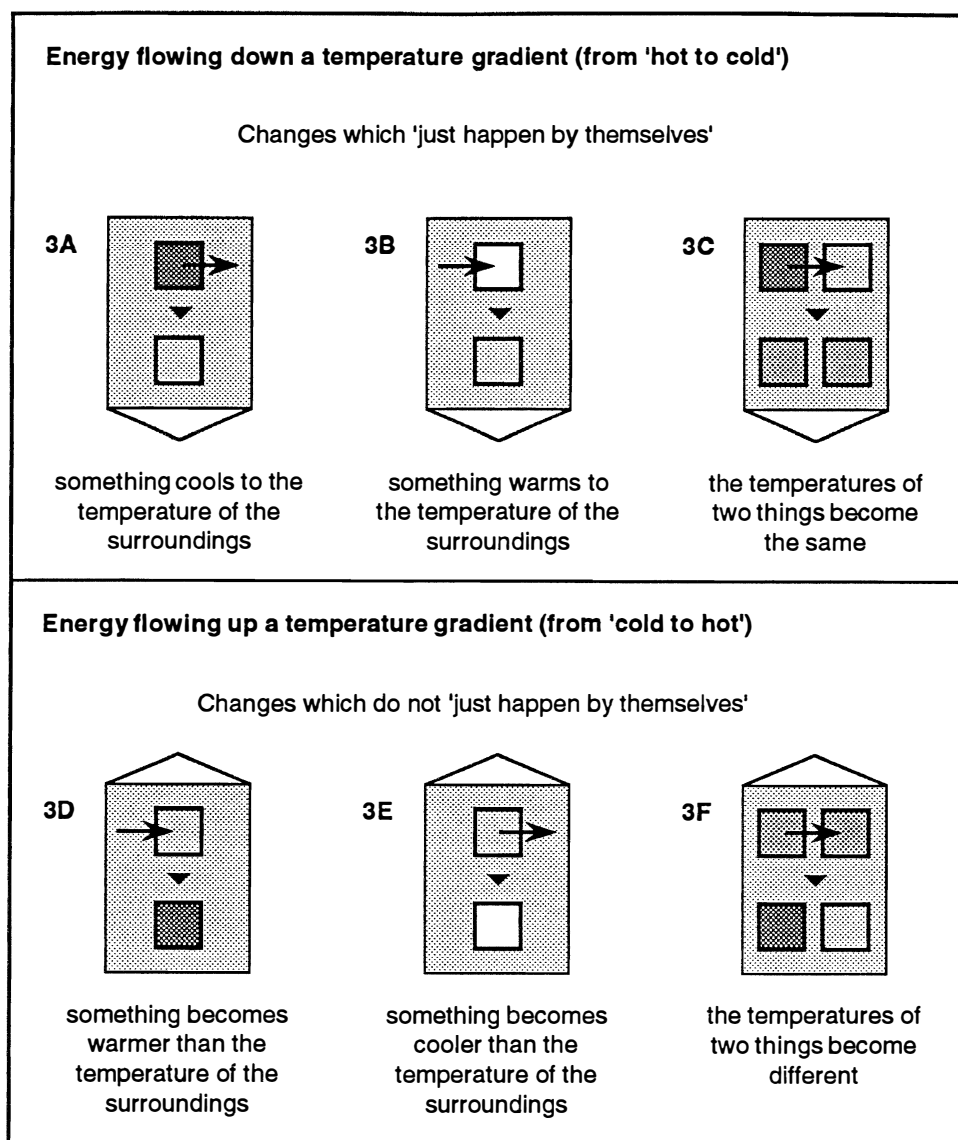
Releasing a blown-up balloon.

## 3 Energy flows and temperature differences

*Energy tends to go from where it's hot to where it's not.*

Now let us make our imaginary Universe more complex still. Suppose that the particles in it do not all move around with the same velocity - particles with more energy move faster. Now suppose that, although the particles themselves are evenly spread out, there is a high concentration of fast-moving particles in one region of the Universe. The fast-moving particles will tend to spread out until they are evenly distributed through the Universe. As they move around, they will also collide and their





**Figure 3**

**Energy tends to flow down temperature gradients**

velocities will change - a slow-moving particle may get a 'kick' from a fast-moving particle, so that they exchange energy. This will also help the process in which the energy spreads out evenly through our Universe.

We can think of temperature as a measure of the *concentration of energy* - the greater the concentration of energy, the higher the temperature. So, as before, we do not need to live in our imaginary Universe to see changes like this - there are countless everyday examples of situations where temperature differences exist and tend to disappear.

When you do the washing up, you put dishes at room temperature into a bowl of hot water. This makes the dishes warmer and the water cooler. Why does this happen? Because of a difference in *temperature*, energy passes from the *hot* water to the *cold* dishes. As this happens the temperature difference gets smaller. Eventually the dishes will be at the same temperature as the water, and no heat will flow from the water to the plates. They are at *equilibrium*. *A difference drives the change, and the difference disappears*. This is rather similar to the previous case, in which some ink is dropped into water. But, whereas, concentration differences cause substances to spread out, *temperature differences* cause *energy* to spread out.

We do not need to know anything about energy in order to observe that differences in temperature tend to disappear. But it is our knowledge of energy which helps us to explain why this happens.

When one thing cools we may not always notice that something else becomes warmer. A hot cup of tea is hotter than the air in the room. Again there is a temperature difference. Here, we notice the decrease in the temperature of the tea. The energy spreads out in the surroundings, though because of the very small temperature change we are less aware that this becomes warmer. We shall later see that many changes (including those of life) are driven by energy spreading out into the surroundings.

Figures 3A, 3B and 3C represent changes in which energy flows down a temperature gradient. Temperature is represented by the shading - the darker the shading, the higher the temperature - and the arrows represent energy flow. Thus, the three pictures may represent a cup of hot tea cooling down (3A), a glass of ice cold lemonade becoming warmer (3B), and cold plates put into a bowl of hot water (3C). Since energy is flowing *down* a temperature gradient, all of these examples are spontaneous - they 'just happen by themselves'.

The reverse processes - in which temperature differences are created - are not spontaneous. Figures 3D, 3E and 3F represent changes in which energy flows up a temperature gradient. These are changes which do not 'just happen by themselves'. It is rather more difficult to create temperature differences than to allow them to disappear, and they are often useful to us. A flame can make some water boil, and an ice cube can cool a glass of lemonade.

### Examples

An electric fire is warmer than the air in a room.  
A Bunsen flame is hotter than the beaker of water it is heating  
A cool glass of lemonade is colder than the air in a warm room.  
The Sun is hotter than the Earth.  
The Earth is hotter than space.

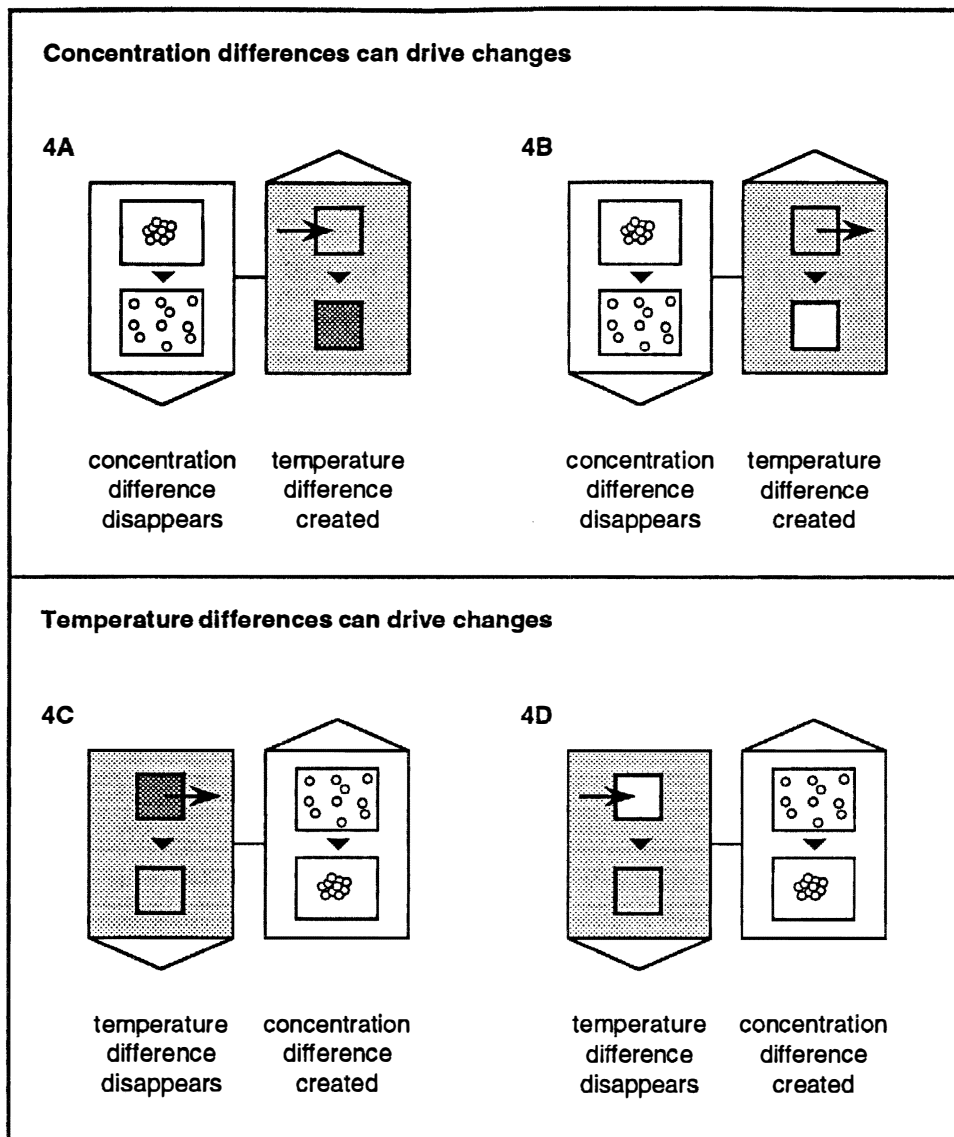
## 4 Differences can create differences

*Some changes will just happen and others won't.  
Those that do just happen can drive those that don't.*

We have seen that differences tend to disappear. If these were the only kinds of change that could ever happen, the Universe would be a rather dull place, running down towards a cold, thin, evenly spread gas.

But it is also possible to *create* differences, even though they do not appear from nowhere. You need a *difference* to create a *difference*. So, while changes in which differences appear do not 'just happen by themselves', this does not mean that they can never happen. Changes may be coupled together so that a change which 'just happens' drives a change which does not.

For example, water in an electric kettle does not spontaneously become warmer. It happens because it is *coupled* to another change happening in the power station. *Particles spread out* when steam in the



**Figure 4**

Changes in which differences disappear can be used to drive changes in which differences are created

turbine expands, and this drives the change in which *energy becomes concentrated* in the kettle. Figure 4A illustrates this. A change which 'just happens' (steam expanding) drives a change which does not 'just happen' (water in the kettle getting hot). Since steam expanding is a change which 'just happens', it would happen whether it was in a power station or not. However, an elaborate collection of devices - turbine, generator, power cables, transformers - enables this change to be coupled to the change which we want to make happen in the kettle.

In the last example, matter spreading drives a change in which something becomes warmer than the surroundings, but it can also make something *cooler* than the surroundings. Plugging a refrigerator into the electricity supply makes it colder, but as before, a driving change (in the power station) creates a temperature difference (see Figure 4B). Here is an example where the traditional account in terms of 'forms of energy' is unhelpful - while textbooks may refer to a kettle as 'converting electrical energy to heat energy', a refrigerator is rather more difficult to explain. It may even reinforce misconceptions such as 'cold energy'. Saying however, that a change which 'just happens' drives the creation of a temperature difference accounts for kettles and refrigerators equally well.



Sometimes it *seems* that differences can spontaneously appear. If water is left to evaporate, it becomes colder than the surroundings - a temperature difference appears. But the reason for this is that the water is spreading out, and so a concentration difference is disappearing. Again, a change which 'just happens' drives a change which does not. A similar case is when you let the air out of a bicycle tyre - you can feel the air and the valve becoming colder. Here, a *pressure difference* disappearing drives the creation of a temperature difference. Both of these examples are also represented by Figure 4B.

Temperature differences can be created when particles spread out, but they may also drive other changes themselves. While it is easy to dissolve copper sulphate in water - just put a crystal in and it will dissolve and *spread out* - it is more difficult to get copper sulphate from solution. One way of doing this is to cool a hot saturated solution. As it cools crystals appear, so this is the opposite of the copper sulphate *spreading out*. The copper sulphate is *bunching together* - it is *concentrating* in one place. Figure 4C shows how a change which just happens (temperature difference disappearing as energy spreads out) can drive a change which does not (concentration difference created as particles bunch together). Here, the coupling between these changes is much more direct than between the power station and the kettle - perhaps this is why we feel a sense of wonder as we watch a crystal grow, and see order in matter appear almost magically from 'nothing'.

At first sight, a block of ice is a bit of a puzzle - it has less energy than the same amount of water at room temperature, and yet it can do more. It can make a drink cooler, and connected to a thermocouple it can even make an electric motor turn. The important thing about a block of ice is that it is at a *different temperature* from its surroundings - a block of ice at the North Pole would not be so useful. This temperature difference can be used to drive other changes (see Figure 4D). For example, icebergs in the Gulf Stream create fog and condensation appears when you open the fridge door.

Changes of state (evaporation, condensation, freezing, melting) all involve matter spreading out or bunching together, or becoming more or less ordered. They also involve energy becoming more or less concentrated as it flows from or to the surroundings, and the change may be driven by a temperature difference. Thus, the pictures introduced so far may be helpful in representing features of these changes, but they omit one significant feature - the attraction between particles which holds them together in liquids and solids. This extremely important part of our story we shall discuss later.

The basic features of this 'picture language' - representing spontaneous and non-spontaneous change and how changes may be coupled - have now been introduced. So far, however, we have only considered changes concerned with concentrations of matter and energy, and we now turn to look at a broader range of changes. (Later in this booklet, in 'A catalogue of changes', Figure 13 shows a complete set of the most fundamental elements of the 'picture language', combinations of which can be used to represent any kind of thermodynamic change.)

So far, in our imaginary Universe, we have not considered any *attraction between particles* - we have assumed that they move around randomly, unaffected by interactions with other particles. Without such attractions, there is no possibility that objects can exist, though many of the real world examples we have already discussed have assumed this - power stations and kettles could not exist unless there were attractions between particles. We shall look later, in sections 6 and 7, at changes at the molecular level, involving the re-arrangement of particles. Before that, we shall look in the following section at the macroscopic level at changes which involve the behaviour of objects.

## Examples

A power station coupled to a kettle

A power station coupled to a refrigerator

Letting air out of a bicycle tyre

Crystallisation, e.g. leaving salt solution to evaporate, cooling a hot saturated copper sulphate solution

Melting, e.g. butter in a hot pan, an ice cream on a warm day

Freezing, e.g. water left in a freezer, a lake on a cold day

Evaporation, e.g. drying your hair with a hair dryer, a puddle drying out

Condensation, e.g. breathing out on a cold day, a window 'misting up' on a cold day

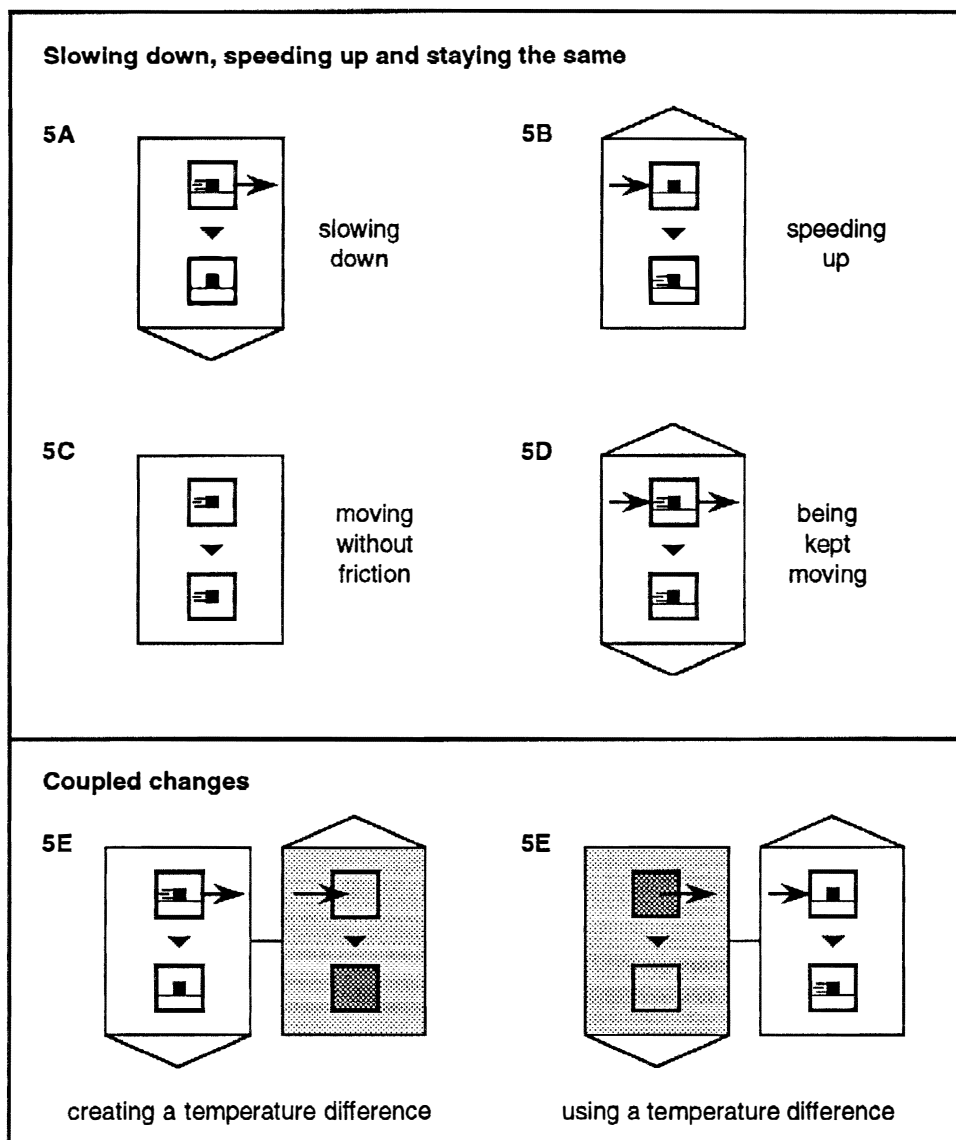
## 5 Moving things and springy things

*Energy can be stored in hot things, moving things and pulled-out springs.*

In an idealised frictionless Universe, moving objects would always keep moving at the same speed. In the real Universe, things that move have a tendency to slow down - a rolling ball stops rolling, the water in a stirred cup of tea comes to rest. As things slow down, energy spreads out - for example, the ball and the ground become a little warmer. There are two senses in which energy spreads out. In a moving object, all of the particles are moving in the same direction, but as it slows down and warms, the particles vibrate more in all directions; energy also spreads out in the sense that it flows from the warmer object out into the surroundings. Even things which appear to keep moving forever may be slowing down - as the Moon goes around the Earth, it pulls on the oceans creating tides and making the water a little bit warmer. The energy spreads out and the Moon's orbit changes imperceptibly.

Figure 5A represents an object slowing down - this tends to 'just happen by itself', so the picture shows a 'down' arrow on the box as energy spreads out. An object getting faster does not 'just happen' - Figure 5B shows this change with an 'up' arrow on the box. In some situations, things may *stay the same*, but we need to distinguish two very different cases. A probe propelled into space would keep moving forever at the same velocity if there was absolutely no friction. This is represented by Figure 5C. No 'up' or 'down' arrows are shown since the situation is 'time-reversible' - if we were shown a film of the probe, we could not distinguish whether it was being played forwards or backwards. A car travelling down a motorway at constant velocity is a very different situation. Figure 5D represents this, and shows an object being kept in a 'steady state' by a constant flow of energy. A 'steady state' is not kept going 'just by itself' - it needs another change to drive it. The constantly moving car is not 'time-reversible' - a film played backwards would, of course, show the car going in reverse, though this is a trivial point. More fundamentally, it would show (if we could see it) gases being sucked in through the exhaust pipe and petrol appearing in the tank. We would know that this could not just happen by itself.

Changes which 'just happen' may happen on their own or they may drive some other change. Figures 5E and 5F show two kinds of coupled change. In Figure 5E, a moving object slowing down is used to create a temperature difference - an example would be the harnessing of tides to generate electricity to make a light bulb hot. In Figure 5F, a temperature difference is used to make something move. This is the classic case of a thermodynamic engine - work may be done as energy flows from a hot to a cold reservoir. Real-life examples would be car engines and power stations, where fuels are used to create



**Figure 5**

'Slowing down' is a change which just happens by itself, but 'speeding up' needs to be driven

temperature differences, and breezes are caused by temperature differences between the land and the sea.

When we make hot steam in a power station, we are storing energy and creating a temperature difference which can be used to drive other changes. Similarly, when we wind up a clockwork toy or pump water uphill to a reservoir, we are storing energy and creating a *potential energy difference* which can be used to drive other changes. Figure 6 shows different kinds of potential energy differences. When you pull the two ends of a spring apart, energy is stored (Figure 6D). When you 'let go' of the spring, the energy escapes and spreads out - the spring and the air around it warm up a little. A stretched spring could stay the same forever until you release it, but once let go, its collapse is a change which 'just happens by itself' (Figure 6A). The same thing applies to any kind of object which has been mechanically deformed.

These ideas do not just apply to mechanical springs - similar changes take place when a gravitational 'spring' is 'pulled apart' and 'released'. Thus, lifting a ball into the air and then letting it drop is rather similar to stretching and releasing a spring (Figures 6B and 6E). One difference is that while the force gets greater the more you stretch a real spring, as you pull something away from the Earth the



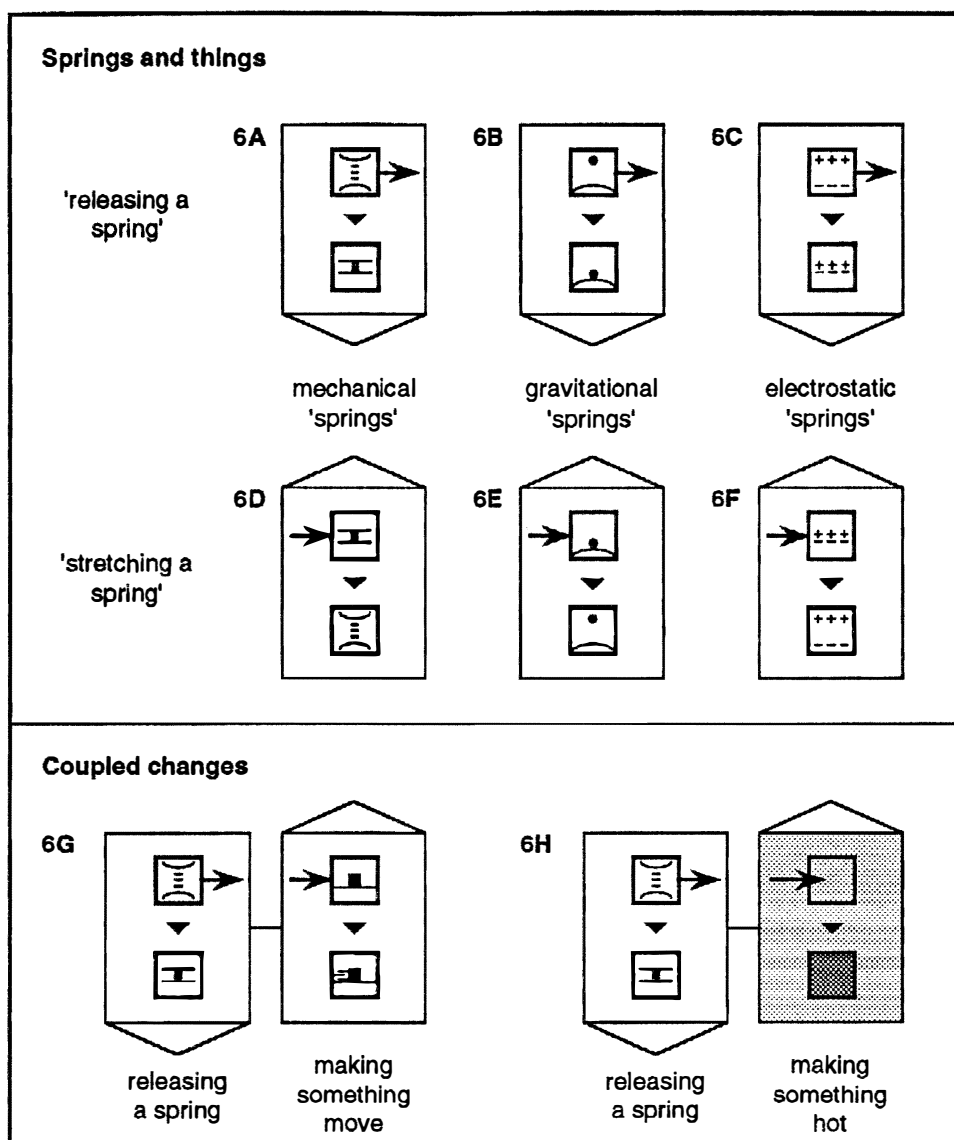


Figure 6

Energy can be stored in and released from mechanical, gravitational and electrostatic 'springs'

gravitational force gets weaker. An important similarity is that when we pull a mechanical spring apart, we do not think of energy being stored in either of the *ends*, but in the *spring* itself; in the same way, when a roller coaster is pulled to the top of the run, it is better to think of the energy being stored in the gravitational 'spring' (the gravitational field) between the roller coaster and the earth, and not in the roller coaster itself.

Things may also be attracted to each other by electrostatic or magnetic forces, and we can think of these as 'springs' in the same way as gravitational forces. Figures 6C and 6F represent an electrostatic 'spring' being pulled apart and released - for examples, pieces of paper pulled away from and attracted to a charged comb. There is, however, an important difference between mechanical springs and these other kinds of 'spring'. As you pull a mechanical spring, the force gets stronger; when gravitational, electrostatic and magnetic 'springs' are pulled, the force gets weaker.

When a spring of any kind is released, the stored energy tends to spread out into the surroundings, warming them a little. But a spring may also be coupled to another change, such as making something move, like a clockwork toy (see Figure 6G). A 'perfect spring' (with no friction) *could* be coupled to another change without energy spreading out at all - for example, a perfectly elastic rubber ball would

bounce up and down forever, and a perfect pendulum would keep swinging forever (though, *thermodynamically* nothing would be changing). Springs may also be coupled to other kinds of changes, for example, Figure 6H shows a spring being released driving a change in which something gets hot - this might represent water flowing from a high reservoir through a hydroelectric power station to generate electricity to make a lamp light up.

Atoms are held together to form molecules by the same electrostatic forces which makes pieces of paper stick to a charged comb. In a chemical reaction, atoms re-arrange to form new molecules. In doing so, some 'electrostatic springs' holding atoms together are pulled apart and others are released. In the following section, we shall look at changes which involve the re-arrangement of atoms, before turning to look at the nature of 'chemical springs'.

### Examples

A rolling ball slowing down and stopping.  
The water in a stirred cup of tea coming to rest.  
The Moon's orbit changing.  
A paper clip getting hot when bent.  
Hammering a piece of lead.  
A probe travelling through space.  
A car travelling down a motorway at constant velocity.  
Harnessing the tide to generate electricity to make a light bulb hot.  
Land and sea breezes caused by temperature differences.  
Plate tectonics.  
Winding up a clockwork toy.  
Pumping water uphill to a reservoir.  
Pulling a roller coaster to the top of a run.  
Pieces of paper attracted to a charged comb.  
A pendulum.

## 6 Particles - joining and splitting, building and breaking

*Particles may spread or bunch - and stay unchanged.*  
*Particles may split or join - and get re-arranged.*

At the beginning of this story about 'why things change', we imagined a Universe consisting of particles moving about randomly. Any differences in concentration will tend to disappear as the particles spread out. When they are spread as evenly as possible, there will be no further change. Figures 7A and 7B show concentration differences disappearing; Figures 7C and 7D show that concentration differences do not spontaneously appear.

Imagine, however, a Universe in which the particles are *attracted* and tend to stick to each other. Now there is another kind of difference which can drive change - differences in *structure* or *complexity*. A regular arrangement of particles, neatly organised into rows and columns, is more *structured* than a clump of particles stuck together in a disorderly way. An elaborate pattern of different kinds of particles is more *complex* than a random mixture.

Where do we see these kinds of changes in the real Universe? Molecules are more ordered in a cube of ice than in water. When the ice melts, *structure* disappears. If water is heated to a *very* high temperature, the molecules fall apart forming individual hydrogen and oxygen atoms. Again, *structure* disappears. When petrol is burnt in a car engine, or glucose is 'burnt' in our bodies, large molecules are broken down to form smaller molecules. *Complexity* disappears, as particles split apart into smaller pieces.

Figure 7E shows a change in which particles become more disordered, such as melting. Figure 7F shows particles splitting into smaller particles, as in a decomposition reaction. Figure 7G shows a large complex molecule breaking down, for example, hydrolysing starch to form glucose. In all of these changes, differences in structure or complexity are *disappearing*. However, this does not mean that they necessarily happen spontaneously or 'just by themselves'. In all of these changes, particles which are attracted to each other are also being *pulled apart* (like the two ends of a spring). So, an energy transfer is also involved, and this may determine the direction of change. For example, at higher temperatures, ice melts as energy flows in from the surroundings and the particles become more disordered; at lower temperatures, it freezes as energy flows to the surroundings, the particles become more ordered and *structure appears*.

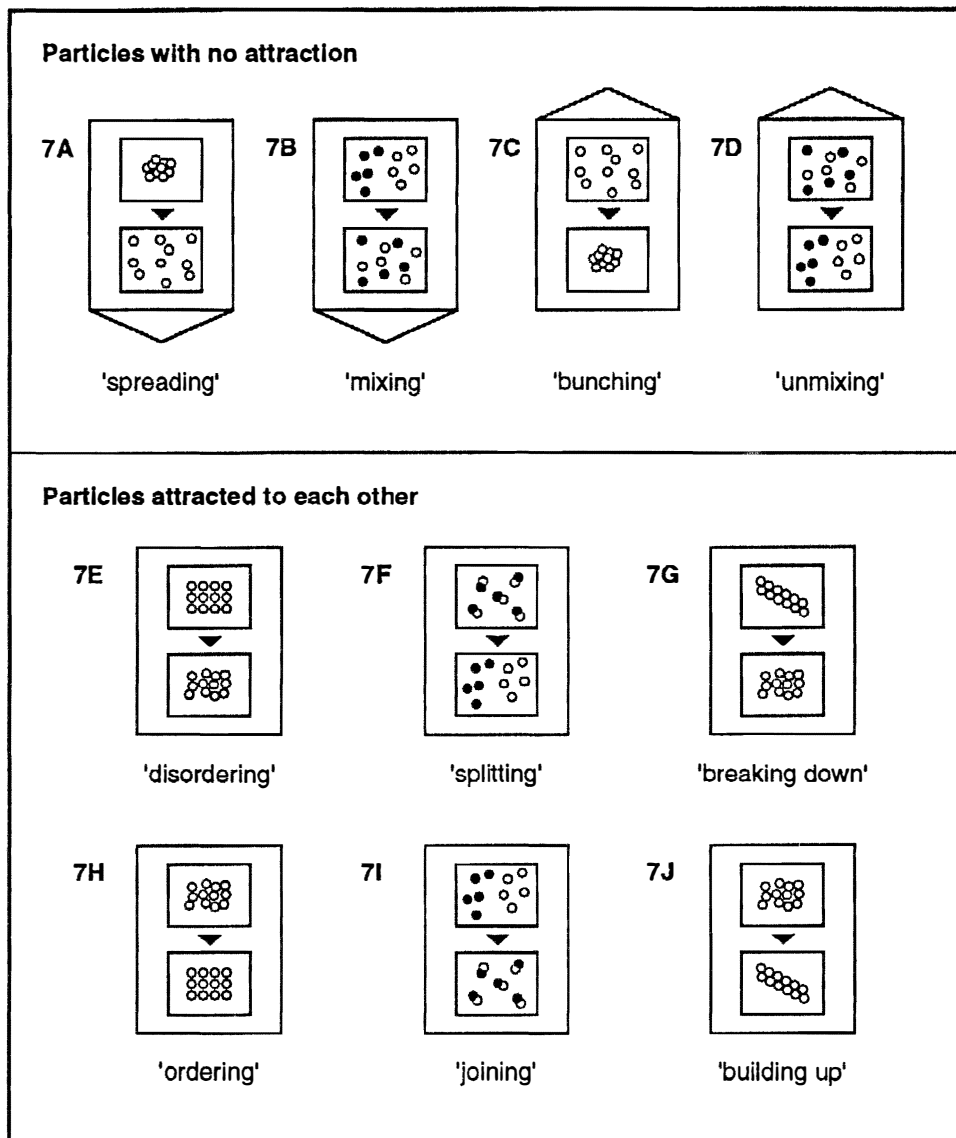
Energy is *always* a factor in changes in which structure appears or disappears as bonds are made or broken. Thus, Figures 7E, 7F and 7G have here been shown *without* the arrows indicating whether these changes 'just happen' or not. Shown on their own without the accompanying energy changes, the pictures would be potentially misleading, suggesting for example, that particles always have a tendency to split into smaller particles. We shall discuss energy changes related to bond-making and bond-breaking in the next section.

Figures 7H, 7I and 7J show the reverse processes, in which structure is created. These might represent, for example, molten lava solidifying (Figure 7H), corrosion (Figure 7I) and the synthesis of polythene from ethene (Figure 7J).

We have seen earlier that differences tend to be useful, especially as it is rather easy for differences to disappear but harder to make them. Pure gold is valuable because of a concentration difference, and a block of ice on a warm day is useful because of a temperature difference. In what ways are differences in structure or complexity of particles in a substance useful? We can recognise substances which exhibit two kinds of 'usefulness' - those which are useful for what they *are*, and those which are useful for what they *do*.

Some substances are useful for what they are. Thus, wood and plastic consist of complex molecules which need to be synthesised from smaller molecules - the creation of complexity at the microscopic level. They are useful because it is from such materials that objects may be fashioned - the creation of complexity at the macroscopic level. Enzymes are also useful molecules because of their very complex and specific structure, which allow them to catalyse biochemical reactions.

Other substances are useful because they can *create other differences*. Thus, fuels are useful because they create *differences in temperature* - they can make something hotter than its surroundings. Sometimes it may be useful for a chemical reaction to make something colder than its surroundings. In a rocket, a fuel is used not so much to create a temperature difference (though it does), but a *pressure*



**Figure 7**

**Kinds of changes involving particles**

*difference.* It produces gases at a higher pressure than the surroundings. We could think of such substances as 'stored differences', and we will look at these in more detail in the following section.

### Examples

Air escapes from a blow-up balloon.

A drop of ink spreads in water.

Air is pumped into a compressed air cylinder.

Salt water is distilled to make pure water.

An ice cream melts.

Water is electrolysed to form hydrogen and oxygen.

Organic matter is decomposed by bacteria in the soil.

The molecules in the liquid crystal display of a calculator become 'lined up'.

Copper, when heated, reacts with oxygen in the air.

A protein is synthesised from amino acids.

(High energy photons arrive at the Earth from the Sun, and the energy is radiated away by a smaller number of low energy photons. This is also an example in which the number of particles changes, though in this case not particles of matter.)



## 7 Storing differences in 'chemical springs'

*A fuel is half a 'chemical spring' which has been pulled apart.*

*Energy spreads when the spring's released - with a push to make it start.*

Many simple changes occur because *either* matter *or* energy spreads out. Salt dissolves because *matter* spreads out and tea cools because *energy* spreads out. In chemical reactions, however, we need to pay attention to what is happening both to matter *and* to energy. Hence, they are perhaps the most difficult kind of change to understand. A spontaneous chemical change happens because matter or energy or both spread out.

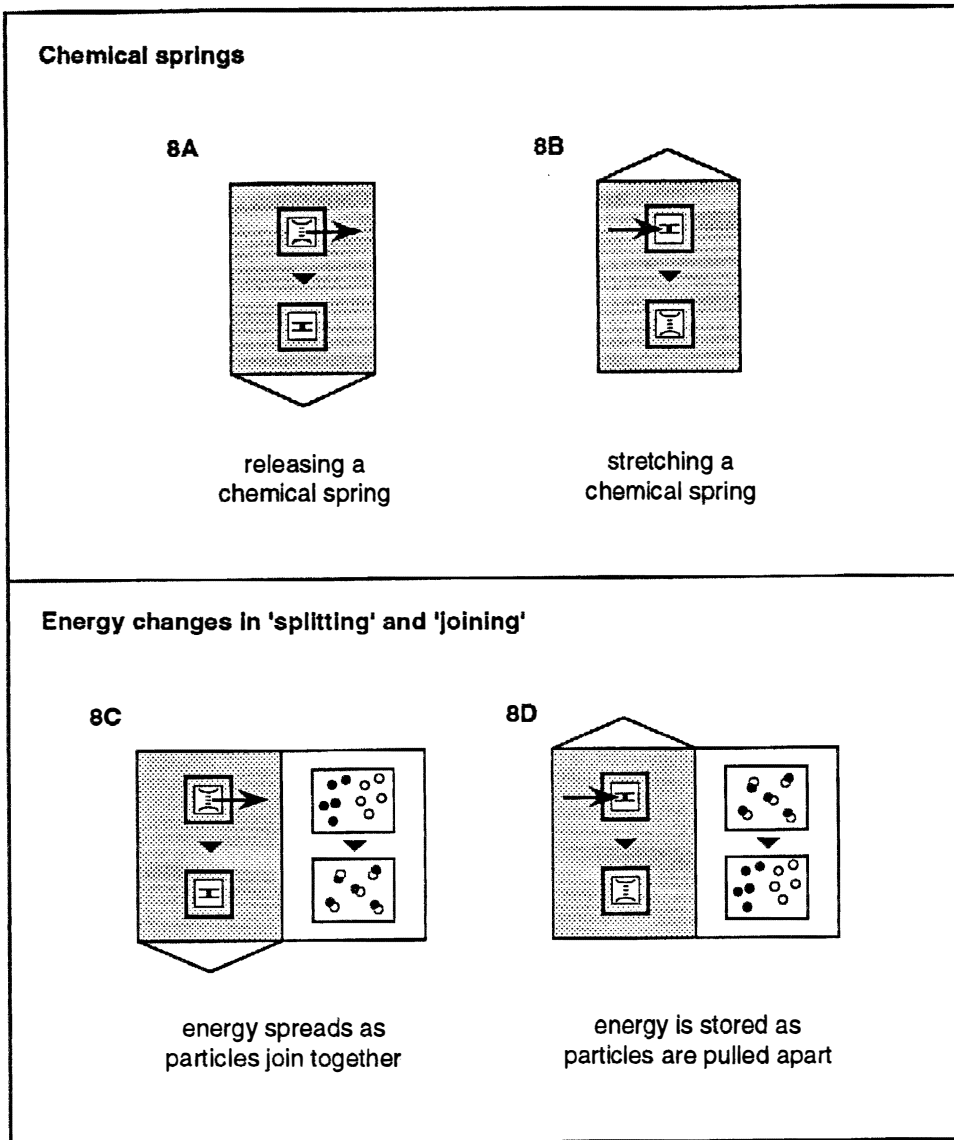
Combustion is an example of a change which is driven mainly by the spreading of *energy*. However, it is wrong to think of energy as being stored in the fuel itself; rather we should think of the energy being stored in the *fuel-oxygen system*. A good example is the hydrogen-oxygen system. When water is electrolysed, hydrogen and oxygen are pulled apart, and energy is stored - it is concentrated in the 'hydrogen-oxygen spring'. Figure 8B represents the 'pulling apart' of a 'chemical spring'. When hydrogen and oxygen are burnt together, the energy escapes and spreads out into the surrounding. Figure 8A represents the 'release' of a 'chemical spring'. Just like a stretched spring, a mixture of hydrogen and oxygen could stay the same forever. To get it going, it needs to be released or 'given a push', but once started, the change 'just happens by itself'. The sound of the explosion when hydrogen and oxygen react is very evocative of a large spring 'snapping shut'.

Figures 8C and 8D represent the change in more detail, showing both what is happening to particles and to energy. A widely held belief is that energy is stored in bonds and released when the bonds are broken. These pictures emphasise that in 'joining' energy spreads out while in 'splitting' energy is stored. And it is the spreading out of energy as particles join together that keeps them together. Thus, a ball which falls off a cliff does not bounce back up to where it was because energy spreads out and is spread amongst many particles. In the same way, when hydrogen and oxygen react to form water, this is rather like falling over a 'chemical cliff' with energy spreading out in the same way. The particles do not 'bounce back', and the water molecule does not fall apart unless energy can be concentrated in the water molecule again.

This idea, that energy is stored when particles are pulled apart, is fundamental to understanding chemical change. To make the point more forcibly, the story about hydrogen and oxygen above has been simplified. In fact, when hydrogen and oxygen burn together bonds are broken in addition to being formed - hydrogen and oxygen molecules break apart before the atoms re-combine to form water molecules. However, with pupils, this is part of the story which can be left until much later.

In nearly all chemical reactions, bonds are both made *and* broken as particles become re-arranged. Thus, it is the relative strengths of the bonds which are broken and formed which determines whether the reaction overall is like a chemical spring being stretched or released. Two examples are discussed below.

Hydrogen, made by electrolysing water, can be used to produce electricity in a fuel cell, but one difficulty in using it commercially as a fuel is that there is no easy way to store it conveniently. Nature



**Figure 8**

**Stretching and releasing 'chemical springs'**

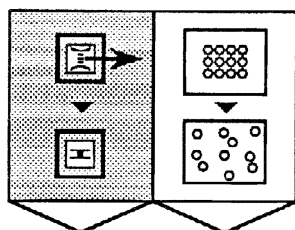
has solved this problem neatly - in photosynthesis, after splitting hydrogen from oxygen, the hydrogen is attached to carbon from carbon dioxide to make glucose. Pulling hydrogen off glucose molecules is easier than pulling it off water molecules. So, we can look upon glucose as a 'hydrogen store' with energy stored in the hydrogen-oxygen spring.

Similarly, talk about 'high energy bonds' in ATP is confusing - when a phosphate group is attached to ADP, it is being pulled away from solvent water molecules. The phosphate group is attached rather loosely to the ADP. Energy is stored in the 'phosphate-water' spring, and escapes when the phosphate group is grabbed back by the water molecules.

We can think of a stretched chemical spring as a 'stored difference'. A fuel is valuable because it allows us to create a temperature difference which in turn can drive a useful change of some kind, such as heating a saucepan of water or driving an engine. In animals and plants, ATP helps drive growth and movement. Again, a difference is being used to create another difference.

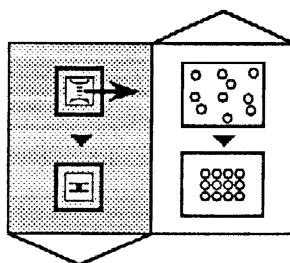
## Kinds of chemical change

9A



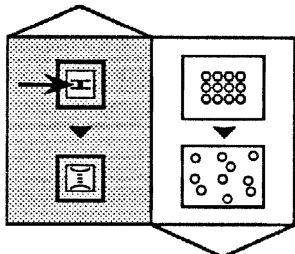
a chemical reaction which can 'just happen' - driven by energy and matter spreading out  
(e.g. a candle burns)

9B



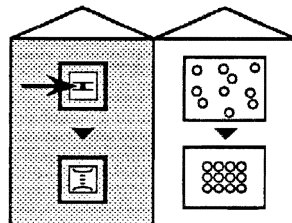
a chemical reaction which may 'just happen' - driven by energy spreading out  
(e.g. magnesium burns)

9C



a chemical reaction which may 'just happen' - driven by matter spreading out  
(e.g. calcium carbonate decomposes)

9D



a chemical reaction which does not 'just happen' - neither energy nor matter spreads out  
(e.g. photosynthesis)

Figure 9

Chemical reactions may be driven by the spreading of matter or energy or both.

We have seen that combustion reactions are driven mainly by the spreading of energy, as 'chemical springs' are released, though in most combustion reactions, matter spreads out as well. In many chemical reactions, however, matter may become more concentrated at the expense of energy spreading out, or vice versa. Many other chemical reactions do not 'just happen by themselves', because neither matter nor energy spreads out. Figure 9 summarises these different kinds of chemical change.

Figure 9A shows a chemical reaction, such as combustion of fossil fuels or respiration, which is driven by the spreading out of both energy and matter. (The picture on the left shows energy spreading as a chemical spring is released. Matter can become more disordered and spread out in various ways as already shown in Figure 7. The picture on the right is a general representation of any change in which matter becomes more disordered or spread out). In Figure 9B, there are two competing tendencies - energy spreading and matter bunching together. Whether the reaction 'just happens' or not depends on whether the effect of the 'energy spreading' is large enough to drive the 'bunching together of matter'. An example is the combustion of magnesium - energy spreads out and this drives the bunching

together of the particles as oxygen gas combines with the magnesium forming solid magnesium oxide. Other examples are rusting, and copper sulphate crystals forming from a hot solution.

Conversely, in all spontaneous endothermic reactions particles become more disordered - this drives the 'concentrating' of energy. Figure 9C shows a change in which a chemical spring may be stretched and energy stored, driven by the spreading of matter. An example is the use of a 'cool pack' applied to strained muscles. The pack consists of solid ammonium nitrate and water. When the solid dissolves, matter spreads out - this drives the separation of the oppositely charged ions (the 'chemical springs'). Energy is taken from the water, which becomes colder, and is stored in the chemical springs. Another example of an endothermic reaction driven by the spreading of matter is the decomposition of calcium carbonate - though this only occurs at a high temperature. Ice melting is yet another example.

Photosynthesis is a change which does not occur spontaneously or 'just by itself' because both matter and energy become less spread out. Figure 9D represents this. Energy is stored as hydrogen and oxygen in water are pulled apart. Matter also becomes more ordered - this happens in various ways. For example, the small proportion of carbon dioxide in the air needs to be concentrated (see Figure 7C), it needs to be separated from the other gases in the air (see Figure 7D) and it is used to create complex molecules (see Figure 7J).

### Examples

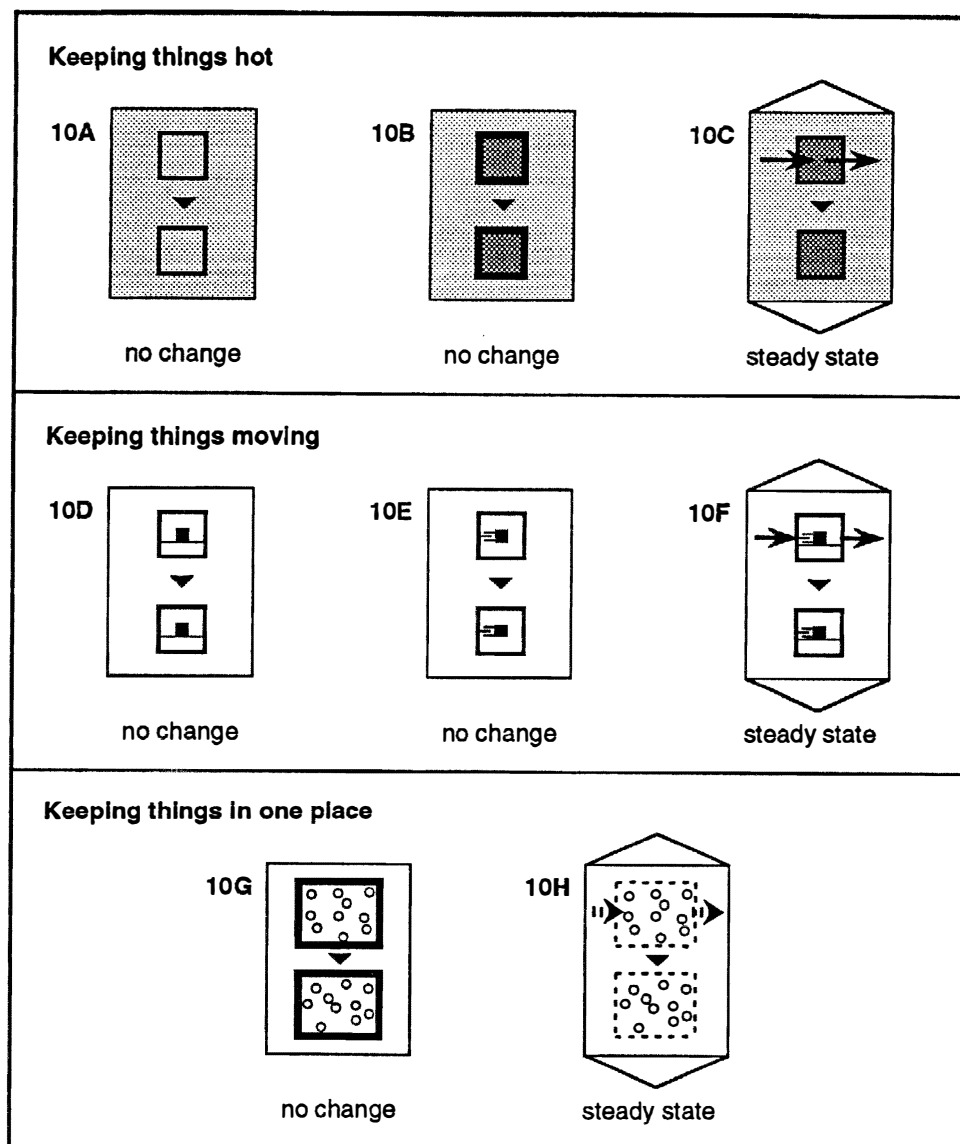
Electrolysis of water  
Burning hydrogen and oxygen  
Burning fossil fuels  
Photosynthesis  
Respiration  
Corrosion  
Smelting

## 8 Steady states - maintaining a difference

*You can stay where you are by standing still,  
But you need to keep running if you're sliding downhill.*

There is more than one way of staying the same. A bottle of red wine on a dinner table and a human being may each remain at an approximately constant temperature, but for very different reasons. The wine stays at the same temperature because it is at the *same* temperature as the surroundings (see Figure 10A). A human body is maintained at a temperature which is *different* from the surroundings.

A temperature difference may be maintained by 'walling it in'. Hot coffee in a perfectly insulated flask would stay hot forever (see Figure 10B). But in the case of the human body, the difference is maintained by using a difference to keep it going. Similarly, a warm room can be kept as it is, at a higher temperature than the air outside, by a hot radiator. Figure 10C shows a steady state system maintained at a constant temperature, away from equilibrium, with a continuous flow of energy - such a system, like other non-spontaneous changes, needs to be driven by a change which 'just happens'.



**Figure 10**

**Ways of staying the same**

A similar situation arises with moving objects, which may need to be coupled to another change to keep them moving. In the real world, objects which are moving tend to slow down, and energy spreads out. Objects do not start to move 'just by themselves' - stationary objects stay still (Figure 10D). Objects may continue to move at approximately constant speeds - the Earth moving around the Sun and a car travelling down a motorway - but for different reasons. The Earth's movement is essentially unchanging - if there is no friction, there is no energy flow, and the object continues to move (Figure 10E). Thermodynamically, however, nothing is happening. In contrast, the car maintains a constant speed because the energy input (from the engine) balances the energy output (losses due to air resistance and friction). Again, this is a steady state system (Figure 10F) which needs to be driven by a change which 'just happens'.

Steady states may also be maintained by flows of *matter*. A simple example would be a blown-up balloon. Balloons are a bit 'leaky' and because there is a pressure difference, air tends to escape from the balloon. This pressure difference could be maintained if the walls of the container did not leak - as in the case of compressed air in a cylinder (see Figure 10G). In a leaky container, the pressure difference could be maintained by a continuous flow of air into the cylinder to balance that escaping

(Figure 10H). Many steady state systems are kept away from *chemical equilibrium* by flows of matter. In an industrial chemical plant, reactants flow into and products flow out of reaction chambers. The composition of the mixture inside a reaction chamber remains the same despite constant chemical change. In the same way, we maintain our bodies in the same chemical state by a constant supply of food.

Many systems are maintained far from balance with the environment by a constant flow of energy or matter or both. Examples of such 'steady state systems' include simple domestic situations, biological systems, and large-scale phenomena, such as a centrally-heated room, a flame, a saucepan kept boiling, a living organism, an ecosystem, a tornado, the Earth, and so on. And by being away from equilibrium, these themselves constitute a difference which can cause other changes, as when a flame heats a saucepan or when we run around.

### Examples

A centrally-heated room.

A human being maintained at a constant temperature.

An incubator.

The Earth maintained at a constant temperature by the Sun.

A river.

An electric drill.

A hurricane.

A flame.

The uptake and loss of water by a living organism.

An ecosystem.

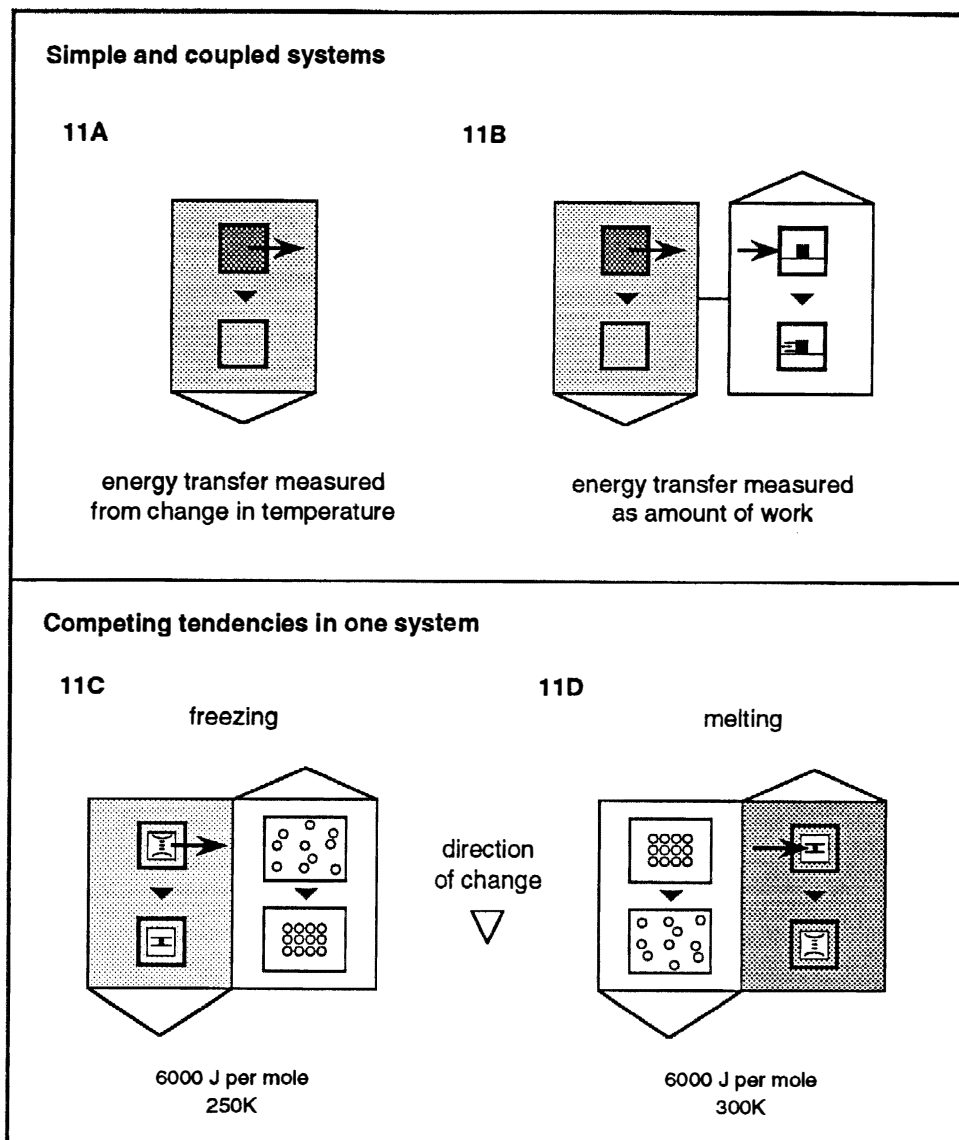
## 9 Making measurements

*"Which way?" and "How much?" are different questions.*

Energy measurements help give answers to two different kinds of question: about which way a change can go, and about how big a change can be. A block of ice cannot boil water in a pan because the temperature difference is in the wrong direction. A burning match cannot do the same, but now merely because it does not provide enough energy, though the change is in the right direction. Many (not all) changes would, if they happened, result in a state which differs in energy from the initial state. If so, the change cannot happen unless the required amount of energy is provided or taken away. Thus as well as knowing whether a change can happen at all in a given direction, we need to know how much change can be expected. Differences decide directions: amounts of energy set constraints.

The everyday notion of energy contains both ideas at the same time, so they are easily confused. A moving football will stretch the goal net but not break a wall (a judgment of *how much*), but if it hits something it will tend to deform or move it (a judgment of *direction*). Human beings who eat too much and don't exercise get fat (*how much*); food is necessary for life to continue at all (*direction*). The language of differences driving change can help, because we can ask two different questions: how much energy has to be transferred to get from A to B, and what difference(s) could drive the change from A to B?





**Figure 11**

**Measuring energy transfers**

Human perceptions of amounts of energy are rather unreliable. We are unduly impressed by the relatively small amounts of energy involved in making things move or lifting them up, as compared with the amounts involved in warming them up. Energies involved in chemical change are even more striking: we live on quite a small mass of food and we drive cars long distances on not many litres of petrol. The fundamental reason is that molecular speeds in thermal motion are much larger than most speeds we are accustomed to, and that chemical bond energies are much larger than the energy of thermal motion (if they weren't, compounds would always be coming apart).

Changes can involve energy being transferred in several ways. Figure 11A shows energy going from something hotter to something cooler. We can measure how much energy goes from one to the other using the temperature change of either. Figure 11B suggests how the spontaneous process of energy going from hotter to cooler can be used to divert some energy to make something move. This diverted energy can be exported along a drive shaft for example, this being indicated by the link between the two processes in Figure 11B. Such a transfer of energy from one thing to another is measured as an amount of work. When this energy arrives, all of it can run downhill and so help to drive a change

(such as getting something moving) uphill. How much change can be produced depends on how much energy is passed across.

The linking between systems by way of transferring energy between them can be done in many ways. Besides being carried by the momentum of a drive belt or by the angular momentum of a rotating shaft, it can be carried electrically, or by mechanical or electromagnetic waves. It is this variety in ways of transporting energy from place to place which is often described in terms of 'forms of energy'. But light, rotation or water waves are not forms of energy. They are carriers of energy. How much is transferred decides how much change can happen at the other end.

By contrast, Figure 11C and D represent changes within one system. For example, when we light a fire the changes all happen within one system, some going downhill and others driven uphill, with the whole being on balance downhill. But when we plug in an electric kettle at home, a change which happens all by itself in one place (the power station) drives a change in another place (the kettle at home). What is transmitted is not just energy: the electrical potential difference created at the power station appears (after changes of voltage in transformers) at the power point in the home. That transportable electrical potential difference can drive the creation of a temperature difference. How much the water is heated depends on how much energy is carried across electrically, but *that* it is heated at all depends on there being a potential difference. Thus the links between systems as in Figure 11B indicate the transfer of energy and of difference.

What is called *doing work* is transporting energy without destroying a difference (without increasing the entropy). A potential difference is valuable because energy going down it all goes downhill. Energy transferred by way of working is similarly valuable. Thus an engine in one place can transfer energy by doing work to drive a refrigerator uphill, paying for this by letting some of the energy arriving run downhill and get spread out. How much ice gets made depends on how much energy arrives. But that ice gets made at all in a warm room depends on the possibility of letting the incoming energy run downhill.

The question how much ice gets made has an answer in terms of energy. To make one mole of ice 6000 J has to be removed from the water. To make ten moles of ice, 60,000 J must be removed. The same value, 6000 J per mole, plays a role in deciding at what temperature water and ice are in equilibrium, that is, what is the temperature below which water freezes and above which ice melts? Spreading 6000 J per mole of water freezing into the surroundings goes downhill. How far downhill it goes depends on the temperature: spreading a given amount of energy in cold surroundings goes further downhill than spreading that amount in warmer surroundings. A clap in a quiet room has more impact than one in a noisy party. So spreading 6000 J per mole in cold surroundings can go further downhill than the ordering of water molecules into a crystal goes uphill. If so, water freezes, as in Figure 11C.

Now consider the process the other way round. Ice will not melt in cold surroundings because getting 6000 J per mole from cold surroundings goes further *uphill* than destroying the crystalline order goes downhill. Such a process won't happen without further external aid. But ice *will* melt in warm surroundings as in Figure 11D. Getting 6000 J per mole from warm surroundings does not go so very far uphill (there is a high concentration of energy on which to draw), and can be more than balanced by the downhill drop corresponding to making the molecular arrangement less orderly. Again, water will

not freeze in warm surroundings, because the downhill drop due to spreading energy into the surroundings is less than the uphill climb to order the molecules.

The equilibrium temperature is the temperature at which the two hills are equal. Water freezes and ice melts, both at the same time, because the uphill and downhill changes are the same, in either direction.

In "Scientific Background" in this booklet, we explain how these calculations can be made.

## Background science

Here, we outline briefly how the story of change driven by differences can be translated into the orthodox language of thermodynamics: of entropy, Gibbs free energy, chemical potential, and so on. Teachers who will be responsible for later work on chemical and physical change, at GCSE and at A-level, will want to see how the qualitative thinking embodied in pictures of change can be made quantitative. And many will want to see for themselves how the links are made, or at least to be assured that they can be made. For each section in 'Telling the story in pictures', there is a section here giving some of this scientific background.

### 1 Backwards and forwards

The direction of spontaneous change is always such that the total entropy *increases*.

The entropy measures how smoothed out a system composed of many particles is, including the arrangement and the distribution of energy amongst the particles. The entropy  $S$  of a system is given by:

$$S = k \ln W$$

where  $k$  is the Boltzmann constant and  $W$  is the total number of microstates consistent with a given macroscopic state. If the matter and energy in a system are unevenly spread out, the number of microstates is less than it might be, so that the system has a smaller entropy compared to a more evenly spread out state.

Thus a low entropy corresponds to the existence of differences: differences of concentration of matter and energy. The direction of spontaneous change is therefore that which tends to decrease existing differences. Matter diffuses down concentration gradients. Heat flows down temperature gradients. Masses fall down gravitational potential gradients. Charges go down electrical potential gradients. And chemical reactions go down chemical potential hills or slopes.

An increase  $\epsilon$  in the potential energy of a particle, when that energy is taken from a system at temperature  $T$ , changes the number of microstates  $W$  (less energy can be shared out in fewer ways). A decrease in potential energy increases the number of microstates.  $W$  is multiplied by the Boltzmann factor:

$$\exp(-\epsilon / kT) \quad (\text{if the potential energy decreases } \epsilon \text{ is negative and } -\epsilon \text{ is positive})$$

so that the entropy changes by:

$$\Delta S = -\epsilon / T$$

When potential energies decrease, the entropy increases. Thus, the reason water ends up in lakes at the bottoms of valleys is that this spreads around the energy to the maximum possible extent. We can correctly say that such differences in potential energies drive change. For this reason, we can say, 'Everything tends to go downhill'. We just need to learn a few new meanings for 'downhill'.

## 2 Spreading and mixing of matter

Why does matter go from where there is a lot to where there is not? If you could write your name with particles that then jumped around at random, it would soon vanish. Particles going nowhere in particular end up nowhere in particular. Any special pattern, such as crowding many particles in one small region, will go away. The most frequent patterns are just those which appear in many ways.

A simple model illustrates some quantitative concepts. Consider a model 'universe' with  $N$  particles each of which can occupy one of  $C$  cells, so that  $N$  cells are full and  $C - N$  are empty. Let them exchange particles with an additional cell. Like the others it will be empty  $C - N$  times for every  $N$  times it is full. When it is empty, the  $C$  cells share an additional particle, changing the number of ways in which particles can be distributed amongst them. Let  $\lambda$  be the ratio  $W_{+1}/W$  of the number of arrangements with and without an extra particle. Since how often an event happens is in proportion to the number of arrangements in which it happens:

$\lambda = (C - N)/N$  which is approximately  $C/N$  if  $N$  is small compared to  $C$ .

The quantity  $\lambda$  is called the *activity*: the factor by which  $W$  is multiplied when one particle is added, or by which  $W$  is divided when a particle is removed. We see that  $\lambda$  is largest when the concentration  $N/C$  is small. A shout in a silent room has more impact than one at a noisy party. Thus taking a particle from a concentrated region diminishes  $W$  by less than adding it to a less concentrated region increases  $W$ . Overall,  $W$  and thus the entropy increases. There is a difference between two regions if there is a difference in their activities.

The behaviour of an ideal monatomic gas can be modelled by imagining the molecules shared amongst imaginary cells with sides about equal to the de Broglie wavelength of particles moving at speeds typical for the given temperature. The activity of such a gas can be written:

$$\lambda = n_q/n$$

where  $n$  is the concentration and  $n_q$  is the 'quantum concentration' if all the 'cells' were to be full.

The atmosphere becomes thinner at higher altitudes. Gravity pulls the molecules down, making the atmosphere denser (more concentrated) lower down. Diffusion from more dense to less dense pushes them up again.

The gravity potential hill goes downhill towards the Earth. The concentration potential hill goes downhill away from it. The atmosphere settles down with a certain decrease of density with height when these two slopes cancel one another. We can equate the two tendencies using the idea of chemical potential:

$$\mu = -kT \ln \lambda \text{ for adding one particle or } \mu = -RT \ln \lambda \text{ for adding one mole of particles.}$$

If we have an entropy change  $k \ln \lambda$  due to shifting molecules from one place or kind to another, we can multiply it by the temperature, change the sign, and regard the result as a difference in potential. It is the potential energy per particle (or per mole) giving that entropy increase if it is dissipated. For a gas, the concentration  $n$  is very much smaller than the quantum concentration  $n_q$ , so the chemical potential is proportional to the concentration (or density or pressure).

Numerically, the gravitational slope near the Earth is 10 joules per kg per metre. Expressed as a chemical potential (per mole and not per kg) it is 0.28 joules per mole of nitrogen per metre. Equated to  $RT \ln (\text{concentration ratio})$  this gives us the concentration (and so density or pressure) ratio

between different heights. The ratio is about 3 to 1 for a height of 10 km. Chemical potential differences work just like other potential differences, driving change.

In general, a chemical potential difference is measured by the external potential difference which just stops the reaction the chemical potential difference drives. An obvious example is osmosis, driven by a difference in concentration and stopped by the difference in pressure produced as a result.

### 3 Energy flows and temperature differences

Why does energy go from where there is a lot to where there is not? Temperature can be thought of as the degree of concentration of energy. Quanta of energy go from high to low energy concentration just as particles go from high to low particle concentration.

We can re-write the Boltzmann factor as:

$$1/T = (k \Delta \ln W)/\epsilon$$

to say that the lower the temperature, the more the entropy increases for a given energy  $\epsilon$  added to a thermal system.

Another simplified model brings out the essentials. Imagine a material made of atoms which have only two energy states, 'high' and 'low'. Adding one quantum of energy switches one atom from 'low' to 'high'. An argument similar to that above about molecules in cells shows that doing this multiplies the number of arrangements of quanta between atoms by the ratio  $N_{\text{low}}/N_{\text{high}}$ . Adding one quantum to a cool block with a large value of  $N_{\text{low}}$  multiplies  $W$  by a lot; taking that quantum from a warmer block with a large value of  $N_{\text{high}}$  reduces  $W$ , but by less. Overall,  $W$  increases. If energy can go at random between the atoms in the two blocks it will go more often *from* the one with more high energy atoms *to* the one with fewer, merely because energy can only come from an atom with high energy and go to one with low energy.

The same idea can be expressed in entropy language. As energy leaves the hot object the entropy decreases. The entropy change is  $Q/T_h$ , where  $Q$  is the energy lost and  $T_h$  is the temperature of the hot object. As energy enters the cold object the entropy increases. The change is  $Q/T_c$  where  $T_c$  is the temperature of the cold object. Since  $T_c < T_h$ , the total entropy change ( $Q/T_c - Q/T_h$ ) is positive and the change is spontaneous.

The flow of heat down a temperature gradient increases the entropy. By contrast doing work is a transfer of energy without any entropy change (lifting loads, making things move). Temperature differences drive one kind of energy transfer, which we call heat flow or thermal transfer. Differences in potential can drive others, which we call doing work.

### 4 Differences can create differences

Differences do more than spontaneously fade away. Differences often create other differences. The gravitational potential difference above the Earth creates the density gradient in the atmosphere. Temperature differences on the Earth lead to storms. The dissipating potential energy of atoms in an explosive makes the explosive hot; the high temperature and pressure makes it explode. Less dramatically, a hot flame makes water in a kettle hotter than its surroundings.



In each case differences are created: regions of *low* entropy arise. As long as the entropy *overall* increases, part of a system can indeed decrease in entropy.

Frost on the window on a cold morning is a striking case. Order and pattern has been made from disorder. Since the molecules cling more tightly together in ice, they go downhill in energy when ice forms. They can go uphill in chemical potential, as their arrangement becomes more ordered. At low temperatures, the uphill climb is smaller than the downhill drop, and ice forms. At higher temperatures the process goes the other way: a sacrifice of molecular patterning (now big) pays for the uphill climb to loosen bonds between the molecules. *Both* freezing and melting create one difference at the expense of another. It is just a question of which wins at a given temperature.

In entropy language, when water changes to ice its entropy *decreases*. But at the same time, energy leaves the ice, going to warm up the cold surroundings, *increasing* the entropy by  $Q/T_s$ , where  $Q$  is the latent heat and  $T_s$  is the temperature of the surroundings. This increase is large if  $T_s$  is small. So at low enough temperatures the entropy increase beats the entropy decrease and water freezes. When the surroundings are at the melting point, the two entropy changes are equal and there is equilibrium.

## 5 Moving things and springy things

Mechanics and thermodynamics deal with different problems. When the Earth goes round the Sun, thermodynamically *nothing has happened*. There is no change; indeed the Earth has circled the Sun in exactly the same way for at least five billion years. But when a clock spring runs down, an engine drives a car, or a footballer kicks a ball, there *has* been a thermodynamic change.

The potential (or kinetic) energy of bodies can drive change, because it can increase the total entropy as it gets randomly spread out. To go the other way we have to get energy from thermal motion, thus decreasing the entropy. This has to be paid for by a larger increase elsewhere. In a heat engine we get energy  $Q_h$  from a hot source at temperature  $T_h$ . The entropy decreases by  $Q_h/T_h$ . To pay for this we throw away energy  $Q_c$  into cooler surroundings at temperature  $T_c$ . The entropy increases by  $Q_c/T_c$ . The amount  $Q_h$  taken from the source can be more than the amount  $Q_c$  thrown away as long as  $T_h$  is bigger than  $T_c$ , so that overall the entropy increases. We must have:

$$Q_h / Q_c < T_h / T_c$$

from which it follows that the amount  $Q_h - Q_c$  we can use to move or lift things is limited by:

$$Q_h - Q_c < Q_h (1 - T_c/T_h)$$

The maximum difference  $Q_h - Q_c$  is very much like the potential energy of a spring. All of it is available for use in whatever way we like. It can be called the free energy of the heat engine - the maximum work available from it.

It is very handy to make differences portable. In that way we can make them in one place and use them in another.

If an engine can drive a shaft, we can use the work it produces in a nearby machine. Better is to create an electrical potential difference, and transmit that along wires. In that case, the destruction of a difference in a power station can pay for the creation of a difference in homes hundreds of kilometres away. Ideally, we do the transmission without loss; that is without entropy increase (by doing work).

To make movement or to lift things we do not so much need energy as difference. A block of ice, colder than the surroundings, can be used to drive an engine. In melting, the ice can be got to take more energy from the surroundings than it needs to loosen the bonds between molecules, and to deliver by doing work the part it does not need.

## 6 Particles - joining and splitting, building and breaking

In a chemical reaction, particles are taken apart and put together again into new ones. There is a tendency for chemical reactions to go in the direction which produces more particles.

Consider the Haber process:  $\text{N}_2 + 3\text{H}_2 \rightleftharpoons 2\text{NH}_3$

This process gets rid of four molecules and produces only two. Adding molecules goes downhill and removing them goes uphill (more molecules can be arranged in more ways), so this is liable to go uphill overall. But if we start with a very low concentration of ammonia, adding ammonia molecules will go a long way downhill. This is why there is always *some* ammonia formed. Also, we start with high concentrations of nitrogen and hydrogen. If so, removing even one nitrogen and three hydrogen molecules might not go so far uphill. A high initial pressure may help, by reducing the uphill side of the equation.

This argument makes it easy to see why ethene polymerises best at high pressures: only a few big molecules are created at the expense of removing many smaller ones.

Other contributions to the overall chemical potential difference will come from changing the numbers of molecules of different species with which they can mix. Generally, removing molecules reduces the number of mixed arrangements, so going uphill in chemical potential difference, while adding them goes downhill.

## 7 Storing differences in chemical springs

The direction of a chemical reaction is determined not only by the changes in the numbers of particles, but also by the energy changes as particles are taken apart and put together. Equilibrium is reached when competing tendencies balance each other.

Chemical equilibrium is a balance between potential differences. For example, to dissociate a hydrogen molecule requires potential energy to be found to tear it apart, going uphill. But dissociating a hydrogen molecule makes two particles where before there was one, so going downhill in chemical potential. When the two opposing hills are equal, we have equilibrium.

The chemical potential hill is higher the higher the temperature. This is because it is easier to get energy out of the random motion of something hot. Thus if the temperature is raised, more hydrogen tends to dissociate, and if it is lowered, more tends to associate.

As a chemical reaction proceeds, the concentrations of different kinds of particles change, and the heights of the chemical potential hills change. Reactions stop when all the potential hills combine to give level ground. Pure water is slightly ionised ( $\text{pH} = 7$ ) because with rather few ions and many molecules the chemical potential hill runs steeply downhill towards the ionised state, so it ionises despite the steep uphill climb to pull the ions apart.

Exothermic reactions go downhill in potential energy. In many cases, the entropy increase as this energy is spread around in the reacting substances and their surroundings dominates other entropy

changes, for example from changes in numbers of particles. Such reactions thus often go, especially at low temperatures where the entropy increase is largest.

Endothermic reactions go uphill in potential energy, needing to grab energy from the thermal surroundings. For this to happen there must be a bigger chemical potential hill going downhill in the direction of the reaction. This might arise from an increase in the number of particles, from movement of particles from high to low concentration, a loss of ordering of particles (as when ice melts), and so on. Endothermic reactions tend to go at higher temperatures, because the entropy penalty for getting energy from something hot is then smaller. Or, to say the same thing another way, chemical potential differences are bigger in magnitude the higher the temperature.

Chemical reactions, for example those in dry cells, can provide free energy able to be used to create potential energy differences or set things moving. A chemical reaction can go if the free energy decreases, that is, if overall it goes downhill. At equilibrium, the chemical potential difference is zero.

Chemical potential difference is more complicated and less intuitive than (say) gravitational potential difference, because it arises from several different sources. Sources of a fall in chemical potential include moving molecules from a concentrated to a dilute region, increasing the volume available to particles, creating more particles by breaking up big molecules, mixing different types of particles together, and removing spatial ordering of particles.

## 8 Steady states - maintaining a difference

Living organisms and centrally heated houses have one thing in common: they are kept in a steady state away from equilibrium. They are kept different from their surroundings.

This is done by continually consuming free energy, in food or fuel. A similar story applies to the Earth. It is kept far from equilibrium by the influx of hot photons from the Sun, destroying free energy by exporting cool photons to the rest of the Universe. This destruction pays for the increase in free energy required for plants to make the complex molecules which provide the free energy we humans eat.

As human beings we are able to make actions. Besides being open systems, maintained in a steady state far from equilibrium by a continual consumption of free energy, we also store free energy. We can act by using up this stored free energy. This is one reason we keep warm, so as to export the accumulated entropy arising from using up this free energy. Thus, although it appears that life circumvents the Second Law, what it does is to exploit it (Schrödinger 1944). It uses free energy to do what is exciting and important in the world, namely to make new things; to create order or pattern; or to make new life.

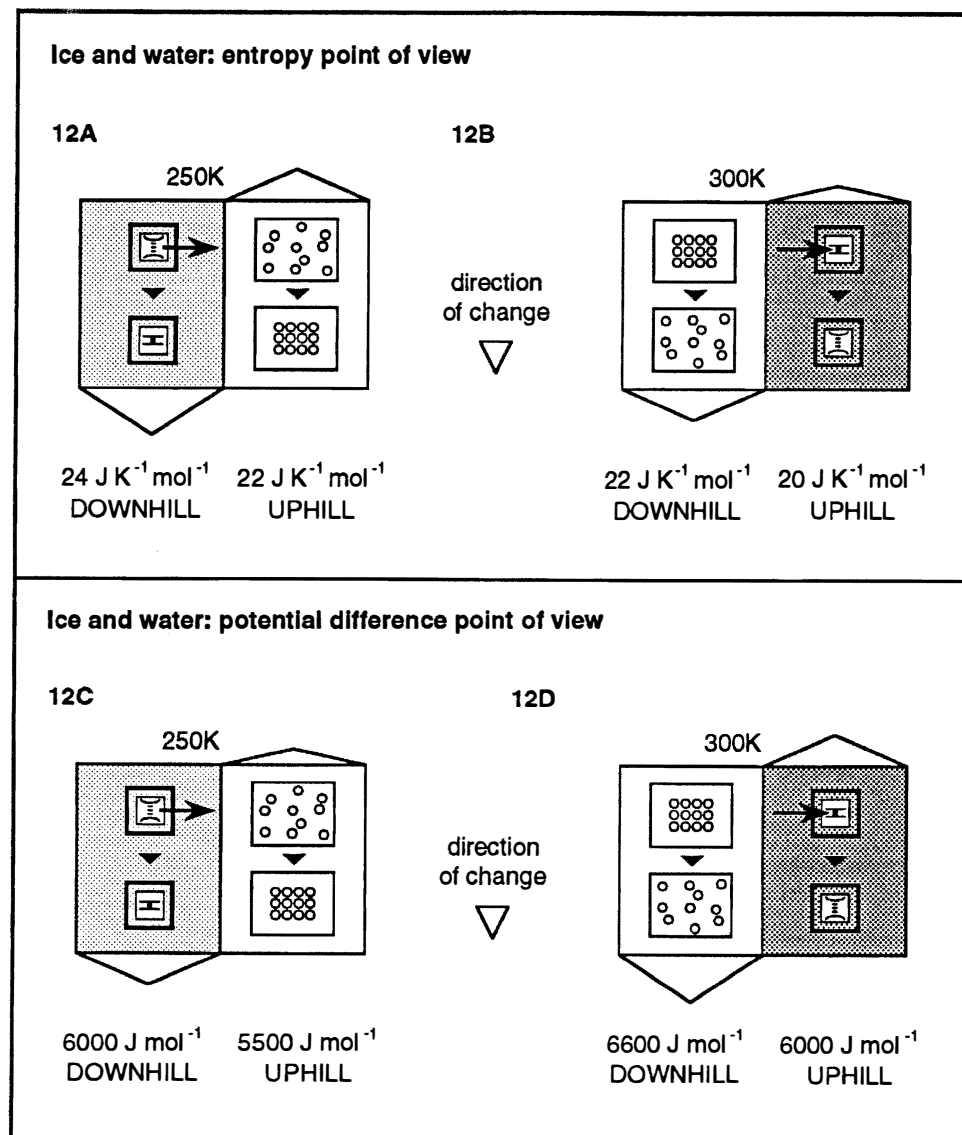
## 9 Making measurements

It is possible to think of the pictures we use as terms to be added up in a calculation, either of a total potential difference or (equivalently) of entropy changes. The pictures are drawn to go down potential hills for spontaneous change. If thought of as representing entropy changes, the entropy must *increase* to go downhill.

For some pictures the potential difference can be calculated. For a spring-like change in which a bond forms, the potential energy difference is just the energy change per particle (or per mole of particles). For particles going downhill by diffusing from high to low concentration the chemical potential difference is just  $-NkT \ln(\text{ratio of concentrations})$ . For  $N$  particles spreading into twice the volume it

is just  $-NkT \ln 2$ . In other cases, such as the freezing of water, or the reaction in a dry cell, the chemical potential difference has to be measured, often by seeing where the equilibrium lies and measuring the opposing potential energy change. Sometimes part but not all of the contribution to the chemical potential difference can be calculated. An example is the concentration terms which appear in expressions for equilibrium constants. Thus we get something like  $[H]^2/[H_2]$  in the equilibrium constant for the dissociation of hydrogen directly from the effect on the entropy, and so on the chemical potential, of turning one hydrogen molecule into two hydrogen atoms, at the prevailing concentrations of each.

Figure 12 shows two equivalent ways of using measured energy changes to understand equilibrium, in the simple case of water and ice, as discussed qualitatively earlier in this booklet (see Section 9 of 'Telling the story in pictures'). The entropy change involved in re-ordering  $H_2O$  molecules from water to ice is  $-22 \text{ J K}^{-1}\text{mol}^{-1}$ . The energy which must be spread out into the surroundings as bonds form is  $6000 \text{ J mol}^{-1}$ . In Figure 12A and B we show calculations in terms of entropy changes. In Figure 12C and D we show exactly the same calculation done in terms of potential differences, which expressed as Gibbs free energy per mole are very familiar to chemists.



**Figure 12**

Two ways of looking at what decides the direction of change

In Figure 12A, showing water freezing at 250K, the energy  $6000 \text{ J mol}^{-1}$  released as bonds form is spread out into surroundings at 250K, increasing the total entropy by  $24 \text{ J K}^{-1}\text{mol}^{-1}$ . This value is obtained by dividing the energy exchanged by the temperature. The formation of order in the ice crystal decreases the total entropy by only  $22 \text{ J K}^{-1}\text{mol}^{-1}$ . The difference is positive in the direction of freezing, and water freezes spontaneously. Figure 12 B shows what happens at 300 K. If ice melts, the same energy,  $6000 \text{ J mol}^{-1}$ , is now taken from the surroundings, and reduces the total entropy. But the reduction, again found by dividing the energy exchanged by the temperature, is now only  $20 \text{ J mol}^{-1}$  (it is easy to get energy from hot things). The entropy change due to going from ordered ice to less ordered water is still  $22 \text{ J K}^{-1}\text{mol}^{-1}$ , but is now an increase. The difference is positive in the direction of ice melting, and ice melts spontaneously. The equilibrium lies at the temperature 273 K at which the two entropy changes are numerically equal, and in fact of course the entropy change of the ice-water part of the system was calculated by dividing the energy exchanged by this temperature.

Figure 12 C and D shows a different way of solving the problem of comparing changes due to energy flow with changes due to ordering molecules, this time in terms of chemical potential difference. In Figure 12C, water freezing, we think of the downhill potential energy drop of  $6000 \text{ J mol}^{-1}$  as driving the reaction in the direction of freezing. We now need a potential energy hill to represent the uphill effect of the molecules becoming ordered. The entropy change  $22 \text{ J K}^{-1}\text{mol}^{-1}$  multiplied by the temperature 250K ( $T\Delta S$ ) is the energy that would have to be got from the surroundings at 250K to produce the same entropy reduction as ordering the molecules produces. It is  $5500 \text{ J mol}^{-1}$  which is less than the potential energy difference in the direction of freezing. So water freezes, going further downhill than uphill. In Figure 12D, we still have a potential energy change of  $6000 \text{ J mol}^{-1}$  but now it goes uphill. The potential energy change  $T\Delta S$  which would increase the entropy of the surroundings at 300 K by as much as removing order amongst the molecules is now larger,  $6600 \text{ J mol}^{-1}$ . The net potential energy difference is now downhill in the direction of water melting. Equilibrium lies at the temperature, 273K, at which the potential energy difference equivalent to the change of order amongst the molecules is equal to the difference in bond potential energy.

This second way of thinking, in terms of chemical potential differences, is the way most chemical equilibria are expressed. For example, in the Nernst equation, the potential difference of a cell is calculated from an expression of the form  $RT \ln[\text{concentration ratios}]$ , which is a chemical potential difference (or, equivalently, an entropy change per mole  $R \ln[\text{concentration ratios}]$  multiplied by the temperature). From an entropy point of view, the calculation using chemical potentials looks artificial, making a constant entropy change look like a temperature dependent energy. But from an energetic point of view the chemical potential is something real (the work one can get out of the system) and is temperature dependent. Also, perhaps, comparing hills in terms of potential energy differences might be thought more accessible than trying to think about entropy changes.

For example, the chemical potential difference due to a large expansion in volume is of the order  $RT \ln[\text{volume ratio}]$ . What bond energy breaking might be paid for by an expansion of 1000 times in volume at a temperature of 1000K? The result is between 55 and 60 kJ per mole. We see at once that it will generally take more than this to make covalently bonded substances dissociate, but that it is quite enough to evaporate water (40 kJ per mole).

## Your questions answered

Some of these questions are related to scientific aspects of energy and change, some to the teaching and learning of the ideas in general and some to the particular approach taken in these booklets.

### Questions about the scientific ideas

#### *What is a thermodynamic change?*

In mechanics, bodies behave (almost) like single particles, despite being made of molecules. All the molecules share a common movement or change of position. To a good approximation, the internal energy of the bodies does not change. But as soon as there is dissipation, we are doing thermodynamics. A perfectly bouncy ball is mechanics; a waterfall is thermodynamics. In general, we are in thermodynamics when changes in the arrangements of molecules and their energy have to be taken into account.

#### *What is the Second Law of Thermodynamics?*

If you have some old socks in one corner of a room, you will eventually smell them if you stand in the other corner. Why? Because molecules move around randomly. So the air molecules and the smelly molecules from the socks mix together. Arrangements of molecules tend to become *disordered*. A similar thing happens with energy. Essentially, what the Second Law says is that at the molecular level *things tend to get jumbled up or disordered*.

Talking about 'disorder' can be potentially confusing with pupils. What we *observe* is that *differences* tend towards *sameness*. A drop of ink put in water produces swirling patterns of colour. After a while the colour will be spread throughout the water. So, the *differences* in the concentration of ink will all disappear and become the *same*. A pupil may think that we should say it has become *more ordered* - it goes from 'untidy' swirls to a 'tidy' even colour - but it is at the *molecular* level that it has become *more disordered*.

The Second Law provides 'time's arrow'. We can often tell when a film is played backwards - a broken cup does not spontaneously assemble itself and waterfalls do not flow upwards.

#### *What is entropy?*

Entropy is a measure of how disordered a system is at the molecular level. Since disorder tends to increase, another way of putting the Second Law is that in a spontaneous process entropy increases. Entropy sounds a mysterious idea to many people, but it can be easily measured and calculated - its units are J/K (joules per degree Kelvin). However, with pupils it makes more sense to talk about *differences tending to disappear* than to talk about *entropy increasing*.

#### *What is the first Law of Thermodynamics?*

Historically, the First Law was formulated after the Second Law. It can be thought of as being the Law of Conservation of Energy - that energy is neither created nor destroyed.



More accurately, it says that the energy of a system changes when energy goes into or out of it, and that it doesn't matter how the energy is made to go in or out. It could be changed by heating it or by doing work on it, and these are equivalent - energy is energy.

What the First Law does is to put a constraint on the possible states of a system. A litre of paraffin can be burnt to boil up some water. The energy transferred from the paraffin will always be the same - the rate at which you burn it or the size of the wick will not affect the amount of energy.

*What is energy?*

One way of thinking of energy is simply as a value which can be calculated. Many different kinds of change take place - a candle burning, a ball rolling downhill, an electric kettle boiling some water - but for each of these you can calculate the total energy before and find that it is the same as the total energy after. We could think of this as a 'book-keeping' approach.

However, in these materials we prefer to talk about energy as 'substance-like'. So, we can talk of energy as being in a certain region, moving from one place to another, having a lot of it or a little of it, making it concentrated in one region or letting it spread out. In the activities, energy is introduced in the context of temperature differences. Temperature is seen as being a measure of the 'concentration of energy', and energy is what flows when temperature differences disappear. This approach to energy is then extended to other kinds of changes involving energy.

*If everything tends to sameness, how can anything ever be created?*

If differences only decreased, life would not be very interesting. In fact there would be no life. It is possible to *create* differences - we can make cups of tea hot, and we can make big molecules from small ones. But we can only do this by *using up other differences*.

For example, water vapour condenses on a cold window. This seems to go against what we said about matter tending to spread out. Here it is being concentrated in a small space - *a concentration difference is appearing*. But *a temperature difference is disappearing* - the water is now the same temperature as the window. A little bit of order has been created in one part of the Universe, but more disorder has appeared somewhere else. Overall, the change is of increasing disorder.

*But surely the Second Law cannot apply to living things?*

The Second Law is *universal*. Our own bodies are bound by it. When our bodies make some protein molecules to repair a cut or we put some books back on the bookshelf, we are creating a little bit of order. But overall we create more disorder - always we are 'burning' food, and energy spreads out from our warm bodies into the cooler air around us. People sometimes misinterpret the Second Law in relation to living things, thinking that the law is somehow 'suspended' until death, when the organism 'obeys' the law as it decays. Living things *constantly* create structures, and so they must *constantly* consume differences.

## Questions about teaching and learning

*Is energy the cause of change?*

No. School science books often suggest that energy is what makes things happen, but they are wrong. It is *differences* that cause change. So, a flame heats a saucepan on water. This does not happen because the flame 'has a lot of energy', but because the flame is hotter than the water (a temperature difference).

*If energy does not cause change, can there be changes where energy is not involved?*

Certainly. Pollution from a factory spreads out into the air. Energy is not involved in this process. It happens because of a concentration difference.

*Isn't heat a form of energy?*

Heat is a term which causes a lot of argument about the way it is used at school level. Strictly speaking, heat is the energy transferred from one body to another due to a temperature difference. It is not the energy contained in a body. What is usually referred to as the heat energy in a body is more correctly referred to as its internal energy. So, if you rub your finger on the table it gets hotter, but you are *not* creating heat. You are increasing the internal energy of your finger and the table by doing work. Because your finger and the table are now warmer, heat may pass from these to the cooler surroundings.

We have avoided talking about heat flow - it is simpler just to say that when a flame makes a beaker of water hot, energy has flowed from the flame to the water. This is helpful in that it reinforces the idea of changes in the arrangement of energy and matter being caused by differences (here a temperature difference).

*Why not teach about forms of energy?*

Much of the talk involving forms of energy is no more than adding verbal ornamentation to descriptions of changes. We can say that burning petrol in an engine makes a car move. We hardly gain any deeper understanding calling this a change of chemical energy to kinetic energy. Pupils do not always find it easy to find the correct labels to attach to these energy changes and often invent their own. So, a child taking part in a race might be seen as converting 'food energy to running energy'. Textbooks, as well as children, also show variations in the terms used for 'forms of energy', which complicates things further.

Further difficulties are introduced in some books, which try to associate a 'form of energy' with an object which illustrates it. For example, a can of petrol may be used to illustrate 'chemical energy', or a battery to illustrate 'electrical energy'. This is inconsistent. Why not make a can of petrol an example of 'heat energy' and a battery an example of 'chemical energy'.

In more advanced work, students will find that there are different ways of making calculations depending on the kinds of energy change involved. At this point, we may be more justified in talking about 'forms of energy'.

### *Why does the National Curriculum talk about energy transfers?*

The difficulties with the 'forms of energy' approach have led the National Curriculum to refer throughout to 'energy transfers'. While the change in terminology from 'transformation' to 'transfer' seems slight, it actually signifies a fundamental change. Talking about energy transfer stresses the importance of thinking about energy as *staying the same kind of thing* but in *going from place to place*, which is the approach taken in this booklet. Often, however, the significance of the new terminology has gone unnoticed, with patent nonsense such as 'chemical energy *transferred* to heat energy'.

However, the term 'energy transfer' is simply a label for an idea - because the term appears in the National Curriculum does not mean that more informal ways of expressing this idea are excluded. So, as well as expressions such as 'energy is transferred from X to Y', we should be encouraging pupils to say things like 'the energy is going from here to there', 'the energy is spreading out', 'energy flows from the hot thing to the cold thing', 'energy is travelling from one place to another', 'the energy is concentrated here at the start, but some of it ends up there', and so on.

### *What ideas about energy do pupils' bring to the classroom?*

In everyday talk, we say that we do, or do not, have the energy to do something. Much research into children's ideas about energy indicates that this is their starting point: that energy is associated with activity and being alive, that it represents a power to act, that it is used up. Quite correctly, children see that taking exercise can make one more energetic, not less. They may see food, not as providing energy but as triggering energy production by the body. In school textbooks, the use of the term 'energy' often slides between two contradictory meanings - as something which is used up (reinforcing the everyday meaning) and as something conserved (which pupils find difficult to reconcile with their own understanding of energy).

### *What do pupils understand about particulate theory?*

An understanding that matter is made of particles is essential to understanding the nature of a substance and of chemical reactions. If change is merely a re-arrangement of particles, mass must be conserved. However, young pupils often think, for example, that a solution will weigh less than the liquid and solid before dissolving, since the solid has disappeared. They are more likely to believe that mass is conserved if they see dissolving as a mixing of particles. In trying to make sense of particulate theory, many pupils come to think that substances *contain* rather than *consist* of particles. For example, when a liquid freezes, the particles moving around *in* the liquid stop moving because they are now trapped *in* a solid. Another common difficulty is the tendency to project from a macroscopic phenomenon to the microscopic behaviour of particles, for example, a solid expands when heated because the particles of the solid become bigger.

## **Questions about the approach in these materials**

### *There are already lots of materials for teaching about energy? Why more?*

These materials are not just concerned with teaching about what tends to be confined to a topic called 'energy'. They are relevant to many different topics across the whole of the science curriculum, and take a novel approach which is based on the idea that changes are driven by *differences*. This can help pupils to see how a few fundamental principles can account for a wide variety of phenomena.

*Why teach about the Second Law of Thermodynamics if it is not part of the National Curriculum?*

The approach taken in these materials encourages attention to be paid to many concepts in the existing curriculum in a way which helps understanding, and can help to unify these ideas and provide a framework for progression. And though the Second Law of Thermodynamics is not explicitly required by the National Curriculum, many ideas can make more sense if some attention is paid to Second Law ideas.

*There are a lot of abstract pictures. Will pupils understand them and won't it take a long time to teach?*

Often, the initial reaction from teachers who have not used the pictures, is that they will be too difficult for their pupils. However, though the pictures look unfamiliar to teachers, our experience suggests that, in general, pupils are able to understand them and use them effectively. Teachers who used the pictures with pupils are often surprised with the level of discussion that pupils are able to achieve, and that the pictures do not require a great deal of time to teach.

*Why are there a lot of terms like 'spreading out' or 'changes that just happen' that I have not come across before?*

There are *not* a lot of new terms. A very few ideas (such as differences, spreading out, 'just happening' or not 'just happening') can be used in a wide variety of cases. And you have come across them before (as potential difference, entropy, entropy increase) but not in a usable form.

*How do these activities complement practical work?*

The materials are certainly not a replacement for practical work, but they do provide ways of thinking about existing practical work. In the support materials, there are a few practical activities, where the ideas are new or less familiar, and which are not usually covered in existing schemes of work.

*There seem to be a lot of new ideas. How can I make a start?*

Many of the activities can be introduced into existing schemes of work with little previous background. This can help in 'getting a feel' for approach. Examples of suitable activities, and how they can be used, are given in the booklet 'Activities in the classroom'. Having gained some experience with what the activities are intended to achieve, they may be incorporated more systematically into existing schemes of work, and later the approach may potentially create a structure for planning revised schemes of work.

*Aren't the ideas too general except for high ability children?*

These activities have been used with pupils of a very wide range of abilities, and while they are challenging for more able pupils, they are also accessible to pupils of low ability. Indeed, because the emphasis of the activities is on group discussion and the use of abstract pictures, they can be particularly helpful for pupils who have difficulties with reading and with written tasks. While in some tasks, getting the 'correct' answer in matching a situation to a picture is important, the essential point is that the picture language is not an end in itself, but merely a device to support pupils in appropriate discussion. Our experience suggests that these pictures are effective in stimulating productive discussions with a wide range of pupils.

## A catalogue of changes

In 'Telling the story in pictures' in this booklet, a number of different pictures were introduced representing a wide variety of changes. These are summarised in Figure 13, with pictures representing fundamental kinds of changes. On the left, are changes which 'just happen', and on the right, changes which do not 'just happen'. Using this restricted set of pictures is helpful in seeing the essential features of different kinds of phenomena, making clear the nature of the coupling between spontaneous and non-spontaneous changes.

While these are the fundamental set of pictures, the wider range introduced earlier are useful if one wants to make finer discriminations between changes. Thus, in Figure 13, any change in which energy flows down a temperature gradient is represented by D1; it may often be useful to refer to more specific features of such a change, for example, whether the system is at a higher or lower temperature than the surroundings, and in this case, the pictures in Figure 3 allow such distinctions to be made. Similarly, A1 represents any kind of 'spring' (see Figure 6), and C1 represents any kind of change in which particles are becoming more spread out or disordered (see Figure 7).

In the 'catalogue' below, the pictures most relevant to each kind of change are indicated. Note that this is not intended to be 'complete' - in many cases, other pictures might have been included, depending on how the system is defined and what are deemed to be the most relevant features. The catalogue is intended to make it easy to look up a number of different examples of phenomena which are related to any of the fundamental kinds of change.

	A1	B1	C1	D1	E1		A2	B2	B3	C2	C3	D2	D3	E2
	spring relaxing	slowing down	particles spreading out	temperature difference decreasing	chemical spring relaxing	unspecified	spring stretching	speeding up	keeping moving	particles bunching together	maintaining a structure	temperature difference increasing	keeping temperature difference	chemical spring stretching
Spring is released	●													
Paper attracted to a charged comb	●													
Radioactive decay	●													
Clockwork toy released	●							●						
Bow and arrow	●							●						
Ping-pong ball released underwater	●							●						
Tides	●							●						
Nuclear bomb	●							●				●		
Nuclear reaction in Sun	●												●	
A rolling ball slowing down		●												
Stirred tea comes to rest		●												
Waves on the ocean		●						●						
A piece of lead is hammered		●										●		
Tidal power lights a bulb		●										●		

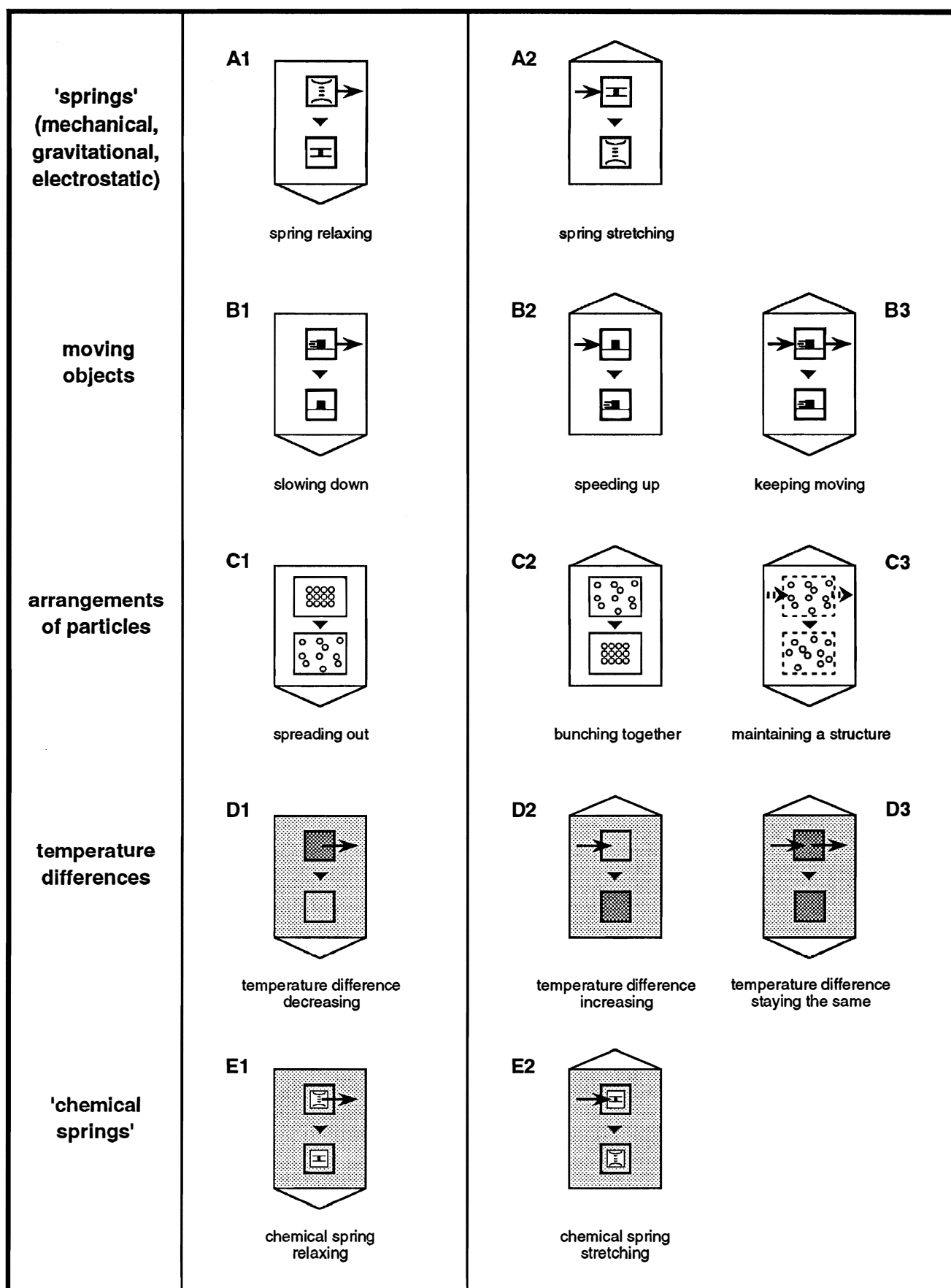


Figure 13 Fundamental kinds of changes

	A1	B1	C1	D1	E1		A2	B2	B3	C2	C3	D2	D3	E2
	spring relaxing	slowing down	particles spreading out	temperature difference decreasing	chemical spring relaxing	unspecified	spring stretching	speeding up	keeping moving	particles bunching together	maintaining a structure	temperature difference increasing	keeping temperature difference	chemical spring stretching
Dissolving			●											
Mixing coffee powder with water			●											
Sugar dissolves in water			●											
Washing dirt from clothes			●											
Air leaks from blown-up balloon			●											
Perfume spreading			●											
Pollution			●											
Salt solution evaporates			●							●				
Air released from bicycle tyre			●									●		
Endothermic reaction			●											●
Ammonium nitrate dissolves			●											●
Melting			●	●										●
An ice cream on a warm day			●	●										●
Butter in a hot pan			●	●										●
Evaporation			●	●										●
A puddle evaporates			●	●										●
Drying your hair			●	●										●
Combustion			●		●									
Respiration			●		●									
Organic matter decomposes			●		●									
Smelting			●		●					●				●
Making iron from iron ore			●		●					●				●
Zinc dissolves in acid			●		●							●		
A hot cup of tea left to cool				●										
Cold lemonade on a warm day				●										
Heating water in a saucepan				●										
Land and sea breezes				●				●						
A hurricane				●				●						
Volcano erupts				●				●						
Tectonic plates move				●				●						
Photosynthesis				●						●				●
Earth's temperature stays the same				●									●	
Freezing				●	●					●				
Water left in a freezer				●	●					●				
A lake freezing on a cold day				●	●					●				
Condensation				●	●					●				
A cold window 'misting up'				●	●					●				
Breathing out on a cold day				●	●					●				
Crystallisation				●	●					●				
Copper sulphate from hot solution				●	●					●				



	A1	B1	C1	D1	E1		A2	B2	B3	C2	C3	D2	D3	E2
	spring relaxing	slowing down	particles spreading out	temperature difference decreasing	chemical spring relaxing	unspecified	spring stretching	speeding up	keeping moving	particles bunching together	maintaining a structure	temperature difference increasing	keeping temperature difference	chemical spring stretching
Clouds form					●		●							
Muscle contracts					●			●						
A car travelling down a motorway					●				●					
Power station generates electricity					●				●					
Corrosion					●					●				
A car rusting					●					●				
Aluminium saucepan corrodes					●					●				
Hot copper reacts with air					●					●				
Magnesium burns					●					●		●		
Burning hydrogen and oxygen					●					●		●		
Water balance in living organism					●						●			
A flame					●						●		●	
A human being					●						●		●	
An ecosystem					●						●		●	
Burning coal					●							●		
Acid neutralises alkali					●							●		
Winding up a clockwork toy						●	●							
Pumping water uphill to a reservoir						●	●							
Pulling a roller coaster uphill						●	●							
An electric drill						●			●					
A river						●			●		●			
Air pumped into cylinder						●				●				
Synthesis of protein						●				●				
Molecules 'line up' in liquid crystal						●				●				
Making aluminium from ore						●				●				●
A kettle becomes hot						●						●		
A fridge becomes cold						●						●		
Centrally-heated room						●							●	
An incubator						●							●	
Water is electrolysed						●								●
A battery is recharged						●								●

## Using the materials for INSET

Though activities can be introduced in an *ad hoc* basis by individual teachers into existing schemes of work, the approach will clearly be of more value if it is adopted in a more co-ordinated way by a whole science department, so delivery of INSET is an issue which needs to be addressed. Some brief guidelines are given here, though more information and materials for INSET are provided with the support materials. For details on how to order the support materials, see page 57 in the booklet 'Activities in the classroom'.

Our experience suggests that in introducing this approach to teachers it is important to illustrate how it can form the basis of simple classroom activities, while at the same time indicating what the essential features of the approach are and where it is leading. The way in which the materials have been structured in this booklet (which tells the 'scientific' story) and in the booklet 'Activities in the classroom' (which gives examples of activities) have been designed to support this.

The section 'Ideas and activities' on pages 2-42 in the booklet 'Activities in the classroom' gives examples of what can be done with pupils at various levels. We have found it important, for at least a few of the activities, that teachers should carry out the tasks as the pupils do them - cutting up slips of paper, making matches, discussing choices, and so on - in order to get an impression of the kind of demands made by this work. A selection of tasks providing a good introduction is shown below:

Sample activity	Idea to illustrate
B Pictures of mixing	simple introductory activity on use of pictures
G Examples of insulation	pictures of energy flows
J Everyday changes	particle pictures
H Things that just happen and things that don't	introducing the idea of coupled changes
O Fuels and food	'chemical springs' and coupled changes
Q Convection currents	more demanding example of the use of pictures

'Telling the story in pictures' in this booklet provides a scientific account of energy and change using the same headings as the booklet with the pupil activities, so this makes it easier to relate the two. The set of figures used to tell the story may be used as OHPs, and are available full-size in the support materials.

Teachers who use the abstract pictures are often surprised that pupils are able to understand and discuss them more easily than they had anticipated. At an INSET in which there are teachers who have not used the materials with pupils, it is useful to have examples of pupils' work from teachers who have. Examples of pupils' discussion are also useful, and can be found on pages 49-56 of the booklet 'Activities in the classroom'.

Figure 13 in this booklet shows the fundamental set of abstract pictures, and for teachers wishing to gain a deeper understanding than that aimed at in the pupil activities, these could be used to make matches to more complex situations, such as those in the booklet 'Background stories for teachers'.

## Further reading

Much research has been undertaken over many years into children's understanding of scientific concepts, including energy and processes of change. A number of these research studies are reported in Driver, Guesne and Tiberghien (1985), while a useful summary of children's ideas about a wide range of scientific concepts, with references to the original research papers, is given in Driver, Squires, Rushworth and Wood-Robinson (1994). There has also been no shortage of ideas about how to teach about energy and change, and many relevant articles are to be found in science education journals, such as the *School Science Review* (Ellse, 1988; Ross, 1988, 1993; Solomon, 1982; Tudor Jones, 1991). Also Solomon (1992) gives a wide-ranging account of the issues, including teaching about second law ideas using the notion of 'running down towards sameness'.

We have found a number of books useful as sources of ideas and information about energy. In particular, Atkins (1998) gives a lucid account of the Second Law, illustrating how a non-mathematical approach to the law can be consistently and usefully applied across a wide range of phenomena. There are many sources dealing with energy issues in relation to technology and society (Cassedy and Grossman, 1990; Foley, 1992; Fremlin, 1985; Kraushaar and Ristinen, 1993; Ramage, 1983).

Teaching about processes of change means more than just teaching about energy. Other ideas relevant to the approach include chemical structures (Atkins, 1987; Ball, 1994), chemical reactions (Atkins, 1991), relative sizes of things (Morrison and Morrison, 1982), life (Schrödinger, 1944), concentrations of substances in living things (Colinvaux, 1980), steady states (Lovelock, 1991) and earth sciences and meteorology (Robinson, 1993).

- Atkins P W (1984) *The Second Law* (New York: Scientific American Library, W. H. Freeman)
- Atkins P W (1987) *Molecules* (New York: Scientific American Library, W. H. Freeman)
- Atkins P W (1991) *Atoms, electrons and change* (New York: Scientific American Library, W. H. Freeman)
- Ball P (1994) *Designing the Molecular World* (Princeton University Press, Princeton, New Jersey)
- Cassedy E S and Grossman P Z (1990) *Introduction to energy: resources, technology and society* (Cambridge University Press)
- Colinvaux P (1980) *Why big fierce animals are rare* (Penguin Books)
- Driver R, Guesne E and Tiberghien A (eds) (1985) *Children's ideas in science* (Milton Keynes: Open University Press)
- Driver R, Squires A, Rushworth P and Wood-Robinson V (eds) (1994) *Making sense of secondary science: research into children's ideas* (London: Routledge)
- Ellse M (1988) Transferring not transforming energy *School Science Review* **69**, 248, 427-437
- Foley G (1992) *The Energy Question* (Penguin Books)
- Fremlin J H (1985) *Power production: what are the risks?* (Bristol, Adam Hilger Ltd)
- Kraushaar J J and Ristinen R A (1993) *Energy and problems of a technical society* (John Wiley and Sons, Inc.)
- Lovelock J (1991) *Gaia: the practical science of planetary medicine* (Gaia Books Ltd)
- Morrison P and Morrison P (1982) *Powers of ten* (New York: Scientific American Library, W. H. Freeman)
- Ramage J (1983) *Energy: A Guidebook* (Oxford University Press)
- Robinson A (1993) *Earth shock: climate, complexity and the forces of nature* (Thames and Hudson Ltd)
- Ross K A (1988) Matter scatter and energy anarchy: the second law of thermodynamics is simply common experience *School Science Review* **69**, 248, 438-445
- Ross K A (1993) There is no energy in food and fuels - but they do have fuel value *School Science Review* **75**, 271, 39-47
- Schrödinger E (1944) *What is Life?* (reprinted in 1967 by Cambridge University Press)
- Solomon J (1982) How children learn about energy: does the first law come first? *School Science Review* **63**, 224, 415-422
- Solomon J (1992) *Getting to know about energy - in school and society* (The Falmer Press)
- Tudor Jones G (1991) Burning - gravitational, chemical and nuclear *School Science Review* **73**, 262, 49-55



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