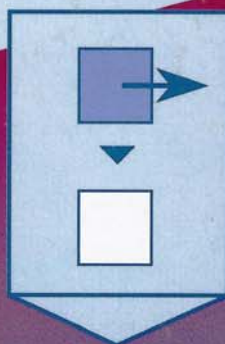
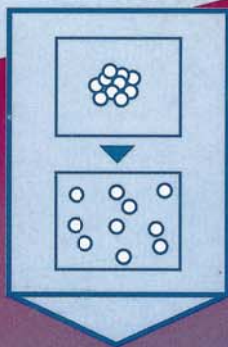


ENERGY AND CHANGE

*Background stories
for teachers*

**Richard
Boohan**

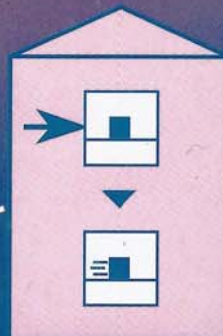
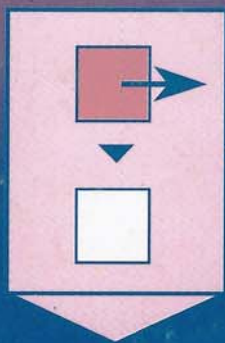
**Jon
Ogborn**



*The key ideas
behind the
materials:*

• Differences
drive change

• Pictures help
understanding



The
Association
for Science
Education

*A Project sponsored by the
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Energy and change

Background stories for teachers

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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 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*. 'Energy and change' is a set of three booklets outlining a new approach to ways of talking about thermodynamic ideas starting from commonsense ways of explaining. 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

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.

About this booklet

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.

Other booklets

Introducing a new approach - 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.

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.

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Introduction

This collection of stories illustrates the wide range of contexts in which the ideas developed in the other two booklets may be applied. Many of the topics dealt with are also to be found in the school curriculum, and while in general the treatment is too advanced for most pupils, there are many ideas which may be appropriately used at school level. But the main purpose of these stories is to provide a broad understanding of energy and processes of change, so that teaching about these ideas at a more elementary level may rest on firmer foundations. While the stories may be read individually, they have been ordered in such a way that fundamental ideas are introduced and developed through the stories.

The key idea is that all changes are driven by differences. The Universe is full of extreme differences of temperature and of crowding of matter. Space is nearly at absolute zero and has a very low density of molecules; stars are white hot with matter crammed into a very dense region. It is these differences which ultimately drive all change in the Universe. Differences tend to disappear, as matter flows down concentration gradients (e.g. atmospheric pollution), or energy flows down temperature gradients (e.g. thermal pollution).

'Going downhill' is a natural metaphor for spontaneous change. In these stories, much use is made of this metaphor, applying the idea not only going down real hills, but also to electrical and chemical 'hills'. In going downhill, potential energy differences (gravitational, electrical, chemical) tend to vanish, because the stored energy is dissipated amongst many particles and will not come together again all by itself. But such downhill changes can drive other changes uphill. Many processes can go in either direction, or can remain in a dynamic equilibrium, because there are both 'downhill' and 'uphill' aspects of the change. For example, ice may melt or water may freeze depending on the temperature of the surroundings. Many chemical reactions (e.g. smelting) are also balances between uphill and downhill changes, and the distribution of air in the atmosphere results from the balance between gravity pulling the molecules down and diffusion making them spread out.

Fuels are molecules which have been pushed up an energy hill. Just as gravitational potential energy differences tend to disappear, as objects fall down and the energy is dissipated, so chemical potential energy differences disappear as fuels burn and fall down the energy hill. In the electrolysis of water to give hydrogen fuel and oxygen, in photosynthesis and in making ATP, molecules are being pushed up an energy hill. In burning, in respiration, in moving muscles, in an engine and in a refrigerator, chemical potential energy differences are disappearing as molecules fall down the energy hill and other differences are created.

Electrical potential energy differences can also drive changes. In a power station, burning a fuel destroys a chemical potential energy difference, but creates a electrical potential difference, which can be made to appear wherever it is needed by using conducting wires. Electrical potential differences are also created in nerve cells and in electrical cells, in both cases, driven by chemical potential differences.

At the end of each story are some abstract pictures which summarise the most important features of the changes discussed. The meaning of these pictures is briefly discussed towards the end of this booklet on pages 44-45. A more extended discussion can be found in the booklet 'Introducing a new approach'. The pictures in this booklet also serve as a quick way of finding stories which illustrate particular kinds of changes.

The Lively Universe

At night, no longer blinded by sunlight, we can glimpse what the Universe is like. We see brilliant stars set in inky blackness. The Universe is full of dramatic differences. White-hot stars exist in icy cold black space. Matter, some of it at enormous densities, is concentrated in lumps between which are vast stretches of almost empty space. These differences are responsible for the beauty of the night sky. But they are also responsible for the evolution of the Universe itself; the birth and death of stars. The changes they drive include the processes which support life, so they are also responsible for the fact that we are alive and able to go star-gazing.

The same forever?

Looking up at the unchanging stars, human beings have often imagined the Universe as that which above all *stays the same forever*. People come and go, civilisations rise and fall, but the stars shine on in their appointed places.

But really the Universe is just the opposite. It is the site of the most violent changes we can imagine. What is more, if it were not, then we would not be here to gaze at the sky. The very chemical elements essential to life - carbon, oxygen, phosphorus, iron - were made in long gone violent explosions of huge stars and left behind as dust to be swept up later into our planet Earth. We are made from the ashes of those exploding stars.

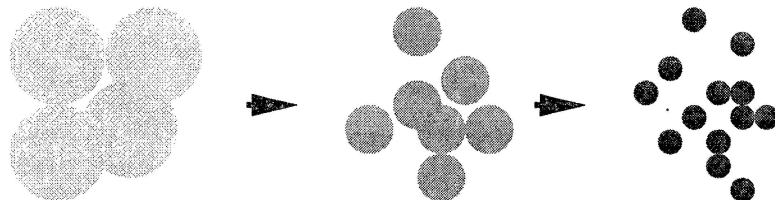
Look up at the sky at night. You see bright stars set in empty black space. This fact alone shows that the Universe must be changing. Light floods out from the hot stars into the cold blackness. A shining star is a changing star, burning up its nuclear fuel. Many stars start as yellowish ones like our Sun, then expand and cool to become giant red stars like Betelgeuse in Orion high in the south in winter, and then shrink and get hotter again to become white dwarf stars like the faint companion of the brilliant Sirius, before finally fading slowly into darkness.

But why is the Universe changing? Could it have stayed the same forever?

Energy goes from where it's hot to where it's not.

The formation of stars

As gas clouds collapse under their own gravitational attraction, they fragment into a number of denser, smaller clouds which become stars in a cluster. Gravity makes a gas cloud unstable.



Violent change from extreme differences

The Universe changes because it is full of differences. It is full of extreme differences of temperature. Stars are white hot and space is icy cold - nearly at absolute zero, the lowest temperature there can be. So energy inevitably floods out of hot stars into the cold space between them, just as a fire warms a room and not the other way around.

The Universe is also full of extreme differences of crowding of matter. In 'empty space' there may be only a handful of molecules in a room-sized region; in stars and planets there are billions in a pinpoint the size of a microbe. The matter in the Universe clumps together like this because gravity only pulls and never pushes. Any accidental swirl in a cloud of gas or dust can bring matter in one region a little closer together than in another and the pull of gravity does the rest. A star or a planet may be born.

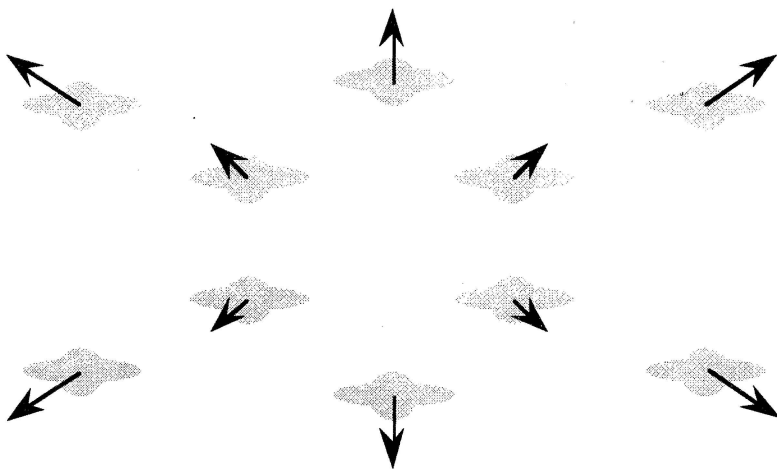
As matter is squeezed together by its own pull of gravity it gets hotter, just as air in a cycle pump does when we squash it. If it gets so hot that nuclear reactions start up, we have a new star.

Differences make change. And it takes a difference to make a difference.

Decreasing potential energy goes downhill

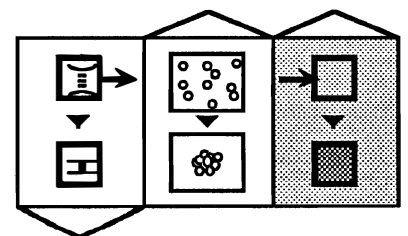
The expanding Universe

The expansion of the Universe creates the space for gravity to act to form stars, galaxies and clusters of galaxies.



Where did all these differences come from? The answer is that the Universe is expanding. The expansion opens up space between particles of matter into which their gravitational pull can drag them together. So in the end all the change in the Universe comes from its expansion. The black, cold, empty space made by the expansion surrounds hot clumps of matter made by gravitational pulling together of matter, and these differences drive all the changes in the Universe. And these changes led, in the end, to there being a small planet near an ordinary star on which there evolved people to wonder at it all.

Left to themselves, particles spread out. But in the Universe, the gravitational potential difference from its expansion makes matter clump together. The gravitational energy is shared out and the clumped matter becomes hot. Nuclear reactions in stars spread further energy into the rest of the Universe, and the stars change and evolve. The temperature and density differences thus created drive all the other changes in the Universe.



Pollution

Pollution is matter where it isn't wanted and may do harm. Thermal pollution is energy where it isn't wanted and may do harm. Both tend to spread all by themselves. Matter and energy both tend to go from where they are concentrated to where they are not. This is why both material and thermal pollution are hard to contain.

Sky and sea

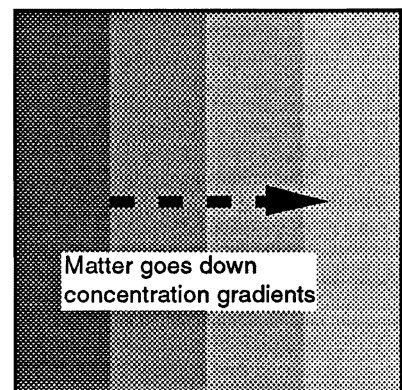
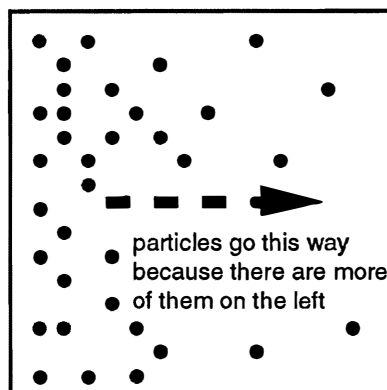
The sky and the sea seem limitless. Smoke from chimneys seems to vanish into the atmosphere, and dirt running down rivers seems to vanish into the sea. For most of human history, there have been too few people engaged in too little activity to make a noticeable difference to the sky or the sea. They seemed unchanged, able to clean up after us. Now, however, following the Industrial Revolution and a population explosion of people on Earth, the effects of human activity can be seen. For example, the concentration of carbon dioxide in the atmosphere has been gradually rising over the past hundred years or so. We should not forget, however, that it was some of the first living things (blue-green algae) which filled the atmosphere with its present concentration of oxygen. Life has changed the planet before now.

Matter goes from where there's a lot to where there's not. It travels down concentration gradients.

Gases released into the atmosphere gradually diffuse and spread until they are uniformly spread out. They do this simply because matter is made of particles - atoms or molecules - which move randomly. Thus if there is one region having many particles of one kind, near another region which has few, particles will go from the first to the second on average, not because they like wide open spaces, but just because there are more particles in the first region available to move at random into the second than there are in the second able to move at random into the first. Chance is blind; more particles move in any given way just where there are more particles anyway.

Concentration gradients

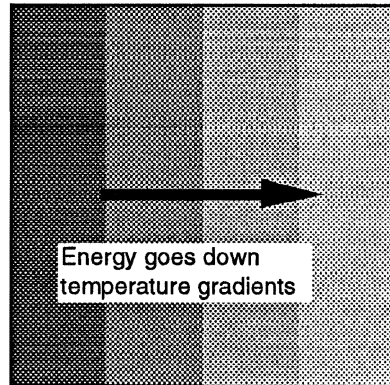
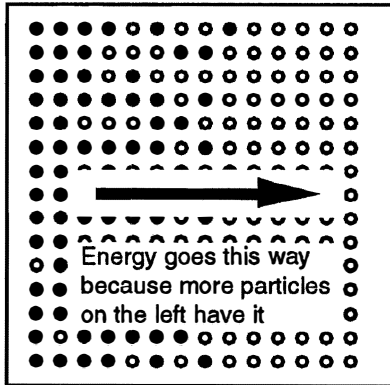
Particles diffuse randomly from higher concentrations to lower ones.



Pollution gets everywhere

By going from higher concentrations to lower ones, the spreading out of matter tends to destroy the very difference of concentration which produces the spreading. If it can, matter goes on spreading out until there are no concentration differences left anywhere. This means that pollutants tend to get everywhere. But we aren't sorry that the oxygen in the atmosphere has become evenly spread throughout it.

Differences drive changes. Changes destroy differences.



Thermal gradients

Energy goes down temperature gradients, from hotter to colder.

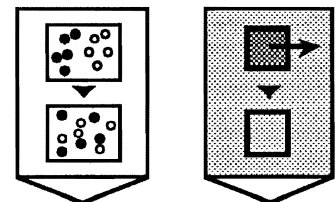
Thermal pollution

Cities are often a little warmer than the nearby countryside. This happens because houses are closer together in cities, and when heated, leak energy out into the surrounding air. Fossil fuel burning power stations necessarily throw away energy either through cooling towers or nearby rivers or sea. All these are examples of energy going all by itself from somewhere hotter to somewhere cooler, something we experience every time the handle of a spoon gets hot. Energy flows down temperature gradients.

Energy goes from where there's a lot to where there's not.

Energy flows down temperature gradients for the same kind of reason that matter diffuses down concentration gradients. A hot object is one in which a high proportion of atoms have a lot of energy; in a cooler object a smaller proportion of atoms have high energies. Temperature is just energy concentration. Atoms can exchange energy with one another. Energy goes from places where there is more per atom to places where there is less, just by this random exchange. The 'haves' tend to pass energy to the 'have-nots' because the 'haves' more often have it to give.

Differences of concentration of matter or of energy cause flows of matter or of energy. These flows reduce the differences of concentration which produce them. Differences in temperature are differences in concentration of energy. Differences of concentration of matter are chemical potential differences.



Sitting in an Energy River

In cold climates, we like our homes to be warm. We want them to be *different* from the cold outdoors. So we light a fire or turn on a radiator. What could be simpler? In fact, we are sitting in a river of energy, flowing from the heater into the room and out through the walls and windows. To make the room warmer, we have either to increase the flow of the energy river, or to make it harder for the energy to flow. Our bodies work in the same way. We stay at a temperature above the surroundings by continually throwing energy away. In both cases, to keep things steady there has to be a continual energy flow.

Energy goes down temperature slopes

Just as water runs down gravity slopes so energy runs, all by itself, down temperature slopes. Something being hot is just a matter of concentration of energy. The atoms or molecules of a hot material each have a relatively large amount of energy in their random thermal jostling. As they collide, they pass energy from one to another. When the molecules of a hot material collide with those of a cooler one, energy gets passed on average more often from those of the hotter material to those of the cooler material, just because the first have more to give than the second.

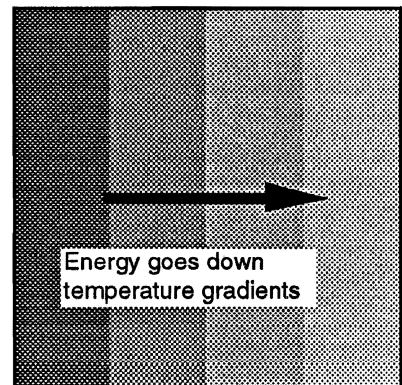
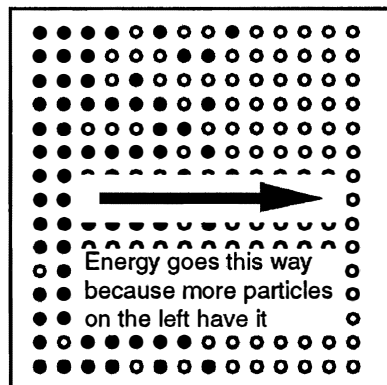
Energy goes from where there's a lot to where there's not.

Energy which is radiated does much the same. All objects above absolute zero radiate energy, and the hotter they are the more they radiate. So if you stand in front of an electric fire, it radiates more energy to you than you radiate to it, and you get warmer.

The spontaneous flow of energy, all by itself, from hotter to cooler is very much like the spontaneous spreading of matter from more concentrated to less concentrated regions. The random movement of particles of matter from place to place or of energy from particle to particle underlies both. Overall, the randomness ensures that the drift is from where there is more to where there is less, so that the difference driving either tends to disappear.

Energy goes downhill

Energy goes from hotter to cooler



Heating a room

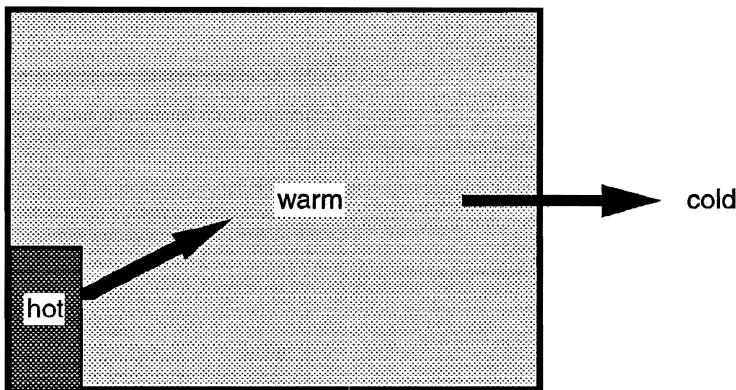
Sitting in a heated room is a little like sitting in a pool in a mountain river. Water tumbles into the pool from above, and flows out of it at just the same rate below the pool. The water level in the pool stays the same. Similarly, energy floods out of a hot heating device, into the room and out again through the walls and windows. The temperature of the room stays the same.

How warm will a 3kW electric heater make a room? Answer: just the temperature at which exactly 3kW will leak out to the outside. If the outside is very cold, it will not be very warm in the room because 3kW will leak to the outside at quite a low room temperature. If the insulation of the room is improved, it will get warmer, because 3kW will only leak out when there is a larger temperature difference to the outside than before.

The thermal flow of energy is driven by a temperature difference.

A heated room

Energy flow through a heated room



Running to stand still

A pool in a mountain stream and a heated room are both examples of *steady state systems*. Both stay the same, away from where they would otherwise be, because of a flow of something through them - water or energy.

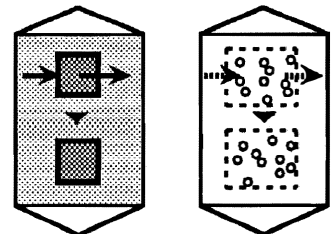
Our bodies are also such steady state systems. Energy is released inside by metabolic processes, and flows continually to the outside, and we stay warmer than our surroundings. If we don't, we die. The Earth is another example. Energy arrives from the Sun at 6000K, and is absorbed and then re-radiated to the cold black Universe. The Earth stays at a comfortable 300K or so, away from the icy cold temperature of space which it would cool down to were there no Sun.

Steady state systems are kept away from equilibrium by a constant flow of energy or matter through them.

Our bodies are also chemical steady state systems, too. Our tissues are continually being re-made as they decay, so that we stay much the same, thanks to a continual flow of chemical materials through us.

Steady states are also much used in the manufacture of chemicals. Feed-stocks arrive at the reaction vessels, are changed within them, and emerge in a new form. The contents of the reaction vessel itself stay in the same state for long periods of time.

Changes are driven by differences, and tend to destroy the differences which drive them. Systems can stay in a steady state, different from their surroundings, by a flow of energy or matter (or both) through them.



Downhill All the Way

Going downhill is a natural metaphor for a natural, inevitable process; one that happens all by itself. But why? Why does water end up in lakes in the bottoms of valleys? Why does garbage end up at the bottom of the waste dump site? The downward pull of gravity is not the whole answer. The essential other part of the answer is that to stop at the bottom of a hill is to have spread around the maximum possible energy.

Roller coasters

Roller coasters are built on the principle that gravity does not necessarily hold us down at the bottoms of hills. Having swooped down the track, the roller coaster cars swoop up again, going almost as high up as they were before. All gravity does is to speed up falling things and slow down rising things. It is not gravity which makes the bottoms of valleys popular places to be. In fact, a roller coaster car spends less of its time at the bottom, which it rushes past, than it does at the top.

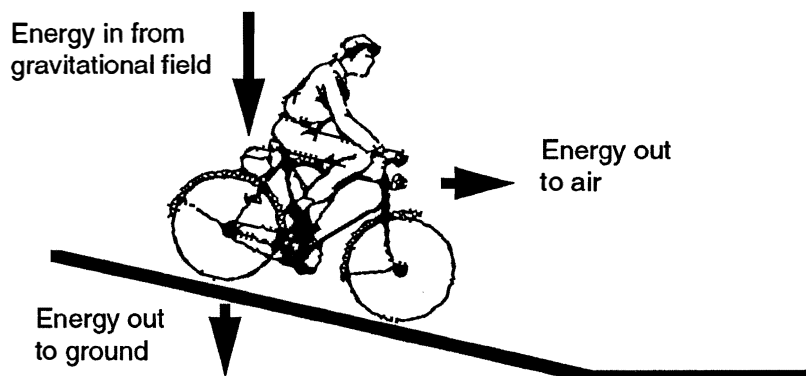
Matter tends to fall down potential energy hills. Doing so dissipates energy widely amongst many particles.

It is friction which is responsible for the inevitable sag of things to the lowest available place. What is friction? It is the giving of energy, previously concentrated in the movement of an object, to create more movement of many many objects. The roller coaster car sets air molecules in motion ahead of it, and rubs on the rails warming them up. The car's energy is dissipated. Just as dissipating a fortune means sharing out the money in small doses amongst many people, so dissipating energy means spreading it out in small doses amongst many particles. That's why things tend to end up at the bottoms of hollows: their energy has been given to other things as they go downhill.

Things tend to stay at the bottoms of hollows, unless we use special means to get them uphill again, just because there is no chance that the energy they had, once spread out, will come together again all by itself.

The downhill tendency

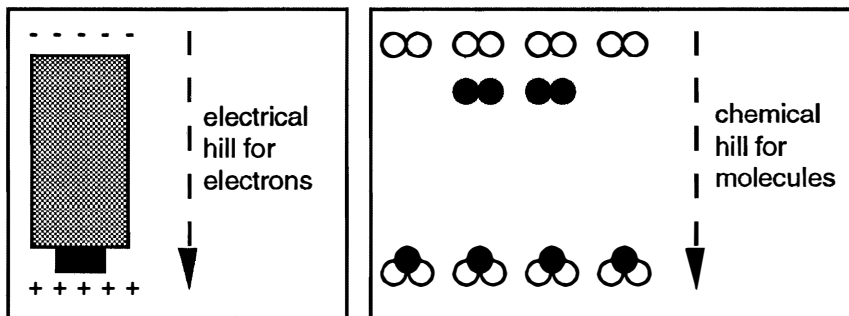
Wherever there is dissipation, things tend to end up at the bottoms of hollows.



Going on forever

If there isn't any resistance to movement, it goes on forever. The Earth circles the Sun just as it has for billions of years. This is best thought of as *nothing happening at all*. We human beings are very impressed by movement, so we think of the endless circling of the Earth as a *change*. But really there is no change at all. The Earth just gets back where it was a year before, and starts all over again. Nor would it make any difference at all which way round it went. More deeply, movement without dissipation has no sense of the direction of time. Changes where there is dissipation do have a sense of time direction - that in which energy is dissipated spontaneously amongst many particles.

Dissipation gives a direction to the flow of time.



Potential hills

Besides gravity hills, there are electrical and chemical hills.

Electrical and chemical potential hills

We are very familiar with real visible hills and cliffs. We are also familiar with springs, which also store energy which dissipates when the spring is released. There are also electrical and chemical hills or springs. A battery provides an electrical hill between its ends, called the electrical potential difference. Electric currents flow down this hill and dissipate energy. A very important feature of electrical hills is that they are transportable - not just by carrying batteries but also along wires, so that the hill made in a power station can be provided in the home. We can dissipate the energy - we call it cooking or heating - just where we want.

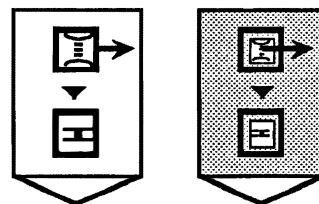
Processes go down potential hills all by themselves, releasing energy. They can drive other processes uphill.

Gravity hills or springs are made by pulling masses apart. Electrical hills or springs are made by pulling electric charges apart. There are chemical hills or springs too. When we electrolyse water we pull water molecules apart into hydrogen and oxygen. The mixture of hydrogen and oxygen is well uphill of the original water; the chemical spring is stretched. If we set the mixture off with a spark it goes back to water with a bang! And the stored potential energy is dissipated.

Because chemical bonds are basically electrical in nature, chemical hills are really electrical hills too.

Some decreases in potential energy produce (smaller) increases in the potential energy of something else. Some just make the surroundings warmer.

Potential energy differences (hill or spring) tend to vanish all by themselves, because the stored energy is dissipated amongst many particles and will not come together again all by itself. But these downhill changes can drive other processes uphill.



Keeping on the Move

A high speed train needs a constant supply of energy to keep it racing across the countryside on its journey from one city to another. But the Moon goes on circling the Earth, and the Earth keeps on circling the Sun, without any energy supply. Where's the difference? Is a supply of energy needed to keep things on the move?

Taking the train to Paris

Most moving things have to push air out of the way, and often slide or roll over rough surfaces. These processes dissipate energy, spreading it around liberally.

Going at 200 km per hour, the train to Paris covers a little more than 50 metres each second. It has to push the air in that 50 metres out of the way. If the front of the train, taking streamlining into account, has a frontal area of around 10 square metres, the air in a volume of 500 cubic metres has to be thrust aside. That much air has a mass of over 500 kg, more than half a tonne. The air just in front of the train will be set in motion at a speed similar to that of the train itself. The rate of supply of kinetic energy to the air works out at over 600 kW, more than half a megawatt. Add in the energy supply because of friction with the rails, and we may expect a power requirement of the order of one megawatt.

We can think of energy being poured into the train from the overhead electrical supply and poured out again via the air set in motion by the train and by the rubbing on the rails and axles. The train is kept in a steady state of motion by a constant flow of energy through it.

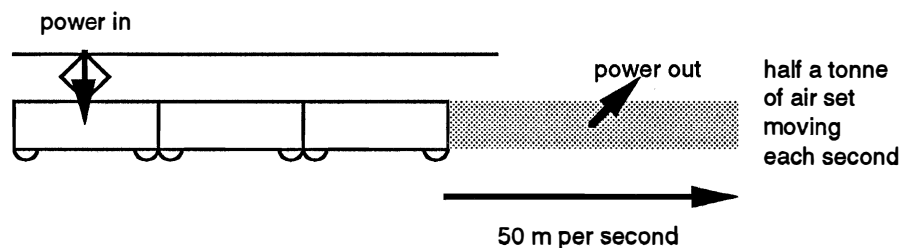
Dissipation of energy goes downhill, happening naturally if it can happen.

If the energy supply is cut off, the train slows down. Why? The train consists of a large number of molecules all headed in the same direction - to Paris - at the same speed. When it pushes the air aside, this co-ordinated motion becomes the uncoordinated motion of air molecules rapidly colliding at random with one another and ending up headed nowhere in particular. Energy has been spread around. It is no longer concentrated in one co-ordinated rush across France.

This is what makes the slowing down of the train a one-way 'downhill' process. The air molecules around the train are never going to gather together to give it a helpful shove. So to get the train moving and to keep it moving we have to get another lot of energy to go downhill, using for example the electrical potential difference across the overhead wires. The difference in relative motion of train and air or ground is kept in being by continually destroying a supply of potential energy.

Keeping a train going

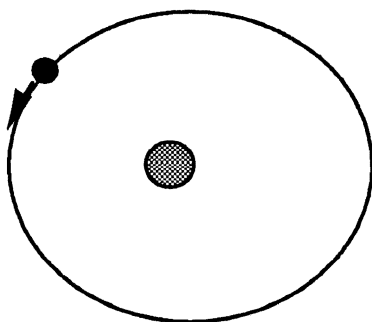
Energy goes into the train, and out again. If more comes in than goes out, the train speeds up. If more goes out than comes in, the train slows down.



Streamlining and reducing drag

The power needed to keep the train in motion is decided, not by how fast it must go but by how fast energy is dissipated at a given speed. Streamlining helps by reducing the effective frontal area of the train so that it no longer has to batter its way head-on through the air, but eases some of it aside more tactfully. Imagine making the streamlining better and better, and reducing more and more the rubbing of wheels on axles and rails. The train could go as fast with less power.

If we could get rid of all sources of dissipation, no power at all would be needed. This seems like a foolish fantasy - we would need a train travelling through a vacuum and not running on rails. However, we know at least one such express train, and we travel on it every day. It is our Earth, going round the Sun at around 100 000 km per hour. It travels through the high vacuum of space, with nothing to get in the way or rub against. The result? *Nothing changes!* The Earth orbits the Sun again and again, and has done so several billion times. Nothing keeps it going.



The Earth just keeps on going round the Sun because none of its energy is given to anything else.

If there is no dissipation, there is no change in time. What is happening just goes on happening without change.

The Earth in orbit

No dissipation means no change. The Earth just keeps on going.

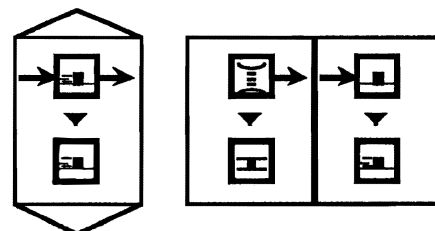
Work - energy transfer without dissipation

Actually, the Earth doesn't go in a perfect circle. Its orbit is an ellipse, sometimes nearer the Sun and sometimes further away. As it falls closer to the Sun, the inward tug of the Sun's gravity speeds it up. As it climbs further from the Sun it slows down. Energy goes back and forth, but without loss, from the motion of the Earth to the potential energy stored in the Sun's gravitational field.

We see this kind of transfer of energy on a smaller scale every day, if we drop something, if a football is kicked high in the air, if a car bounces on its suspension. Gravitational, electric and magnetic fields can store energy in this way, and can transfer it to the motion of particles. On the atomic scale, this is all there is. There is no dissipation. What we call dissipation is the result of the tendency of the movements of huge numbers of atoms or molecules to get less co-ordinated.

The transfer of energy without dissipation is called *work*.

Most movements dissipate energy. It goes from the co-ordinated motion of the particles of a few objects to the uncoordinated motion of very many particles. No energy is lost, but the possibility of creating changes is lost. If there is no dissipation, there is no overall change in time.



Frost and Flood

Nothing beats a cold drink filled with ice cubes on a hot day. And little beats the magic of frost on the window or snow falling in winter, both made from that familiar wet stuff, water. In cold weather, water freezes and we get snow and ice. In warm weather ice and snow melt and we get mountain torrents. Freezing and melting are the reverse of one another. What decides which way the process goes? Answer: how cold or warm it is. But why?

Melting goes downhill when it's warm

Ice melting in a warm room is a typical, one-way, downhill process which happens all by itself. All we have to do is wait. Even wrapping the ice in insulating newspaper just postpones the inevitable for a while.

Melting destroys order amongst molecules. But it also concentrates energy, creating a potential energy difference.

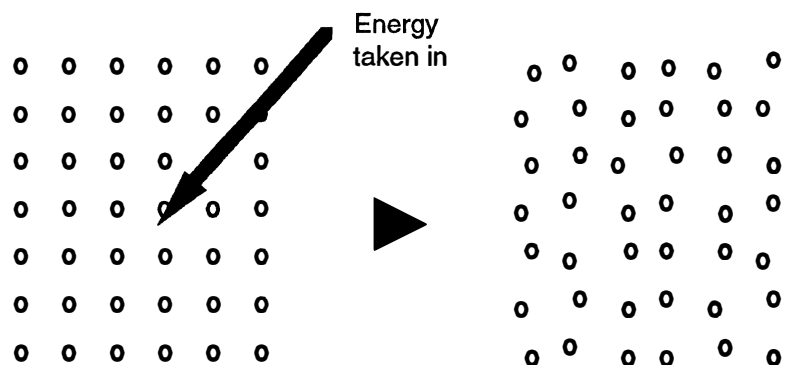
One reason melting goes downhill is that a tidy fixed molecular arrangement, reflected in the elegant patterns of frost on the window, is being destroyed. Pattern is being lost. Regularly arranged arrays of water molecules making ice crystals become the familiar messy runny stuff we call water. If that were all, there would never be ice. It would collapse naturally into water all the time.

To make water from ice, bonds between water molecules holding them in place have to be torn apart, thus storing or locking up potential energy (6 kJ per mole). And this energy has to come from the warm air or water outside, taking energy by chance from their jostling molecules. This process is uphill. But if the surroundings are warmer than the ice, energy goes downhill all by itself from warmer to cooler, and can supply the need.

When the surroundings are warm, the downhill process of destroying order is more important than the uphill one of concentrating energy, and ice melts.

Melting

Melting destroys molecular order but takes in energy



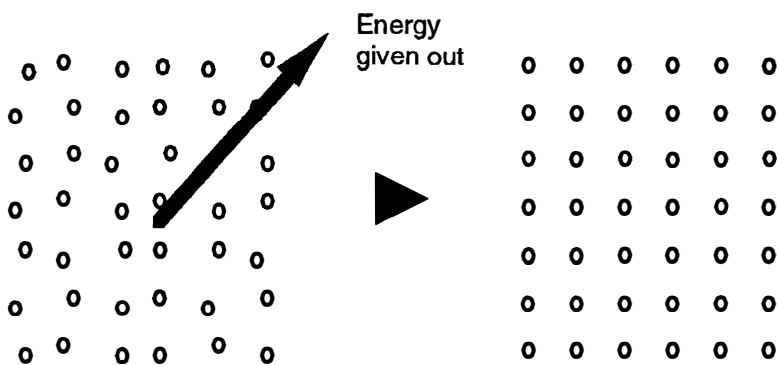
Freezing goes downhill when it's cold

One reason freezing goes downhill is that to make ice from water, bonds must form between water molecules, releasing 6 kJ per mole of stored potential energy to be spread around in the surrounding air or water. This energy is spread amongst the jostling molecules of the cold air or water outside. If the surroundings are colder than the water, energy goes downhill all by itself from warmer to cooler, taking energy from the water. If that were all, there would never be water. It would turn naturally into ice all the time.

Making ice from water also however goes uphill. Freezing goes uphill because a tidy fixed molecular arrangement, reflected in the elegant patterns of frost on the window, is being made from an irregular arrangement. Pattern is being produced. Regularly arranged arrays of water molecules making ice crystals are made from the familiar disorganised messy runny stuff we call water.

When the surroundings are cold, the downhill process of spreading out energy is more important than the uphill one of creating order and pattern, and water freezes.

Freezing creates order amongst molecules. But it also dissipates energy, destroying a potential energy difference.



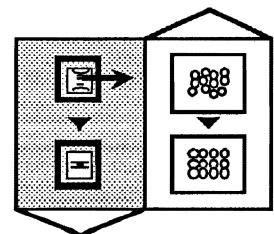
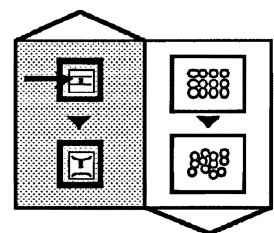
Freezing

Freezing creates molecular order but gives out energy

Forwards or backwards but always downhill

Which way the water goes - from water to ice or from ice to water - depends on which direction is downhill overall. What is uphill for melting is downhill for freezing, and vice versa. The change in the ordering of molecules is as far uphill or downhill in either direction. The difference lies in how hard it is to get energy from the surroundings, or how much is gained by adding energy to the surroundings.

When it is cold outside, the surroundings have little energy per particle, so that adding more makes a big difference. The spreading of energy is then a long way downhill (and concentrating the same energy would be a long way uphill, taking energy from particles which share little). Then freezing wins and the molecular arrangement goes uphill to greater order. When it is warm outside, removing energy from particles which share a generous amount already is not too difficult, and the concentrating of energy is thus not far uphill (nor would spreading it be far downhill). So melting wins and energy is taken in from the surroundings.



Many processes can go in either direction. Which way they do go depends on which way is downhill overall, in the circumstances.

Is smelting like melting?

In all mythology, the getting of metals from ore is associated with fire, whether the furnaces of metal makers or the volcanic furnaces underground. Why should fire be needed to get metals? Is fire alone enough? What is the role of the charcoal or coal which smelters also use? Why were only some metals able to be extracted by people in ancient cultures? Why are some metals so much more expensive than others?

The metal makers

The making of metals has been so important to human activity that two periods of pre-history - the Iron and Bronze Ages - have been defined by the products of their metallurgy. Over the centuries, more and more metals have been extracted and used, many rather recently in history - aluminium, magnesium and titanium for example. Gold, the very symbol of value, is soft and not very useful, though resistant to corrosion. The hilt of Alexander's sword may have been of gold, but its blade was of iron. For many purposes, iron is vastly superior, yet gold is much more expensive than iron. The reason is simple: there is very little of it in the Earth's crust. Its price is high because it is hard to get together what little there is. On the other hand, aluminium is hugely abundant in the Earth's crust, and yet it too is more expensive than iron. Like iron, it exists as an ore, and is very difficult to extract from that ore. Aluminium costs a lot because, although there is plenty, it is hard to get out.

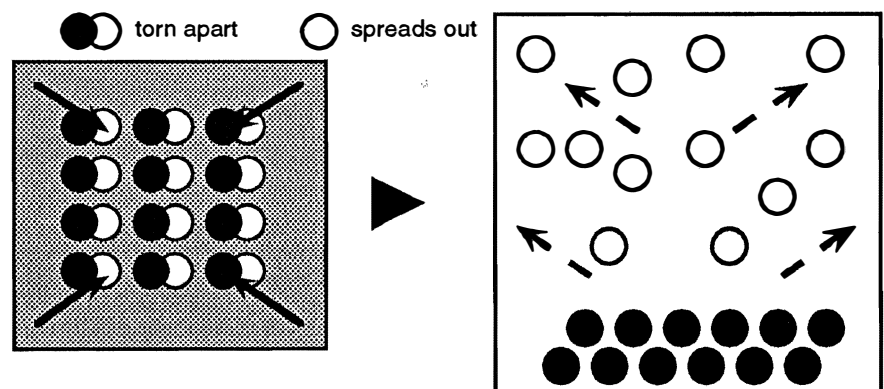
Fire and alchemy

Mercury is rather easily obtained by heating its ore. It has been found in graves over 3000 years old, and was known to the Greeks and Romans. Its ore is the sulphide - cinnabar. Heating the ore drives off sulphur and leaves liquid mercury behind. This use of fire to create rather than to destroy impressed the alchemists of the Middle Ages and their patrons, and for them mercury and sulphur were the two fundamental elements of the Universe. Iron is not so easy to obtain from its ores just by heating: the temperature needed is several thousand degrees and this isn't easy to achieve in simple furnaces. Getting metals in this way is rather like melting: a high temperature makes concentrating energy to break bonds easy enough to be driven by the tendency of molecules to spread out or get less ordered.

A high temperature is a high concentration of energy. Hot things give up energy less reluctantly than cold things.

Metals from fire

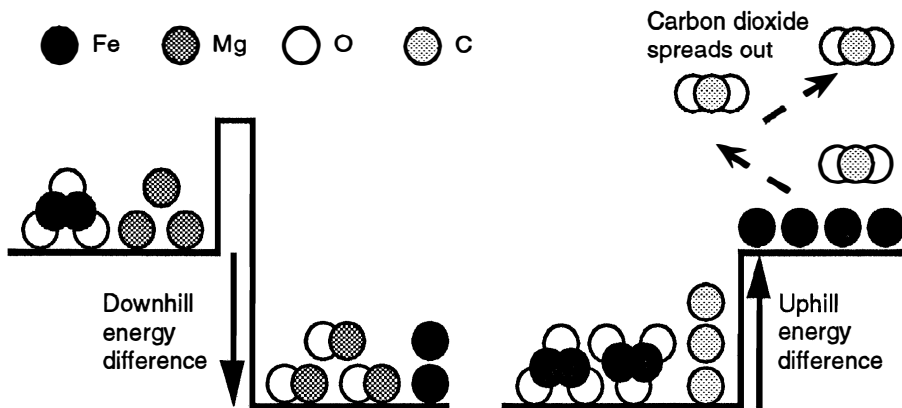
The concentrated energy of the fire makes breaking mercury sulphur bonds not too difficult so that the spreading out of sulphur is enough to drive the process.



Concentrating energy, or molecules

The difficulty of extracting a metal from an ore, say an oxide or sulphide, depends on how strongly the metal is bonded to the other element. The stronger the bonds, the more energy that has to be concentrated together in one place to pull them apart. By making the ore very hot in a furnace, we make the concentrating of energy to break the bonds less difficult, so that the subsequent spreading out of the other element is strong enough to drive the concentrating of energy. An ore forming is the same process in reverse. As bonds form between (say) iron and oxygen, the energy released and spread out into the cool surroundings is enough to pay for the necessary concentrating together of oxygen molecules from the atmosphere into the ore.

It is always hard to concentrate energy in one place. But it is less hard the higher the temperature and the less energy which needs to be concentrated.



Two ways of smelting iron

1 Make the production of iron go downhill in energy

2 Go uphill in energy, but downhill in spreading out carbon dioxide

Smelting

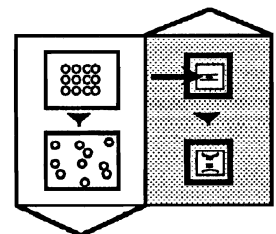
Smelters of ores do not rely on fire alone. They provide another element to combine with the oxygen of the ore. This works in two ways: one obvious, one surprising.

An example of the obvious way to smelt is using magnesium to get iron from iron ore, in the thermite process. Magnesium bonds much more strongly to oxygen than iron does, so if oxygen is torn from iron and clings to magnesium the net effect is to release and spread out energy. Magnesium makes a deeper potential energy hole for the oxygen to fall down than the iron hole it has to climb out of. Thus the smelting of iron with magnesium goes downhill, spreading energy.

Processes go down potential energy hills because that spreads energy out. They can go up energy hills if something else spreads out.

An example of the surprising way to smelt is to use carbon - coke in blast furnaces or wood charcoal in many developing countries. Carbon is *less* strongly bonded to oxygen than is iron, so the process concentrates energy overall, and does *not* spread it out. So how can it happen? It is driven by the fact that carbon dioxide is very dilute indeed in the atmosphere, so that making carbon dioxide is a strong spreading-out process. If the temperature is high enough, the difficulty of concentrating the necessary energy is not too great, and the spreading of carbon dioxide into the air is enough to make the process happen.

Some ways of smelting go uphill in energy. The process is driven by the spreading out of matter. For this to be possible, the concentrating of energy must be made less difficult, by using a high temperature. Smelting uses the spreading of matter to pay for the concentrating of energy as bonds are pulled apart.



Flying High

Jet planes fly high because the air is thinner higher up, and makes less drag. But not too high - they need air to burn fuel. Mountaineers also find the air thinner as they climb upwards. Actually, seen from space, the Earth's atmosphere is just a thin blanket around it. How does the air thin out as you go up? What keeps it close to the Earth? And what keeps it up?

The answer is that gravity pulls the air in towards the Earth, but the tendency of matter to spread from where there's a lot to where there's not keeps it from all falling to the ground.

Our thin blanket of air

To us on Earth, the sky seems very high. We have little sense of the atmosphere as a thin blanket hugging the Earth. Of course, climbers know better. At the 8 km height of Mount Everest there is much less air to breathe than at sea level. And at a height above the surface of only 100 km, merely around one percent of the Earth's radius, the atmosphere is so tenuous that it hardly affects an artificial satellite speeding through it.

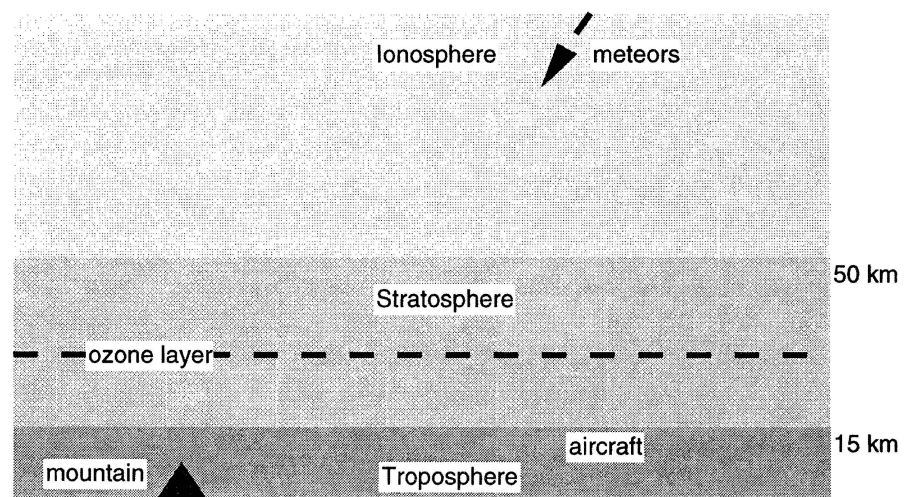
Matter tends to fall down potential energy hills

It is gravity which holds the atmosphere close to and hugging the Earth. To get air - or anything else - high above the Earth energy has to be provided. If it falls that energy is released, and generally gets spread around. That's why things tend to end up at the bottom of hollows: the energy released gets given to other things as they go downhill. Going downhill under gravity is the very emblem of 'a change which happens naturally'.

If that is so, then why does the air stay up at all? Why doesn't it all fall to the ground and lie at our feet? The air doesn't all fall down because there's another slope, which goes downhill *away* from the Earth. It is a hill of density difference.

The Earth's atmosphere

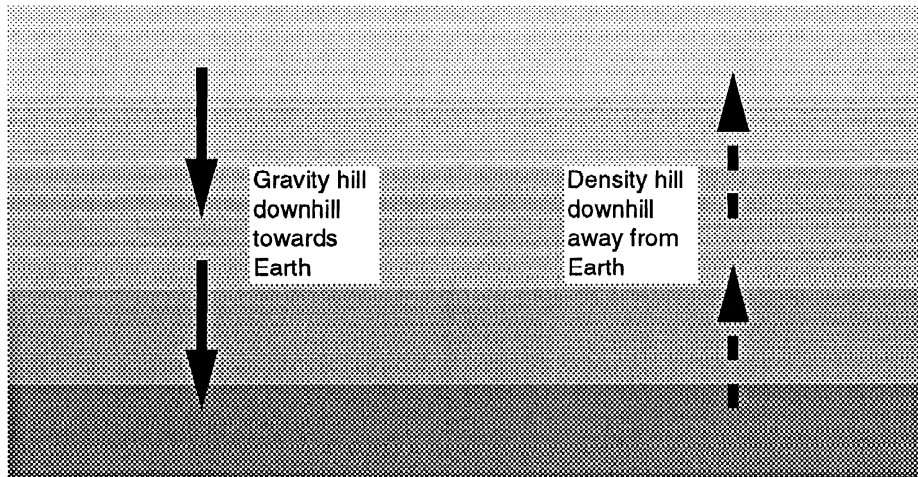
The atmosphere is a thin blanket wrapped around the Earth. The ozone layer is only 30 km up (London is more than 30 km across). At the top of a high mountain the air is already quite thin.



A hill going back away from the Earth

If the air all fell to the ground, there would be a lot near the Earth and none further away. Air molecules naturally diffuse from regions where there are many of them to regions where there are fewer. They do this because they just go anywhere at random, but there are more available to go anywhere in a dense region than in a less dense one. So chance sends them away from dense regions into less dense ones.

When air falls down under gravity, the atmosphere gets more dense lower down than higher up. So air starts to spread upwards again. The atmosphere settles down when the falling tendency due to gravity is just balanced by the tendency to spread away from the Earth because of the differences in density near it and away from it. We can think of two hills. The gravity potential hill slopes downhill towards the Earth. The density - or concentration of molecules - hill slopes downhill away from the Earth.



Gravity hill and density hill

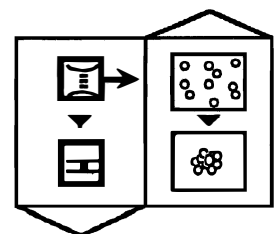
The gravity hill is downhill towards the ground; the density hill goes downhill away from the ground.

It is not too hard to calculate the slopes of the two hills, which will be equal when the atmosphere is in balance. The gravity slope is 0.28 kJ per mole per kilometre (10 J per kg per metre; 1 mole of nitrogen molecules being 28g), or 2.8 kJ per mole for the height of 10 km at which jet planes fly. The slope of the density hill depends on the *ratio* of the densities at different heights. It is given by $NkT \ln(\text{ratio of densities})$. A ratio of density (or pressure) of about 3.8:1 gives a difference of 2.8 kJ per mole to balance that of gravity. The air around the jet plane is nearly four times less dense than on the ground.

The density hill is a hill of chemical potential difference which balances the gravitational potential difference

We see also that the way the atmosphere thins out is that over equal distances the density or pressure drop by equal ratios (if the temperature is constant, which it is high in the atmosphere).

Left to themselves, particles spread out. The gravitational field of the Earth pulls air molecules towards the Earth, making it more dense lower down. This then leads to air spreading away from the Earth, from more dense to less. The atmosphere is in balance when the two tendencies are equal.



Life Burns its Fingers

Living things have filled the Earth's atmosphere with a twenty per cent charge of a dangerous pollutant. Its name? *Oxygen!* Yes, the very gas we rely on to breathe was made by living organisms, and is a danger to life for the very same reason that we use it to live. Carbon, the basic element of life, readily burns in oxygen. We burn it slowly in our bodies. Luckily for us, most organic compounds only burn rapidly at high temperatures. Less luckily, burning can itself create those temperatures. So watch out for sparks!

Life winds up the hydrogen-oxygen spring

Fuels are molecules which have been shoved up an energy hill by being torn apart, waiting to come downhill again one day.

Life began in water. Using sunlight, early living organisms - the blue-green algae - found a way to tear apart water molecules and to keep its hydrogen for themselves while throwing the waste oxygen away into the atmosphere. Just imagine if they had happened to store the hydrogen in vast fuel tanks dotted around the Earth. It would be obvious that a huge difference had been created, ready and waiting to be used, or more likely to explode and make water again. What living things do instead is to store the hydrogen, combined with carbon and oxygen, in their own fuel tanks - the carbohydrates such as cellulose of which plants are made. When we light a wood fire, or burn petrol, we are using up those fuel tanks.

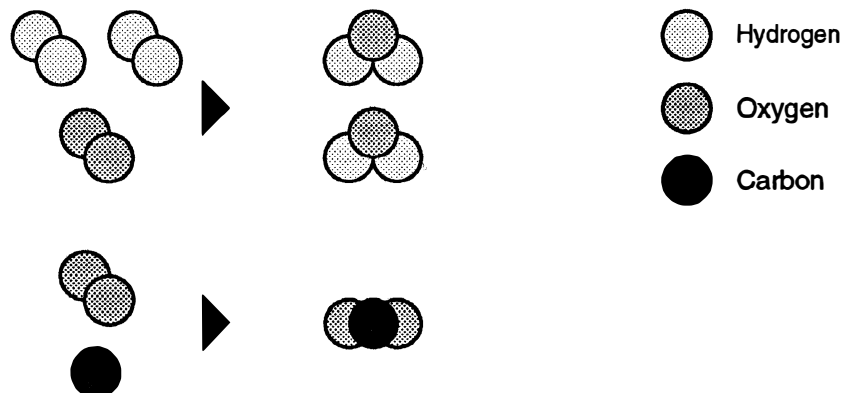
Decreasing potential energy goes downhill. The energy gets spread around, making things hotter.

Something burning is just the kind of process we most easily understand as happening naturally; as happening all by itself; as going downhill. Once started, fires just go on burning without help, and it may be all we can do to put them out. It is easy to see why, once we imagine the pulled-apart oxygen and hydrogen as a vast wound-up spring, and burning as that spring releasing its stored up energy, spreading it generously around. We even see the spreading-around going on, in the hot flame of the fire as it warms us.

The problem is that we can't see the spring. When molecules are torn apart, they go uphill in energy, and that stored potential energy is invisibly there and able to be got back again. And stored potential energy being released and spread around warming things up is very much downhill. It goes downhill *because* the energy gets spread around and diluted.

A fire

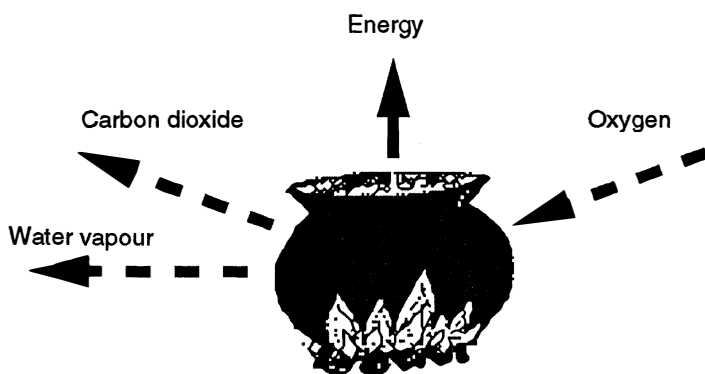
In a fire, oxygen - once torn out of water - snaps back into combination with carbon and hydrogen.



Burning makes hot

Making one mole of carbohydrate (say glucose) using sunlight goes uphill in potential energy by some hundreds of kJ for each mole of each constituent. Burning it comes down a similarly large hill. We can see why fires can be hot if we reflect that even at 1000K the energy spread around in the moving molecules is not yet ten kJ per mole. A fire can hope to be as hot as the sunlight which helped make its materials, with energy concentrated now in the random motion of molecules and not in the energy of torn-apart bonds.

Destroying an energy difference can create a temperature difference.



What happens in burning

In burning, carbon dioxide and water vapour are spread around, and so is energy. But the oxygen has to be collected in.

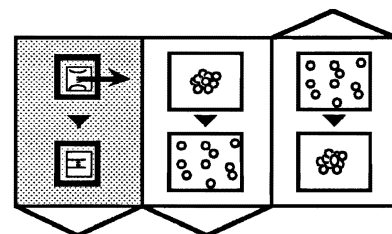
Burning is not downhill all the way

Besides going downhill because of spreading stored potential energy around liberally, burning wood also goes downhill because the carbon, hydrogen and oxygen previously locked up in the close confines of complex carbohydrate molecules is itself spread around. One large complex carbohydrate molecule turns into many smaller molecules, mainly carbon dioxide and water. Breaking up few large molecules into many small ones goes downhill, and so does spreading these molecules into the large volume of the atmosphere.

Making more particles, and spreading particles into a larger volume, or mixing them with others, are all downhill processes.

But burning does not have it all its own way. Oxygen, spread dilutely in the atmosphere by photosynthesis in ages past, has to be collected in if burning is to be able to happen, and this process goes uphill. One way to stop something burning is to starve it of oxygen, making this job even more uphill. A good way to do that is to provide a blanket of carbon dioxide, so that spreading out carbon dioxide also goes less far downhill, because there is plenty there already.

In burning, oxygen bonds once again to hydrogen and to carbon, coming downhill again from the ancient splitting of hydrogen and oxygen. Energy spreads out. Matter spreads out too, sending carbon dioxide and water vapour into the atmosphere. But the oxygen essential to burning has to be drawn in uphill from the atmosphere.



Living off Sunlight

Sunlight seems an unlikely sort of food. Yet plants use it to make cellulose and starch out of carbon dioxide and water. How is it done? The answer concerns a clever device evolved early in the development of life on Earth, which draws carbon dioxide in from the air, combines it with hydrogen torn out of water, and throws away the spare oxygen from the water. This dangerous waste product changed the atmosphere, oxidising rocks but also permitting the evolution of animals which use it for moving around to eat and avoid being preyed upon.

Energy goes downhill from hotter to cooler. High-energy photons turn into many more low energy photons.

Decreasing potential energy goes downhill.

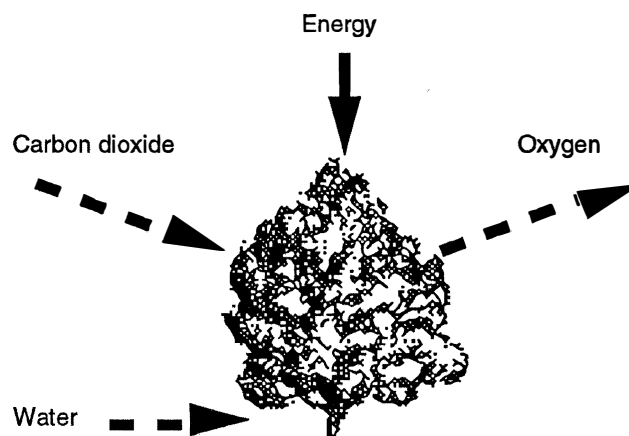
Hot photons flood in, cool photons flood out

The Sun is *hot*. Its temperature at the surface is around 6000 K. Hot objects radiate energy, and the hotter they are the more concentrated is the energy in the radiation. Packets of radiation - called photons - from the Sun each have more energy than the packets of radiation from a cooler object, such as the Earth. On their eight minute journey from the Sun to the Earth, the photons interact with nothing and arrive unchanged, as 'hot' as when they left. Most of them are absorbed by the ground, sea and atmosphere and are re-radiated to the Universe as a much larger number of lower energy photons at a temperature of around 300 K. Plants have found a way to tap into this downhill process, essentially one of energy going downhill from hot to cold, to drive reactions in which matter is assembled into complex molecules from simpler ones, an uphill process.

The essential thing is for the plant to catch the photon on its way downhill. The molecule responsible for this is chlorophyll, which makes plants green. The chlorophyll molecule can trap a photon of blue or red light, and store its energy as potential energy in the molecule. The excited chlorophyll molecule initiates a series of changes, in which hydrogen is pulled off water molecules and combined with carbon dioxide drawn in from the air, to make glucose. Glucose molecules are then assembled in ribbons to make cellulose, and in tree-like patterns to make starch. At each step, potential energy from the original photons is reduced, the energy slowly being spread around and ultimately mostly re-radiated as low-energy photons.

Photosynthesis

Ultimately, the difference between hot and cold is what drives photosynthesis.



Catching light but not letting go too soon

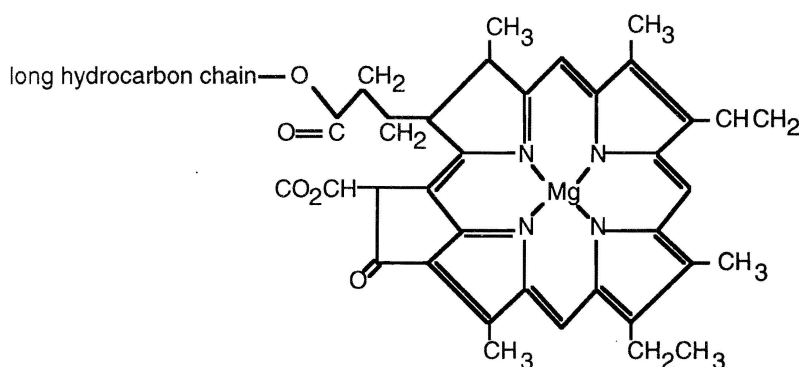
The danger for a chlorophyll molecule, having trapped the energy of a photon from the Sun, is that it will let it go again in a flash of light (fluorescence). This is avoided by using the potential energy to push away an electron down a chain of three other molecules. Now lacking an electron (passed elsewhere), the chlorophyll molecule takes part in reactions which perform the crucial trick - snipping hydrogen off oxygen in water. These hydrogen ions make the cell fluid nearby more acidic, and these differences in acidity cause the reactions which make glucose to take place. 'Hot' photons have been used to make a chemical difference, first of concentration of hydrogen ions, and then of complexity (glucose from carbon dioxide and hydrogen).

One reason why plants need fertilisers is that the difference in acidity works by making the 'universal' potential-energy carrier adenosine tri-phosphate (ATP) from adenosine di-phosphate (ADP). Plants cannot do photosynthesis without a supply of phosphates, which farmers often have to provide at some expense.

One difference being destroyed can create another.

The chlorophyll molecule

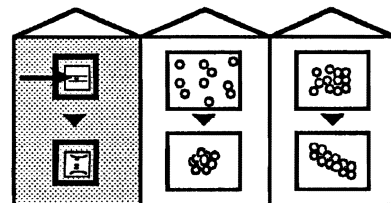
The square core of the molecule can absorb the energy of a photon by re-arranging the electrons in the square.



Every step in photosynthesis destroys a difference to make another. 'Hot' photons in a cool environment are used to make excited chlorophyll molecules. Excited chlorophyll molecules are used to move electrons from one molecule to another, making ions. Ionised chlorophyll is used to cut hydrogen out of water, and make a difference in hydrogen-ion concentration - acidity. The difference in acidity is used to build ATP from ADP. The presence of ATP in water, able to go back downhill to ADP in water, is used together with enzymes to build glucose from carbon dioxide and water. It's hard to believe that the carbon in a block of wood was all concentrated from its dilute form in the atmosphere, and that this was done by sunlight. Instead of photons from the Sun falling directly downhill to become cooler photons re-radiated by the Earth, some are caught and made to drive this complex process as their energy trickles more indirectly downhill.

Overall, energy going from hotter to cooler drives the concentrating of carbon dioxide and the building up of complex molecules.

Light is a special kind of potential energy: the travelling kind. Hitting the Earth, its high-energy photons go downhill to become a larger number of low-energy (cooler) photons. This process can be used to drive complex chemical reactions uphill, building plant material from carbon dioxide and water, and so indirectly providing food for animals.



Fuel for Home and Factory

In a modern industrial economy, we need to be able to create changes when and where we want, in factory, shop or home. One way to do that is to use transportable fuels such as oil, gas or coal. Fuels are what are called 'energy resources' in discussions about industry and the economy. What exactly is a fuel? And what does it mean to 'use up' a fuel, if energy itself cannot be made or lost?

Transportable potential energy stores

Energy runs down potential hills and can create other changes on the way down.

Imagine an economy based on springs. Lorries and trains would travel the country, carrying loads of wound up springs, delivering them to homes and factories, and taking away loads of unwound springs. There would be vast depots where springs were wound up, ready for re-use. Suppliers of springs would compete on the amount of energy stored and on the compactness of the storage devices.

A wound up spring can be used to create change because it is a store of potential energy. And the store can be taken from place to place. Changes can be made to happen if the energy runs down the potential hill and is spread around. When this happens, the energy is not lost, but the possibility of making things happen is lost.

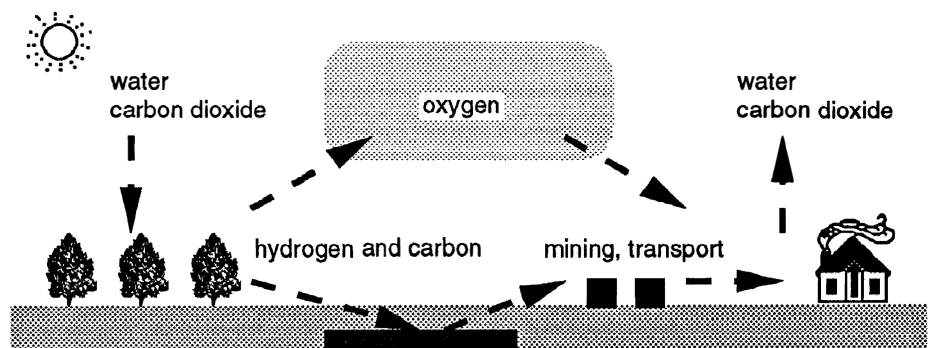
Pulling chemical bonds apart goes uphill in potential energy.

Now imagine another economy based on winding up chemical springs using water. In depots, water would be split into hydrogen and oxygen, perhaps by electrolysis. Pulling apart the molecules of hydrogen and oxygen is the stretching of a molecular spring. A pair of cylinders, one of hydrogen and one of oxygen, would be delivered to each home or factory, where they would be used to make things happen, either by burning them together or by cleverer methods. The end result - water - now an unwound spring, could be transported back for re-use.

The fuel economy we have - gas, oil, petrol, coal - is actually very much like this, *except that we don't transport the oxygen*. And we don't do the pulling apart of molecules ourselves. Instead, we rely on photosynthesis in ages past having torn apart water into hydrogen and oxygen, storing the hydrogen in carbohydrates and then hydrocarbons, and throwing away the oxygen into the atmosphere. The oxygen has naturally spread throughout the atmosphere, so it is already where we need it and doesn't have to be carried there. So we just mine hydrocarbons and carry them where we need them, calling them 'fuel'.

Origin of fossil fuels

Photosynthesis tears apart hydrogen and oxygen in water. Plants store the hydrogen in carbohydrates, which decay into hydrocarbons. We can burn the hydrocarbons (and the carbon) in the oxygen which was thrown away into the atmosphere.



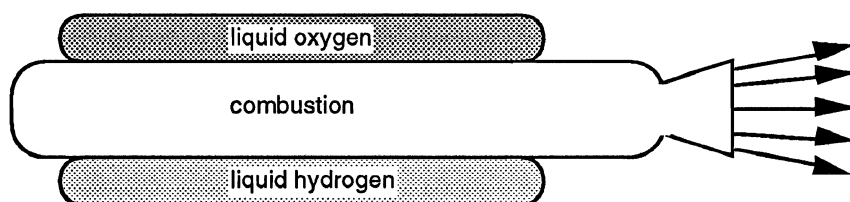
Just find a path downhill and go down it

In the imaginary spring economy, to get back the energy stored in a given spring we have to release *that* spring. It is not the same for molecules which have been torn apart. Any hydrogen molecule will react with any oxygen molecule to release potential energy. And for that matter, oxygen having been produced from water in the first place, it can react and run downhill in bonding to some other atom or molecule, such as carbon or iron. Indeed the oxidised minerals in the Earth came from such a process, initiated by living organisms generating oxygen.

For these reasons we cannot easily locate the potential energy associated with a fuel. All we know is that it took an uphill energy change to make the fuel, and that in reacting it goes downhill again, not necessarily down the same hill. A brick lifted out of one hole doesn't have to fall down the same hole to deliver energy.

We cannot always assume that the oxygen will automatically be there to provide a downhill pathway. In a rocket engine, for example, which has to operate outside the atmosphere, both components of the chemical spring have to be put into the rocket. Some use tanks of liquid hydrogen and liquid oxygen. Others react powdered aluminium with the oxygen-rich substance ammonium perchlorate.

It takes two to make a bond and so go downhill.



A rocket engine

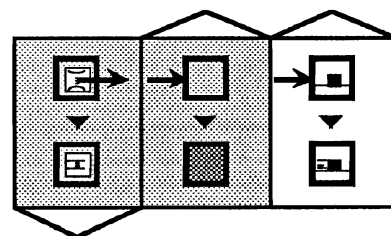
Rockets and jet engines work by burning fuel in an asymmetrical chamber, so that escaping gases produce thrust.

Getting the 'go' from burning

We may want to use fuel just to keep us warm, in which case burning it is the most direct way. But we also want to burn fuel in engines, to make things move or push things uphill. Burning fuel in a closed chamber produces hot high pressure gas: the potential energy difference is destroyed and temperature and pressure differences are created. This pressure difference can be used to create motion.

The way to produce systematic large scale motion, as opposed to the violent motion of an explosion, is to make the combustion chamber asymmetrical - that is, one-sided. Thus, in a rocket engine, one end of the combustion chamber is open and hot gases rush out, creating thrust. In a car engine, one end of the combustion chamber is a moveable piston, which is pushed by the compressed gas and is used via a crankshaft and gearbox to turn the wheels of the car. A difference in potential energy at the molecular level has been used up in order to create a difference in relative motion on the large scale.

Fuels are stretched molecular springs. A difference is destroyed to pull molecules apart, and the potential energy difference created can be used up later, at the time and in the way that we want, to make other things happen.



Wind and Rain

The Sun shines steadily on the Earth, keeping it warmer than the icy blackness of space. But the Earth is not simply quietly warm. Huge air currents circulate in the atmosphere, and water is drawn up from the oceans and falls again as rain. Violent hurricanes or tornadoes sometimes develop. The weather is kept in a state of continual and not very predictable change by the Sun's steady glow.

Our warm greenhouse

Objects above absolute zero spontaneously radiate energy. The hotter they are the more they radiate.

With a constant energy input and constant energy output, an object can be in a steady state away from equilibrium.

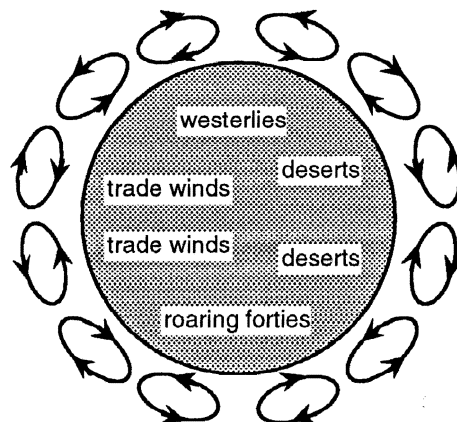
The Earth intercepts a tiny part of the sunlight flooding out from the Sun. Some is reflected and some absorbed. The part which is absorbed would warm up the Earth a little more, except for the fact that the Earth radiates energy out again into the cold blackness of space. The Earth stays at that steady temperature at which the two balance. Sunlight provides about 1.5 kW per square metre at the top of the atmosphere. Balancing that input over a disc the size of the Earth against the radiation expected from a warm sphere into space at very near absolute zero, the temperature to be anticipated for the Earth is surprisingly low, well below freezing. How is it that the average temperature on Earth is noticeably higher than this?

What keeps the Earth warmer than it 'should' be are the 'greenhouse gases' in the atmosphere, including carbon dioxide. Carbon dioxide and other gases transmit the short wavelength light and heat radiation from the Sun rather well, but they do not transmit well the long wavelength radiation from the Earth's barely warm surface. The Earth has to get a little warmer to radiate out as much as is coming in. Water vapour is also important in getting energy to the top of the atmosphere.

The result is that it gets colder as you climb mountains. The atmosphere is cold above and warm below. The scene is set for the atmosphere to get on the move, as warm air from below rises. There is also a temperature gradient from the equator to the poles, because the surface of the Earth faces sunlight head-on near the equator, and at a tilt near the poles, diluting it over a bigger area. All this produces a number of huge convection currents in the atmosphere, which we experience as Trade Winds, Westerlies and other regular air-streams.

Convection in the atmosphere

The Trade Winds, the Roaring Forties, and other main wind systems derive from these large convection currents.



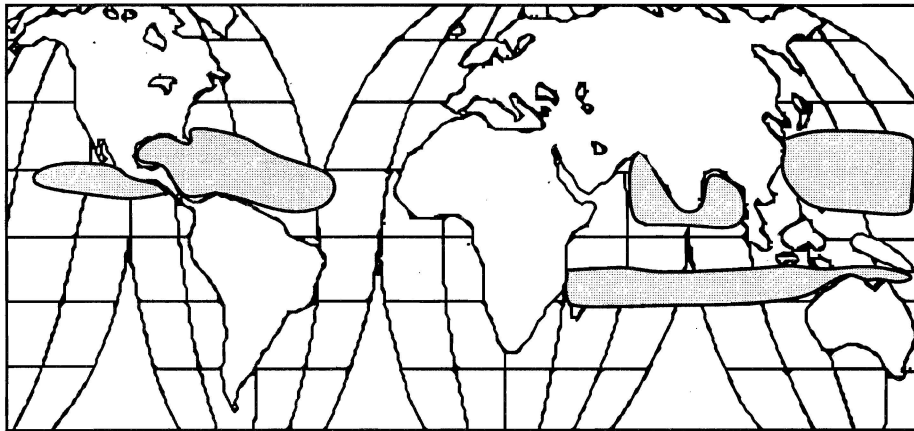
The atmosphere as an engine

The atmosphere, warm below and cool on top, is inherently unstable. Regions of warm air have lower density and pressure than colder air nearby. If the warm air is wet with water vapour, its density is lower still. The pressure differences cause winds to blow, and the density differences cause the warm air to rise. In this way, the temperature differences set large masses of air in motion, and the atmosphere behaves like a steam engine, in which a furnace is used to set wheels turning.

Overall, the effect of convection in the atmosphere is to transport energy from the equator to the poles. It is this temperature difference which drives the large scale movements of air. But there are local variations too. Near the equator, the sea temperature is high enough for a lot of water to fill the air above it. This very warm wet air can rise rapidly. The rotation of the Earth sets the rising air spinning. As it rises and cools, the water vapour in it condenses, releasing the large amount of energy stored when the water molecules were torn out of the sea. The resulting swirling mass of air, with torrential rain, is what we call a hurricane or typhoon. Again, a temperature difference produces a huge and destructive amount of motion.

The poles would be the best place for setting rising air spinning, and the equator the worst. But to get a warm enough ocean one must be near the equator. For this reason hurricanes arise only in two narrow belts north and south of the equator. This part of the atmospheric engine needs special conditions.

Differences in temperature can be the source of differences in motion.



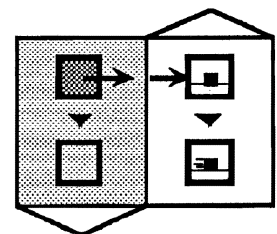
Hurricane and Typhoon belts

Hurricanes turn temperature and humidity differences into large scale destructive motion. They originate over seas warm enough to evaporate easily but far enough from the equator for the Earth's rotation to set winds spinning.

Deserts

North and south of the equator are two belts of deserts around the Earth: in the northern hemisphere they include the Sahara, Saudi Arabia, the Gobi, and the North American deserts of Arizona. In the South they include the Australian deserts and the Kalahari. These desert regions arise from the convection of air in the atmosphere. They lie where the warm wet air rising at the equator comes down again, having shed its water and cooled.

The Earth is kept in a warm steady state, far from equilibrium, by radiation from the Sun. The 'greenhouse effect' produces an atmosphere which is warmed from below, so that convection currents can start. The atmosphere behaves like a huge natural heat engine.



Energy on Tap

We turn on the tap and water comes out, and we don't think much about where the water comes from. We plug a vacuum cleaner into a wall socket and off it goes. It isn't often necessary to think about how the possibility of getting some machine to work is transmitted from one place to another. Anyway, what actually is transmitted?

Levers, transmission belts and gears

Energy can be transmitted mechanically from place to place. The amount transmitted is measured in terms of work.

Using a crowbar, I can lift a heavy stone using a much smaller force. But the price is that I have to push the long arm of the crowbar down much further than the stone gets lifted. Forces can be magnified, but the energy transfer - force times distance moved - can't be. The gearbox of a car makes the wheels turn slower than the engine, with the advantage that there is more torque at the wheels than at the drive shaft so that the car can go up steep hills. But the wheels can't get more energy than the engine delivers.

Energy can be transmitted in this way with no appreciable dissipation. The measure of energy transfer done mechanically is work - force times distance moved or torque times angular distance moved.

Energy transmitted mechanically travels on mechanical waves of various kinds. Waves can travel with little or no dissipation.

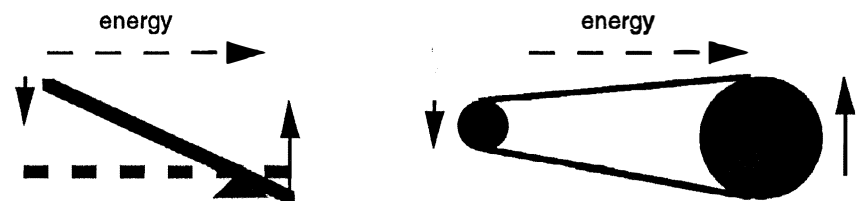
How does the energy get from one end of one of these drive systems to the other? It travels on mechanical waves. If one end of a drive shaft is started moving, a torsional (twisting) wave travels to the other end, and starts that end moving. If one end of a crowbar is pushed down, a flexural (bending) wave travels to the other end and lifts it. If a pulley wheel is started turning, a tension (stretching) wave travels along the drive belt and starts the other pulley moving. If I hit one end of a nail with a hammer, a compression wave travels down the nail and sends the tip further into the wood. These waves travel quickly, so we think of the effects as instantaneous.

As we watch an ocean wave approaching the shore, we see a constant pattern of movement travelling towards us. Water far out to sea moves up and down, and a moment later the water nearer to us goes up and down in just the same way. A wave is a way for a co-ordinated pattern of movement to propagate unchanged, with very little dissipation. Of course waves tend to spread out, but if provided with the right conduit, all the energy can travel along the conduit with the wave.

Work is energy transmitted from one place to another with negligible dissipation. It provides a way of making potential energy or relative motion which is available at one place available at another.

Doing work

Energy is transmitted along levers, via drive belts, gear chains and drive shafts.

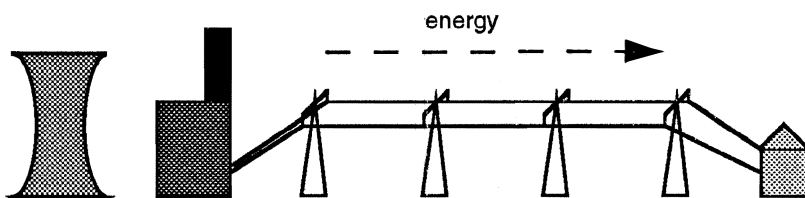


From power station to vacuum cleaner

Not so long ago, factories were full of long drive belts around the walls transmitting power to the machines in the factory. They were inconvenient and dangerous, and there was no way to send energy over long distances. Nowadays we use electricity. A power station a hundred kilometres away can provide power in homes and factories.

The spinning dynamo at the power station produces a potential difference: a voltage across the wires coming from it. This difference is created, ultimately, by destroying potential energy differences as the molecules of the fuel combine in its combustion chambers. By stretching conducting wires across the countryside, this potential difference is made to appear across pairs of wires in thousands of electric sockets, wherever it is wanted. How does it get there? It travels on an electromagnetic wave, guided by the conductors which act as a conduit for the wave. If the distance to the power station is a hundred kilometres, any change in the potential difference takes a third of a millisecond to arrive, being transmitted at essentially the speed of light. Just as the potential for movement is transmitted by mechanical waves, so electrical potentials are transmitted by electrical waves.

This electrical transmission is not only used for carrying energy from one place to another. Using the telephone, we use the same idea to transmit information, carried by changes in the electrical potential across a pair of wires. The impression we have that the transmission is instantaneous is due once again to the large speed of electromagnetic waves.



Electrical energy transmission

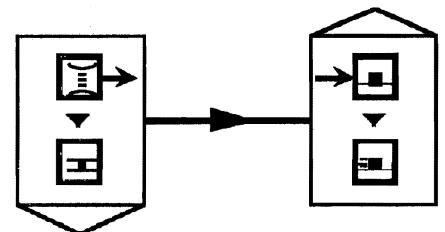
Conducting wires transmit a potential difference across long distances.

Electrical work

What arrives in the home or factory is an electrical potential difference, an electrical hill down which electrons can fall and make other changes happen. The changes we find it desirable to have happen are very varied. They include dissipating the energy immediately in order to heat a home or to cook food. They include getting things to move, in electric motors driving appliances in the home or machine tools in the factory - the ultimate dissipation is now delayed for a while as the energy is relayed to mechanical movements. They also include using the electrical potential difference to tear apart tightly bound atoms and molecules, for example in getting aluminium - intended for cooking pots and aircraft bodies - from its oxidised ores such as bauxite.

When energy is drawn from the potential difference, charges flow in the wires. The work done is the potential difference times the charge flowing. The rate of transmission of energy (the power) is the potential difference times the current.

Energy can be transmitted from place to place with little or no dissipation. Waves carry patterns of movement or potential differences without dissipation. Transmitting energy like this is called doing work.



Travel by Fire

Fire has kept people warm since the dawn of human history. Only more recently have we found how to use fire to make things travel, starting with gunpowder and rockets, and then steam and petrol engines. Now fire takes people into space. How is it done? How can a hot flame be enough to get things to move?

Electricity from a temperature difference

Energy goes all by itself from hotter to colder.

There is a simple demonstration which shows that a temperature difference is all that is needed to turn an electric motor. Two aluminium plates, each dipping into a beaker, have a semiconductor thermopile between them. A motor is connected across the thermopile.

If one plate dips into hot water, and the other into cold water, the motor turns. To see if it is just the hot water which does the trick, replace the cold water with hot. The motor stops! What is needed is a temperature difference. A final check of this idea is to run this little engine from ice, with one plate in ice and the other in cool water. The motor turns again, though rather feebly since the temperature difference is small.

If this demonstration seems unrealistic, notice that essentially the same idea is used to power spacecraft from sunlight.

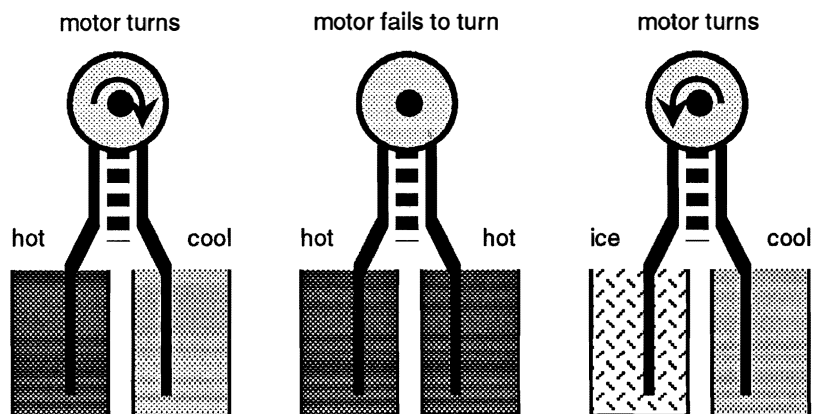
Hot material in cold places can be used as fuel. So could cold material in hot places.

In principle, then, we could transport hot water bottles around instead of fuel. Or we could transport ice and use it as a fuel. Both could be used as long as the surroundings were at a different temperature. This is actually done, of course, when we use geothermal energy, for example using natural hot water geysers.

What we mostly do instead is to burn fuels to make matter hot in the place where we want it to be hot. The inevitable leakage of energy from hotter to colder makes it useless to try to store or transport material with temperature differences. Instead we rely on the potential energy difference locked up in a fuel and the oxygen with which it burns.

Electrical heat engine

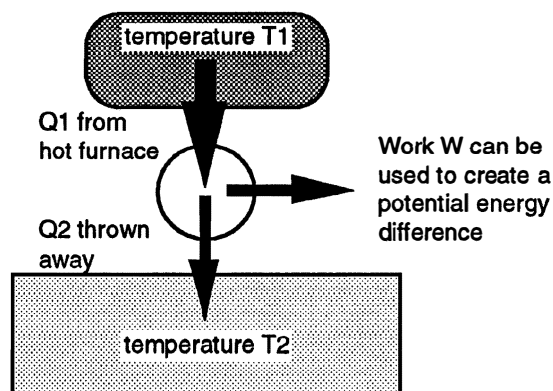
A temperature difference is enough to drive a small electric motor.



The Motive Power of Fire

The Motive Power of Fire was the title of Sadi Carnot's 1824 book attempting to explain the limits on what steam engines can do. The essential idea is that some but not all of the energy 'driven downhill' by a temperature difference can be used to go uphill and create a potential energy difference or movement which can create such a difference. The bigger the temperature difference the larger is the fraction of the energy flow which can be used to make a potential energy difference. The reason is that creating a potential energy difference is to concentrate energy. To do that there must be at least an equal compensating amount of spreading out of energy. If all the energy from a hot furnace were used to lift weights or move things, none would flow into the cooler surroundings, and there would be no spontaneous spreading of energy at all. So some *must* be thrown away if we are to get work from fire.

If the furnace is twice as hot as the surroundings (in absolute temperature) then only half the energy from the furnace need be thrown away and half can be used to drive machinery. In general the amount of energy which must be allowed to go to the cool surroundings must at least be in the same ratio to that which flows out of the furnace as the ratio of the lower to the higher temperature.



$$Q2/Q1 > T2/T1$$

$$W = Q1 - Q2$$

$$W < Q1 (1 - T2/T1)$$

Engines which are driven by the flow of energy from hotter to colder have limited efficiency.

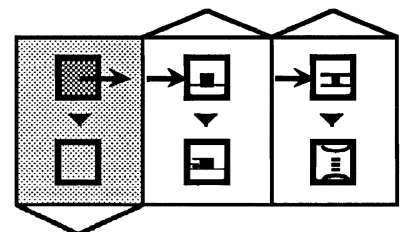
Wasteful heat engines

The way to avoid waste is not to let energy go down temperature gradients

Fire inside the engine

In petrol and diesel engines, the fire which drives the engine is inside the engine. Petrol or diesel vapour explodes in the engine, and the hot gases push on a piston in the combustion chamber. But the engine still works essentially by creating a high temperature and using the downward rush of energy from hot to cold to use some of it to do work. The same limitations as above apply.

Heat engines use the spontaneous downhill flow of energy from hot to cold to create uphill changes, getting things to move or lifting things up. Enough of the energy must flow out at the lower temperature for the effect of the engine to be downhill overall. This limits the efficiency of such engines.



Keeping cool makes such a difference

A lot of trouble goes nowadays into keeping things cool. Supermarket displays are chilled to keep food fresh. Refrigerated trucks keep their engines running to keep their loads frozen. Homes and public buildings are cooled in hot weather, at considerable expense. Why is it hard to keep things cool? How is it done?

Desert coolers

It takes a difference to make a difference

In hot dry climates, there is an easy way to keep rooms cool. Dry air from outside is blown through a fabric or fibre screen kept wet by dipping into water. Water evaporates into the dry air blown through the screen, and cool damp air comes into the room. The water molecules have to come apart, going uphill and taking energy from the air, so cooling it. This uphill process can only happen because of the spreading out of water molecules into dry air. It is the difference in humidity between the air outside and the wet screen which allows the difference in temperature to be created.

These coolers are no use at all if they are just put inside a room. Soon all the air in the room becomes humid, the evaporation stops, and the room is hot and wet instead of hot and dry, and everyone in the room is worse off than before. The cooler *must* be put in a window so that it continually draws in new *dry* air from outside.

The cooling only works if the difference in humidity is kept up. This means that the water in the cooler needs topping up frequently as the water evaporates. It isn't easy to get a full night's sleep with such a cooler!

A refrigerator keeps a temperature difference in existence.

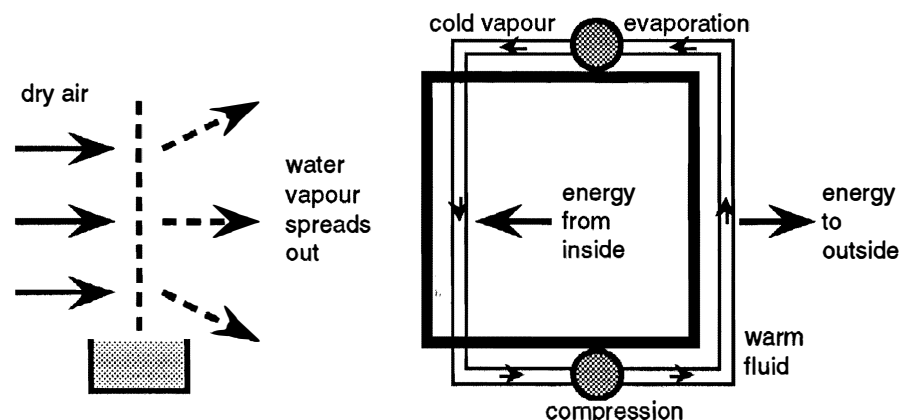
Several kinds of refrigerator work by evaporating a fluid. Unlike the desert cooler, most keep the fluid and its vapour sealed inside the device. The difference in concentration of vapour near the fluid, which gets the fluid to evaporate, is kept in being by pumping the vapour away as soon as it forms.

If the refrigerator is sealed, the vapour has to turn back to fluid again; to be compressed, and to spread out into the surroundings the energy released as its molecules cling together. All this creation of differences, of temperature and pressure, requires the destruction of some other difference.

Two ways to keep things cool

1 Cooling by evaporation of water.

2 Cooling in a continual cycle, evaporating and re-compressing a fluid



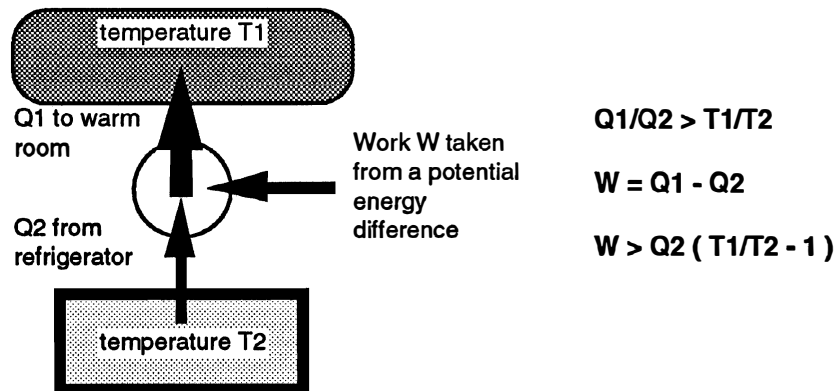
Getting energy to go from cold to hot

Energy spontaneously goes from warmer to cooler. That is why in a refrigerator the vapour inside the 'fridge has to be made *colder* than we want the inside of the 'fridge to get, so that energy will flow spontaneously out of the 'fridge. But now we have to pass this energy on somewhere. That is why the finned heat exchanger to be found outside the 'fridge at the back has to be kept *warmer* than the room. Then energy will flow spontaneously out into the room.

For all this to happen, we have to do what seems impossible, to get energy to run overall from colder (inside the 'fridge) to warmer (the room), when it naturally goes the other way. But that is why we need the refrigerator in the first place.

The secret is in letting energy run down a potential difference, so as to drive this uphill process. The potential difference is usually electrical, driving a pump which keeps the 'fridge going. But there are chemical refrigerators too, and others which burn fuel. In the end, the refrigerator can push energy uphill from cold to warm because, miles away in a power station, energy is running downhill from hot furnace to cooler surroundings, and creating a potential energy difference as it does so.

A potential energy difference is used up to create the temperature difference in a refrigerator.



Refrigeration

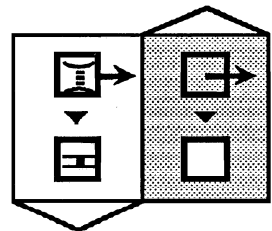
A potential energy difference is used up so as to push energy uphill from cold to warm.

Keeping cool has to keep a difference

How cold can the inside of a fridge get? Despite insulation round it, energy leaks in all the time from the warm room outside, just because of the temperature difference. If we pump energy out of the fridge faster, the temperature falls until energy leaks in as fast as it is pumped out. If the day get colder, less energy leaks in and the fridge again cools down until the amount leaking in is the same as the amount pumped out.

The job of a refrigerator, like the job of a central heating system, is to keep a temperature difference going, despite energy leaks which always tend to destroy that difference. The only difference is that one pumps energy out and the other pumps it in.

Refrigerators create and keep in being a temperature difference. They make energy go uphill from cold to hot, making it more concentrated. To do this they use up a potential energy difference, spreading its energy around.



Running, Jumping and Standing Still

On a warm terrace in the summer, ants scurry about, birds fly overhead, and humans go about their business. Movement to achieve a goal is common to all animals. Humans often use the possibility of action to *create* order or change: children piling up bricks; grown-ups building houses; people scrambling uphill. We take all this for granted. *Moving is just what animals do.* But where does the possibility of movement or action come from? What goes on to make action and movement possible? The key lies in how muscles work, and in how they are driven by ATP.

Puller and pulled

Muscle is made of interleaved parallel fibres. It contracts when one set of fibres pulls on the other, sliding the two sets past one another. Interleave the fingers of both hands, and pull one hand by bending the fingers of the other, to get the general idea.

The 'puller' molecule is called myosin. It grabs and tugs the 'pulled' molecule, which is called actin. The myosin molecule is shaped like a golf club. But the head of the club can bend, and it is this bending which contracts muscles, ultimately letting us run and jump. Its action has four steps: grab, bend and pull, let go, straighten up.

- 1 myosin head grabs an active site on actin
- 2 myosin head bends, pulling actin sideways
- 3 myosin head lets go
- 4 myosin head straightens, ready to grab the next active actin site

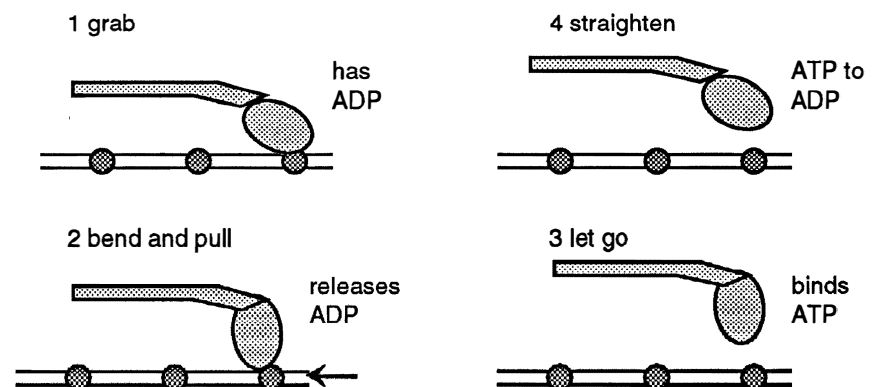
After these four steps, a myosin molecule has dragged an actin molecule a short distance along its length, and is ready to do so again.

This is what molecules do to make us move. But how do they come to be able to do it? Where is the source of the changes they undergo? The answer is the biological powerhouse molecule, adenosine tri-phosphate or ATP.

Actions can be made by destroying a difference.

Muscle fibres

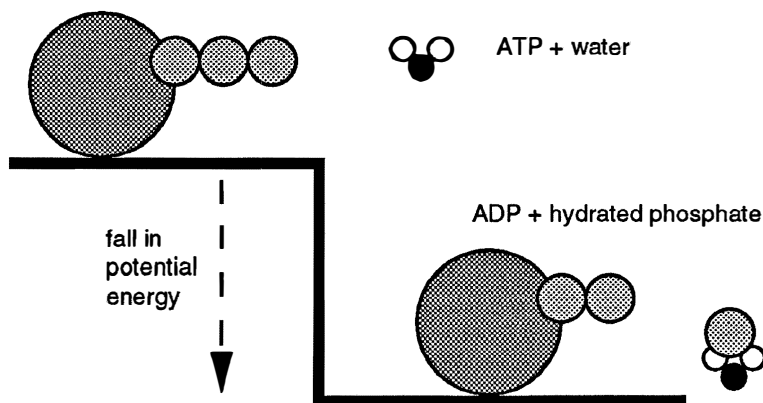
Muscle contracts when the pulling molecule myosin grabs an actin fibre, bends and pulls on the actin.



ATP falls over a chemical cliff

Farmers spend a lot of money giving plants fertilisers containing phosphates. Plants need phosphates to build ATP. And we get phosphates from eating plants. ATP drives many biological processes by falling over a chemical cliff; by releasing stored potential energy. This downhill process helps drive many of the uphill processes in animals and in plants, including photosynthesis, electrical signals in nerves, and the movement of muscles.

The ATP molecule has a compact ring of atoms, with a rod-like attachment of three phosphate groups. The third and outer phosphate group is not very strongly attached. The chemical cliff over which the molecule can fall is to lose its outer phosphate group to the tight clutches of water molecules, to which the phosphate group becomes strongly bound. There is therefore a drop in potential energy if this happens.



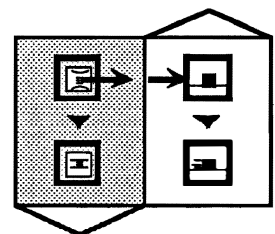
Falling in potential energy spreads energy around. It goes downhill.

The ATP-ADP cliff

ATP falls in potential energy if water molecules grab one of its phosphate groups.

The myosin molecule bends or straightens as ATP or ADP attaches to or breaks free of it. At step 3, when bent, it can acquire an ATP molecule, and this makes it let go of the actin. But being attached to myosin makes it easy for water to grab the outermost phosphate group of the ATP at step 4, leaving ADP attached to the myosin, which then straightens out. With ADP attached, at step 1, the myosin can bond to an active site on actin. Having done so the ADP is released and the myosin molecule does its essential bending. The whole cycle destroys ATP, which has continually to be built up again in other processes, using food supplies to do so.

Our running and jumping come from the downhill destruction of potential energy as ATP is broken up. As the ATP changes, it attaches to and alters the shape of special protein molecules in muscle, causing muscles to contract. Thus out of a chemical change we get our movements and our ability to climb hills.



Blood

The blood picks up life-maintaining oxygen in our lungs and drops it off again in muscle and other tissue where it is needed. How can this change happen both ways, and what makes sure it happens in the right way in the right places? It would be very bad if the blood took oxygen from our bodies and delivered it up to air in the lungs! The main answer is simple: matter goes from where there's a lot to where there's not. In the lungs, the air is rich in oxygen and the blood isn't; in muscle tissue the blood is rich in oxygen and the tissue isn't. The same cause explains both changes: why oxygen is grabbed by the blood and why it is given up by the blood.

How blood picks up oxygen

The rust-red colour of blood comes from oxygen attached to iron. The iron is held in a pocket in the folded chain of the protein haemoglobin, carried in the blood. Oxygen dissolved in the blood in the lungs can bond to the iron in the haemoglobin, and so be carried by the blood.

Changes go downhill. And there is a difference which goes downhill when oxygen becomes attached to iron in haemoglobin. It is the drop in potential energy as the spring of the bond between oxygen and iron snaps shut. It amounts to a downhill drop of around 50 kJ per mole, not very different from the downhill fall of a water molecule pulled from water vapour into liquid water. So here is a reason why the blood picks up oxygen: the spreading around of this energy as it is released.

If that were all, oxygen would always stay stuck to haemoglobin. But the downhill energy change doesn't have it all its own way. Taking oxygen away from others dissolved in the blood is a change going *uphill*. Any change which reduces the number of particles goes uphill. At body temperature, and with the amount of oxygen in solution having a pressure of a few mm of mercury, this uphill difference is very similar in size to the 50 kJ per mole downhill energy drop.

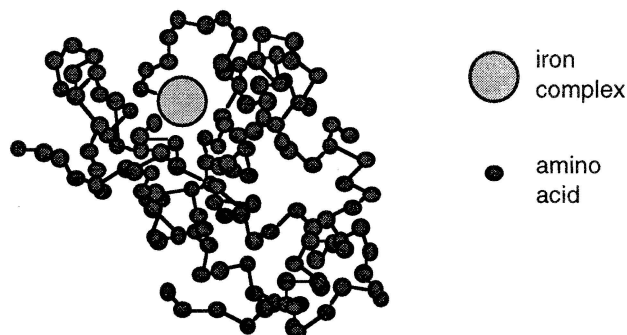
However, if the downhill drop is bigger than the uphill rise, the change is downhill overall, and haemoglobin picks up oxygen.

Decreasing potential energy goes downhill

Removing particles goes uphill. Adding more such particles goes downhill.

Part of haemoglobin molecule

Four folded protein chains nest together to make up haemoglobin. A model of one such chain is shown. Each has an oxygen-trapping pocket containing an iron atom waiting to bond to an oxygen molecule.



How haemoglobin lets oxygen go

How far uphill it is to take oxygen out of the blood depends on how much there is there. If there is plenty, it isn't very far uphill to take some molecules away. If there is less, it is a bigger uphill struggle to get any more. So if the blood has a lot of oxygen in solution the bigger downhill energy drop wins over the smaller uphill removal of molecules, and haemoglobin picks up oxygen out of solution.

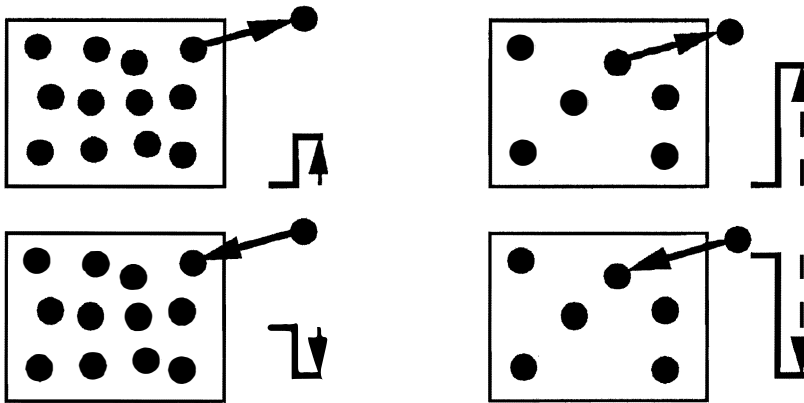
What about the change going the other way: haemoglobin giving up oxygen? Oxygen molecules leaving the clutches of iron atoms have an upward energy hill to climb (50 kJ per mole high). But adding molecules to the solution is now downhill. If there is very little oxygen in solution, this downhill drop is large. Thus the downhill effect of putting more oxygen molecules into solution can now beat the uphill energy difference needed to tear oxygen away from the iron. In this way, oxygen leaving haemoglobin can also be downhill overall. So it can happen too.

The hill for adding or removing particles is called the chemical potential difference.

The size of the chemical potential hill is given by an expression of the form $NkT \ln [\text{concentration}]$

Uphill and downhill

Adding or taking away particles makes more difference the fewer there are.

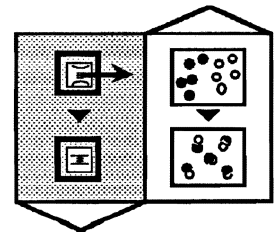


All this is why the change can be downhill overall in either direction, depending on how much oxygen is dissolved in the blood. Oxygen is given up easily to haemoglobin (not too far uphill) when there is plenty of it, as in the lungs. It is taken greedily from the haemoglobin (a long way downhill) when there is little of it, as in needy tissue.

A change which goes either way will have competing tendencies driving it

A small further difference affects the balance. If most haemoglobin molecules carry oxygen, it is a downhill change for some to lose it. But if hardly any carry oxygen it is downhill for some more to gain it. Only when around half do and half don't is it neither uphill nor downhill to lose or gain oxygen. But this is only a small hill; one or two kJ per mole.

If there are two competing differences driving a change, the change goes in the direction in which the larger difference goes downhill. Losing potential energy as a bond forms, spreading it around, goes downhill. Collecting enough energy to break a bond goes uphill. But taking molecules out of solution goes uphill, while putting them back goes downhill. This hill of concentration is small if there is plenty there and high if there is little.



Shapely Molecules

Life depends absolutely on enzymes. They control and make possible a host of reactions, including digestion. And they do all this by having very special shapes, with nooks and crannies in which molecules can meet and mate. How does an enzyme get its special shape? And how can a shapely molecule assist others to react?

Folding naturally into shape

Protein molecules are long chains, made of amino-acid links each of which is specified by the genetic code in the gene which makes that protein. Each protein chain folds up into a very particular shape, often roughly globular but with distinctive hollows and protuberances of definite shape and containing definite chemical groups on its surface. These features operate a lock and key system, providing sites at which particular other molecules can be held to encourage them to bond, or where they can be attacked by other molecules. In this way enzymes help control a wide range of biochemical processes. Protein molecules are truly protean: chains of different sequences of the same few amino acids form a huge variety of shapes.

Haemoglobin is one of these shapely molecule, made of four similar parts, each coiled up in a special way to leave a pocket holding an iron atom (which makes blood red) whose job is to carry oxygen around the body.

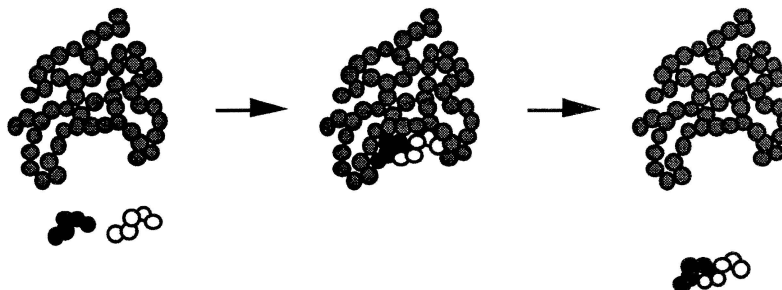
All these molecules depend very much on finding the right shape. How do they do it, all by themselves?

Simple orderly molecular shapes tend to get more disorganised.

We could imagine stretching a long protein chain - it will have hundreds or thousands of links - into a long straight line. Many of its links are flexible. As soon as we let it go, the battering from other molecules in the fluid around it would set its links twisting and wriggling as they share in the general thermal motion. If nothing else happened, the chain molecule would soon form a tangled ball, like a tangle of wool. It will be roughly spherical in shape because a non-spherical shape has special directions in it and so more orderliness than a sphere. A chain molecule which actually does this is rubber. White latex from trees consists of tiny spherical coiled up chains. When we stretch a rubber band we are uncoiling those chains.

Action of an enzyme

Each enzyme folds up into its own special shape. Its surface has a place which is the right shape to bring together molecules which then react.

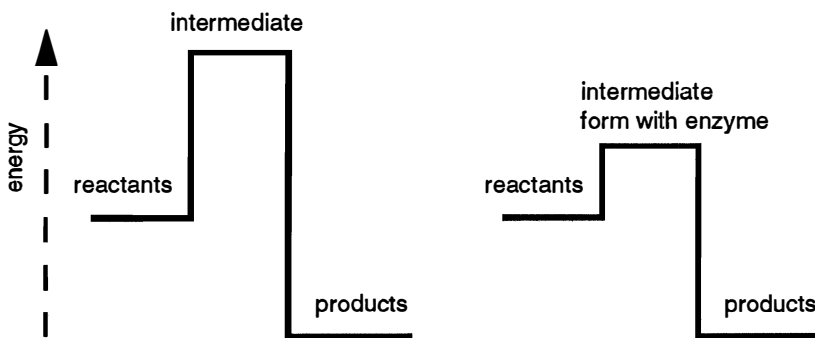


Falling naturally into a very special shape

The random coiling of chains will not produce the particular special shapes of proteins. However, unlike rubber which is made of identical links, proteins are each made of a unique sequence of links, each being one of a number of different amino acids. An amino-acid link can bond to another elsewhere in the chain. Also, each contains groups which bond more or less strongly to water molecules.

As the protein chain randomly twists and turns, groups on links which bond well to water molecules will from time to time turn to face such molecules. As they cling together, energy is released and soon shared out amongst the general random movement, not easily able to return. Links which can themselves bond together will also come together at random, and will tend to stay that way, again because of the general spreading out of the energy released. Before long, under these influences, the protein chain soon folds up into its characteristic shape, with groups which repel water molecules tucked away inside away from them, and groups which attract them tending to be on the outside.

Random chain twisting and energy spreading as bonds form compete to decide the shape of the protein molecule.



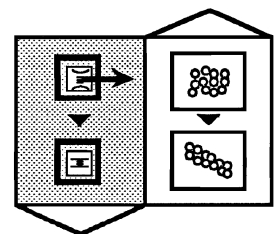
Enzymes help specific reactions

An enzyme can reduce the energy barrier for a specific reaction.

Enzymes work by providing special sites on their surfaces at which two molecules which are to react can be held. Most such reactions have to climb over an energy hill, because the atoms have to be re-arranged into an intermediate form. The energy to climb over the hill has to be got by chance battering from nearby molecules, and the higher the hill the less likely this is to happen. The enzyme can reduce this energy hill, by helping with the re-arrangement. In this way an enzyme can make a specific reaction much easier, and thus make it go more rapidly. The rate of production of an enzyme can thus be used to control the rate of a specific reaction.

A protein can also have its shape changed by attaching other molecules to it. It can then do a different job. Ion pumps in nerves and myosin in muscles are examples.

The specific shape of a protein molecule is decided by a competition between the random tangling of links in its chain and the random spreading out of energy as parts of links bond to each other and to the water around.



Think Electric!

Our nerve cells carry electrical impulses which tell muscles to contract, which bring signals back from eyes, ears, nose, mouth and skin, and which communicate between cells in the brain as we think about things. How can a cell produce an electrical signal? How are the electrical voltages made? How big can they be? It is done just by concentrating charged ions in the nerve cells.

Difference in concentration makes a voltage

Nerve cells work by pumping charged potassium ions into them and pumping charged sodium ions out of them. The 'pumps' are protein molecules in the walls of nerve cells which alternately open and shut to the inside and the outside. This makes the interior fluid of a nerve cell rich in potassium ions and poor in sodium ions, compared to the fluid outside.

Particles go from where there are a lot to where there are not.

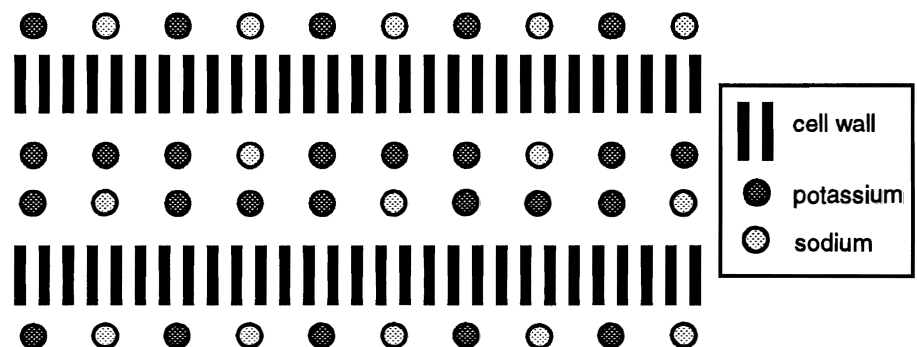
Differences, such as the difference in concentration of potassium and sodium ions between the inside and outside of a nerve cell, tend spontaneously to disappear. Potassium ions diffuse out of the cell, and sodium ions diffuse in. Particles go naturally from where there is a good supply to where there is a shortage.

To keep up the difference in concentration, protein ion-pumps are needed. An ion pump used by nerve cells consists of a protein molecule which alternates its shape. With one shape it has a hollow open to the outside to which a potassium ion can cling. With the other shape, the hollow is open to the inside of the cell, and the potassium ion enters the cell, while a sodium ion attaches to the hollow ready to be expelled at the next change of shape. The pumping action is driven by the near-universal cell-driving molecule, adenosine tri-phosphate (ATP).

This is how the salt we eat helps us to think.

Ions inside and outside nerve cells

Nerve cells have a high concentration of potassium ions and a low concentration of sodium ions, as compared to the fluid outside the cell.



Concentration and potential difference

Gas compressed in a cylinder has a higher chemical potential than that outside, and rushes out of the cylinder, down the potential hill, if the tap is opened. Ions concentrated in a nerve cell have a higher chemical potential than those outside, and tend to diffuse out of the cell down the potential hill, which has to be kept in being by the protein ion-pumps.

Electrically charged ions repel one another, so if they are crowded close together store electrical potential energy. A region of concentrated charged ions is at a higher electrical potential than a less crowded region.

The potential difference can be calculated from the ratio C of the concentrations. If C is about 10 (typical of nerve cells) then the chemical potential difference is:

$$NkT \ln C = 5.7 \text{ kJ per mole.}$$

This is not very big. Translated into an electrical potential difference for singly charged ions carrying a charge $Ne = 96\,400$ Coulomb per mole, it is:

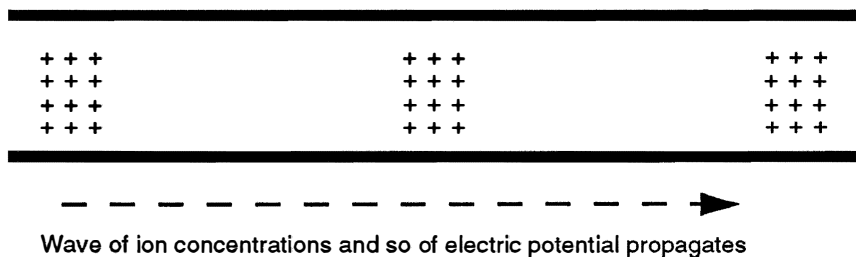
$$5\,700 \text{ kJ per mole} / 96\,400 \text{ C per mole} = 60 \text{ mV.}$$

Typically electrical potentials from nerve cells are a few tens of millivolts (compare the 1.5 V for a dry cell), as this rough estimate suggests.

The source which drives nerve cells uphill, creating concentration and electrical potential differences, is ATP. To do it, the ATP molecule drops downhill, losing a phosphate group to the strong clutches of the surrounding water.

Difference in concentration is difference in chemical potential

Ion concentrations make electrical potential differences

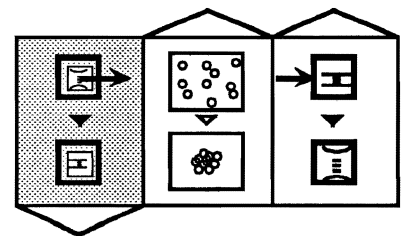


Nerve signals

Nerves transmit signals by propagating a wave of concentration disturbance along them.

Nerves have to transmit electrical signals, so that our brains can tell our fingers what to do, or so that our eyes can let our brains work out what is in sight. Protein molecule gates in the cell walls of nerve cells open, letting ions rush in or out after the pumps have built up a concentration difference. These surges of ions initiate local pulses of concentration which travel along the nerve cells. And these pulses are the electrical signals the nerves carry.

It takes a difference to make a difference. ATP drives ion pumps which concentrate ions inside nerve cells. This difference in concentration makes a difference in electric potential.



Packaged Electrical Difference

Batteries are everywhere, in torches, watches, cameras, radios, cassette players. Batteries can be powerful enough to drive cars, or tiny enough to go in heart pace-makers. A battery is a packaged form of potential difference. We speak of a battery being 'live' - ready to make something happen - or 'dead' - unable any longer to cause a change. How is electrical potential difference created? How does a battery stay ready to work when we want it to?

Reactions which stop themselves

A battery is a chemical reaction which holds itself in suspense; whose success temporarily stops it proceeding further. The reaction produces opposite electrical charges at each end of the cell. The electrical potential difference produced opposes the reaction which produced them. So the cell waits, 'live', but in the meantime doing nothing but stay in balance. If the ends of the cell are joined by a wire, charges can flow round the wire, and the chemical reaction in the cell makes more charges to replace them.

Chemical reactions go down chemical hills, often by falling in potential energy and spreading that energy around.

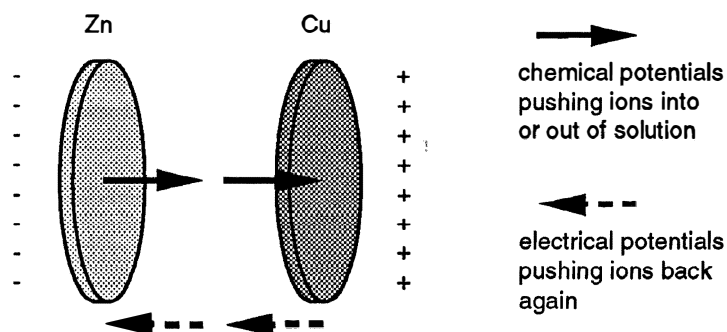
To be useful to make cells, a chemical reaction must shift electrons from one chemical species to another. Such reactions are more common than one might think, including iron going rusty, since all oxidation and reduction amounts to the shift of electrons. They are called redox reactions. We can even make electricity from the combining of oxygen and hydrogen to produce water, in a cell called a 'fuel cell'.

If zinc metal is put into copper sulphate solution, zinc atoms give up electrons, becoming zinc ions in solution, and copper ions in solution collect those electrons and become copper metal plating the zinc. The reaction happens spontaneously, so it must go downhill, chemically speaking.

The trick in making a cell is to make the giving up and taking in of electrons happen at different places. In the original voltaic piles, discs of metals such as zinc and copper were kept apart by wet paper or cloth. Zinc atoms became zinc ions, leaving electrons on the zinc. Copper ions became copper atoms, taking electrons from the copper. But the negative charge on the zinc pulls zinc ions towards it, stopping the reaction there. And the positive charge on the copper pushes copper ions away, stopping the reaction there too.

Cells: reactions in balance

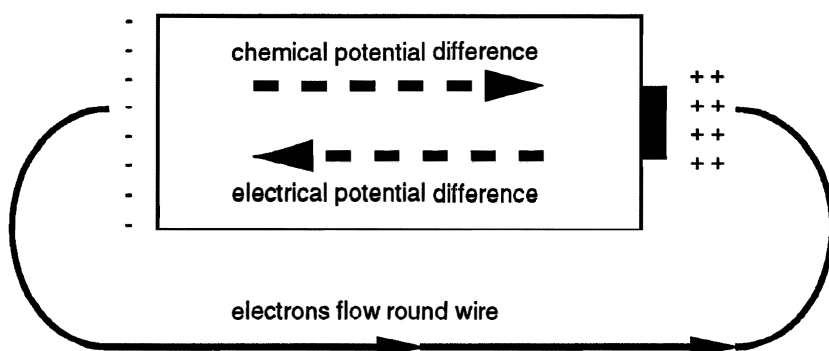
The reactions at each plate charge up the plates until the effect of these charges stops the reactions.



Measuring chemical potential difference

The electrical potential difference which just stops a chemical reaction provides a way to measure the push behind that reaction. That for zinc atoms producing zinc ions is 0.76 V. Since the reaction shifts two electrons, one mole of ions produced shifts a charge of $2 \times 96400 \text{ C}$, and so has an energy hill of about 145 kJ per mole. That for copper ions becoming copper atoms is 0.34 V, with an energy hill of about 65 kJ per mole. Both are values measured under 'standard conditions'. The net result is that a cell made with copper and zinc gives a potential difference of $0.76\text{V} + 0.34\text{V} = 1.1\text{V}$.

Different types of cell differ in voltage because the cell reactions are driven more or less strongly. The lead-acid accumulator, giving 2 V, is driven rather strongly. Ordinary dry cells, giving 1.5 V, are driven by a rather smaller chemical potential difference. Even weaker are mercury 'button' cells for calculators, at 1.35 V.



Current in a wire from a cell

When electrons flow round an outside wire, the reaction in the cell proceeds to replenish them.

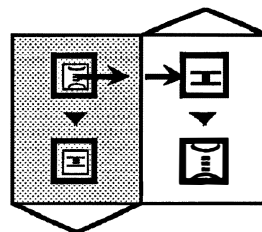
Current from a cell

If the charged plates of a cell are connected by a wire, electrons flow round the wire. This reduces the charge on the plates a little, so that the cell reactions are no longer completely stopped. So they start up again, replenishing the charges on the plates. The more current that is drawn, the more the reactions have to go to keep up.

Finally, of course, the chemicals in the cell are used up, and no further reaction can take place. The cell is 'dead'. We have to buy a new one, or 'recharge' the cell by passing an electric current thorough it the other way so as to drive the cell reactions in the opposite direction, re-constituting its original chemical composition. In this case the chemical reaction is being driven uphill, by providing a larger electrical downhill push from outside.

Electrical potential differences drive electric currents. Chemical potential differences drive chemical reactions.

It takes a difference to make a difference. A chemical potential difference can make an electrical potential difference. The electrical potential difference can drive an electric current.



Uphill by Chance

To escape from the clutches of its neighbours, a molecule of water needs to be hit hard enough to climb out of the energy hole they make for it. To fuse together in the Sun, two protons need to move fast enough to climb the energy hill made by their mutual repulsion. Such energy has to be got by chance collisions. How likely is this to happen? What effect does this have on how fast such changes can proceed?

Going uphill in order to get somewhere

Particles may have to climb a potential energy hill before a change can happen.

When Hannibal invaded Italy from France, he had first to take his army and its elephants over the Alps. He had to go uphill over a barrier in order to go downhill later. Molecules often find themselves in Hannibal situations. Unlike Hannibal, however, they cannot get uphill by determination and by using stored reserves of energy. They have to do it by chance; by getting accidentally pushed over the hill.

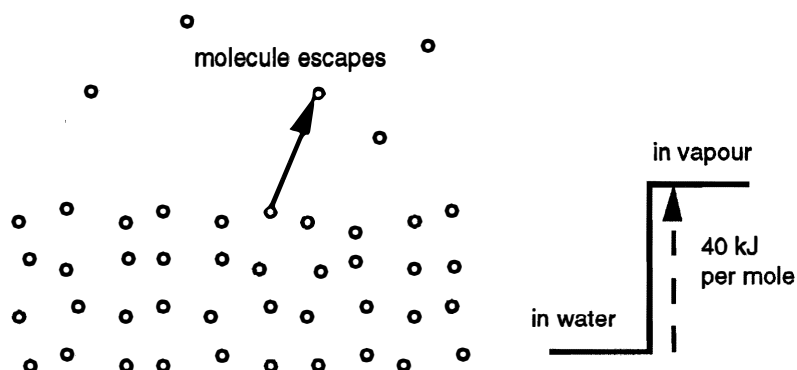
Water molecules attract one another. This is what holds liquid water together. To get free of its neighbours a molecule has to be torn away from them. It has to get up a potential energy hill about 40 kJ per mole high. Of course, molecules continually jostle one another, but they do not on average have anything like this much energy. At 300 K they have only between 2 and 3 kJ per mole of thermal energy. So to escape, a molecule has to be lucky enough to get between ten and twenty times the average energy which any molecule has, just by being hit hard enough by chance by other molecules. This doesn't happen often. But it does happen sometimes: there are billions of collisions every second, after all. That it doesn't happen often is why water lies around in puddles for a long time after it has rained. That it does happen sometimes is why puddles do in the end evaporate.

The chance to get over an energy hill gets better the higher the temperature.

A lot of other changes are held in check in the same way. For the oil in a car engine to flow and lubricate the cylinders, oil molecules must push past one another. That needs energy too. At low temperatures, many fewer molecules acquire by chance enough energy to shoulder past their neighbours, but at higher temperatures this happens more often, because each molecule has more energy on average. That is why engine oil is much runnier when it is hot than when it is cold.

Potential energy hills to climb

A water molecule needs between ten and twenty times the average thermal energy at 300 K to escape from the liquid.



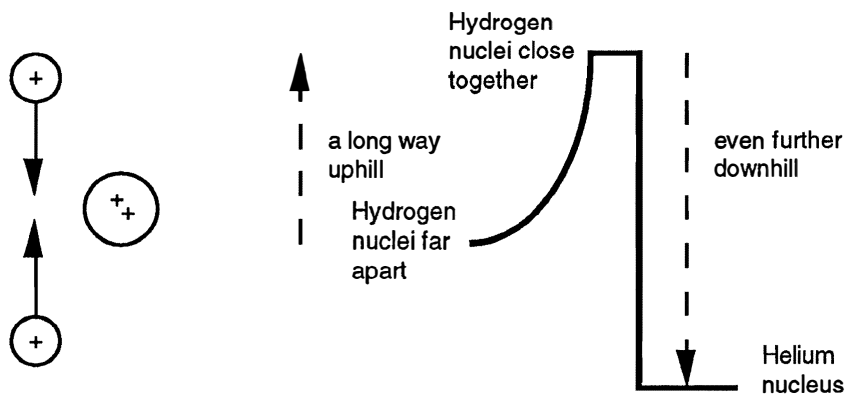
Our long-lasting Sun

At the centre of the Sun the temperature may reach ten million degrees. That seems hot enough for anything to be possible. But it isn't. The average energy per particle is nearly a hundred thousand kJ per mole. This is more than enough to tear atoms apart into ions and electrons. But it isn't enough to get protons close enough together to fuse to make helium, which is what has to happen if the Sun is to generate energy. To fuse together, two protons have to collide fiercely enough to touch, while being pushed apart by their electrical repulsion. This electrical hill is about a hundred million kJ per mole high, a thousand times larger than the average energy per particle.

The result is that fusion of hydrogen to helium in the Sun hardly ever happens. In fact, the power generated in each tonne of the Sun's mass is about that of an ordinary torch bulb. There is so much Sun that the total energy released is enormous. But it is only a minute part of what the Sun is capable of. So the Sun, like other stars, is very long lasting, thanks to the difficulty of getting up a very big hill by chance.

The fusion produces energy because, when protons do climb the electrical Alps, they find a deeper nuclear valley awaiting. They fall down it, because of the nuclear attraction, and the energy is released and ultimately comes our way as radiation from the Sun.

Energy is released after a hill-climb if there's a deeper hole on the other side.



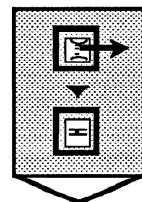
Hydrogen fusion in the Sun

Very rarely, two protons get close enough together to fuse into a helium nucleus.

Enzymes work by improving the odds

Many reactions which are important to the survival of animals and plants, such as the making and breaking down of ATP, would not happen fast enough to be useful without the help of enzymes. The energy hills that have to be climbed are too high. Chance collisions can get molecules over low hills much more often than they can get them over higher hills. So the enzyme lowers the hill. It does so by providing a niche on its surface in which the molecules are held in such a way that the reaction is easier. In this way the enzyme makes the reaction happen much faster.

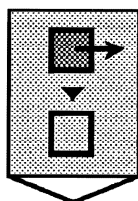
Molecules can climb potential energy hills by chance. The rates of many reactions are controlled by the size of the hill to be got over before the reaction can happen.



About the pictures

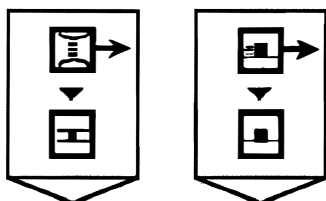
Each of the picture symbols we have used corresponds to a particular kind of term in the calculation of entropy or free energy changes.

Thermal energy flow



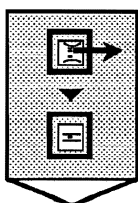
Energy added to a substance and dissipated amongst its molecules adds to its entropy. Energy taken from a substance decreases its entropy. The magnitude of both changes depends on the temperature. The *lower* the temperature the *larger* the magnitude of the entropy change, so adding energy to something cold increases the entropy much more than adding the same energy to something hot. Similarly, taking energy from something hot reduces the entropy by less than does taking the same energy from something cold. For this reason energy goes spontaneously and naturally from hot to cold, since this increases the entropy overall.

Potential and kinetic energy: large scale



Potential energy is energy stored in a field. If the potential energy of macroscopic objects becomes dissipated by being shared randomly amongst their molecules, the entropy increases. Similarly, the kinetic energy of a macroscopic object is the correlated motion of all its parts, and if this is dissipated by being shared amongst its molecules, the entropy increases. Both potential energy and kinetic energy are generally dissipated by means of friction of various kinds. In the idealised case where there is no friction, energy can pass from potential to kinetic (from field to moving object) and back again with zero change in entropy. Such a process has no natural direction and no sense of time. Thermodynamically, *nothing happens*.

Potential energy associated with bonds



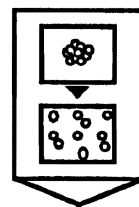
When two chemical species bond together, they are at a lower potential energy than when they are apart. The forming of bonds releases energy to be spread thermally amongst the molecules of the matter concerned. This process increases the entropy. In order to break bonds, energy must be taken from the thermal motion of molecules and stored as potential energy. This reduces the entropy. The influence on the direction of chemical or physical change can be expressed in several equivalent ways. The entropy change for breaking one bond of energy e is e/kT ; the change in the number of microstates is the Boltzmann factor $\exp(-e/kT)$.

Molecular crowding and patterning

The entropy is also affected by changes in molecular crowding or patterning. It increases when there are more molecules. It increases when molecules become more widely spaced. It increases when molecules are arranged in less orderly patterns. These changes can be expressed as entropy changes or changes in numbers of microscopic arrangements. They can also be expressed as chemical potential differences, in which form they can be compared directly with the effects of changes of energy.

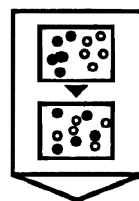
Molecules spreading out

The entropy increases if molecules spread out to occupy a larger volume, since they have more spatial ways of being arranged. It decreases if they are squashed into a smaller volume. If a molecule is added to a region of low density, the entropy increases by more than if it is added to a region of high density. Similarly, removing a molecule from a high density region reduces the entropy by less than does removing one from a low density region. This is why molecules go spontaneously from high to low density regions; the net effect is an increase in entropy. The effect can also be expressed in terms of the chemical potential difference. For example, for dilute substances such as ideal gases or dilute solutions the chemical potential difference between regions of concentrations c_1 and c_2 is $NkT \ln(c_1/c_2)$, per mole of molecules going from one to the other. The chemical potential difference is an energy: that energy change at temperature T which would have the same effect on the number of microstates as does the transfer of molecules.



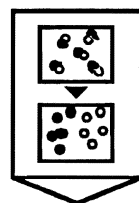
Mixing

When different species of molecules are present together, there is a part of the entropy due to the interchange of molecules of different species. The entropy increases as the different kinds of molecules get more mixed up together. Thus pure substances have lower entropies than mixtures, and there is a spontaneous tendency of molecules to mix. The presence of hydrogen and hydroxyl ions in pure water and its consequent pH of 7 owes something to this effect. Despite the energy needed to form the ions, some are always present because making new species (the ions) adds to the possibilities for mixing (it also increases the number of particles overall - see below).



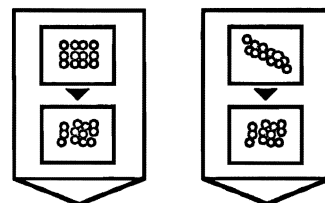
Making more particles

The entropy is increased when there are more particles, because more particles can be arranged in more ways than before. This effect favours the breakdown of complex molecules into their component parts. A good example is the explosive TNT, a large molecule which rearranges itself into a large number of smaller molecules, such as carbon dioxide, water, nitrogen oxides etc. Since there is also a net release of energy and the products are gases instead of solid, the entropy increases on all counts. This is why TNT is spontaneously explosive.



Destroying pattern

The entropy is increased when a regular orderly array of particles loses that spatial order, as when a solid like ice melts. If particles are patterned, there are fewer ways of re-arranging them than when they are disordered. One kind of patterning is that in the many crystalline forms. Another kind is, for example, the magnetic patterning which lines up molecular magnets. Yet another is the shape of complex molecules such as polymers, simply patterned when stretched out in long chains and less patterned when they coil up randomly. Stretching a rubber band lets you feel the tendency of polymers to coil up again once stretched.



Changes all add up

Most changes involve both energy changes and changes in the crowding, number or patterning of molecules. All contribute to the total entropy change. If the total entropy increases, the change can happen, even if some contributing processes decrease the entropy. Overall, every process is downhill. But parts of it can be driven uphill by larger downhill changes elsewhere.

Index of topics

Certain concepts, such as energy flow, temperature, and potential difference are common ideas running throughout these stories, and are thus not included here. In this index can be found the more important examples which are discussed in the stories using such ideas.

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