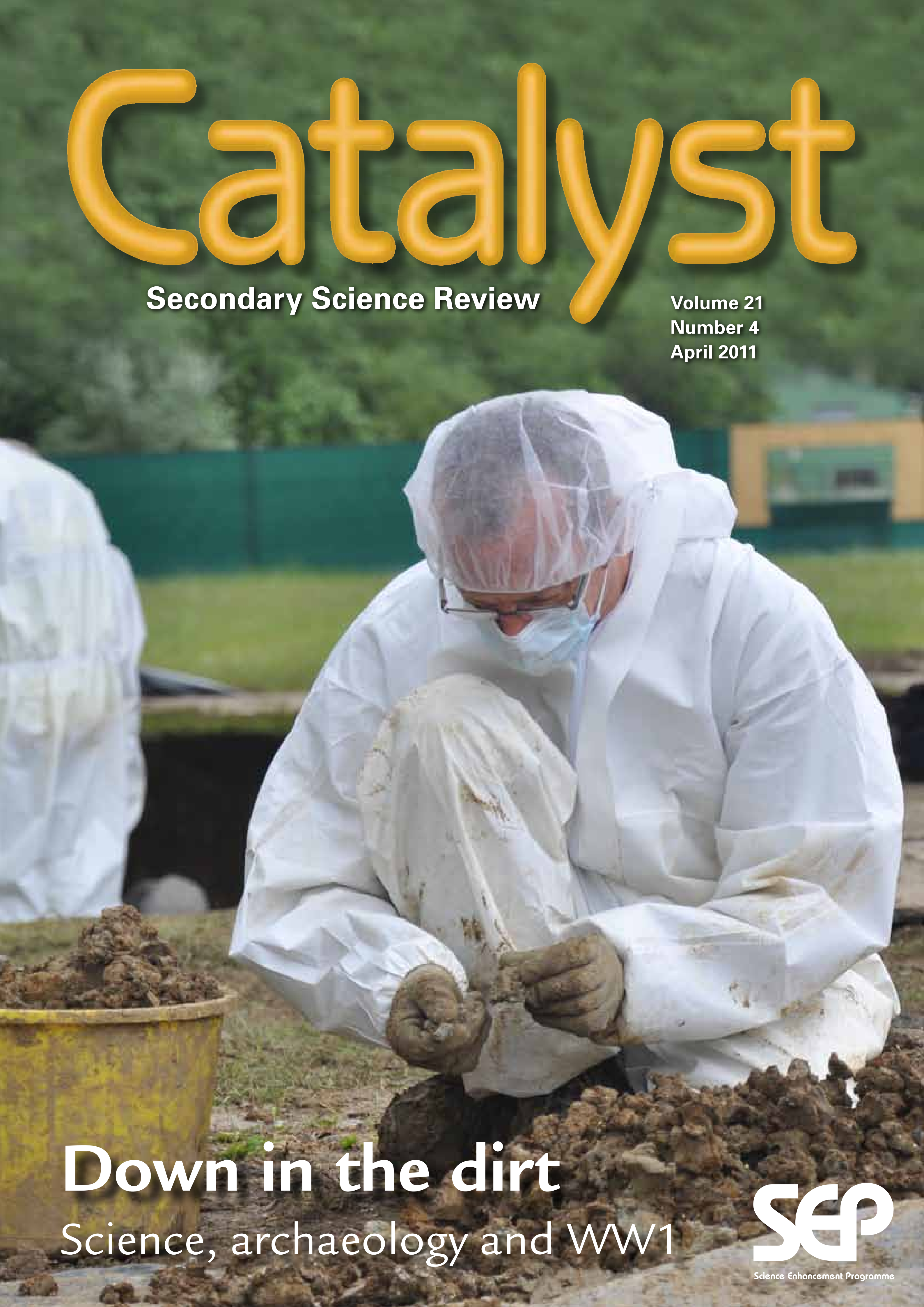

Catalyst

Secondary Science Review

Volume 21
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April 2011

Down in the dirt

Science, archaeology and WW1

SEP
Science Enhancement Programme

Catalyst

Volume 21 Number 4 April 2011

The cover image shows a member of the Oxford Archaeology team working with spoil excavated from First World War graves at Fromelles in northern France – see the article on pages 1-3. (Photo OA/Tim Loveless)

Contents

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Science and history

In the first article in this issue of CATALYST, Emma Brown of Bradford University looks at the part science has played in identifying the remains of some of the fallen of the First World War. This has required a combination of techniques from biology, chemistry and physics, together with an understanding of the history of the time. It makes for a fascinating story.

Here's another story from the past. In the 19th century, philosophers sought to define science's limits. Some claimed that there were questions that science could never answer – for example, what are stars made of? Then, in 1859, Bunsen and Kirchhoff used spectroscopy to analyse starlight and identify the elements present in stars. On pages 8-11, Vicky Wong explains how spectroscopy is used today. On page 12 she shows how to make your own spectrometer, and on the back page we look at one of the biggest spectrometers, built to measure the mass of the neutrino, the smallest known particle of matter.

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Emma Brown

Science on the Western Front

Identifying the missing from the Great War 1914-1918

In the years 1914-1918, troops from Britain and its Dominions, as well as men and women from France, Belgium and eventually the United States, were at war with Germany and Austria-Hungary. The Western Front saw some of the fiercest fighting with huge numbers of casualties. Emma Brown of Bradford University describes the part played by science when new graves of the war dead are found.

The Western Front in 1917 from a map of the time

The total number of military dead in WW1 is estimated at 8.5–10 million. In the mud and confusion, many of the dead did not have proper burials. Many temporary graves were destroyed by later shellfire. There are some 100 000 missing and assumed buried on the fields of the Somme alone, so it is not surprising that the remains of soldiers of the Great War are occasionally recovered during archaeological investigations.

Key words
DNA analysis
isotopes
corrosion
evidence

Archaeologists digging by hand at the mass grave, Fromelles

The No Man's Land Archaeology team discovered three soldiers from trenches around Serre in 2003 and the Plugstreet soldier in 2008 (see Box). Then, in 2009, 250 mostly Australian men were also found buried in a mass grave in Pheasant Wood, near the French town of Fromelles. With the aid of scientists, archaeologists, historians and organisations such as the Commonwealth War Graves Commission, every effort is made to identify the missing and re-bury them in war cemeteries.

Historical records

Several different approaches can help us to identify the individuals whose remains we find. Firstly, the service records of men who enlisted to serve in the Great War contain information that may be of use in the identification process, such as the soldier's age, place of birth, occupation and height. He would have also undergone a medical examination to ensure he was fit for service. In some cases, previous injuries were noted. Occasionally dental records exist, as was the case with the Plugstreet soldier.

Box: The Plugstreet Soldier

Private Alan James Mather was born in Inverell, New South Wales, Australia, in 1879. He was a prize-winning winemaker. He enlisted in the Australian Infantry in January 1916 and was killed in action on 7th June 1917 at Messines. He was 37. He was described by his commanding officer as 'one of my best and most trusted men'. Alan was discovered by the No Man's Land team during the excavation of the German front lines near Ploegsteert Wood in 2008. A combination of scientific techniques established his identity.
Private Mather was reburied with full military honours at Prowse Point Cemetery, near Ploegsteert, Belgium on 22 July 2010.

Private Alan James Mather

The full military funeral of Private Alan James Mather at Ploegsteert Cemetery

The quality of information available from service records varies. In the case of Australian soldiers, extensive and thorough service records survive and are free to access online via the National Archives of Australia. Sadly, the service records of men from the UK are in a very poor condition as they were severely damaged during the Blitz of 1940-41.

The chemistry of personal effects

A useful starting point for the identification of unknown soldiers is the examination of their personal effects. Metal items, such as shoulder titles and other regimental insignia can tell archaeologists the nationality of the force the solider served with, which was the case with the Plugstreet Soldier, who was found with intact 'Australia' shoulder titles and the 'Rising Sun' general service badge.

The Rising Sun badge of the Australian Army found with the Plugstreet soldier and in use during WW1

These badges were made of brass, an alloy of copper and zinc. Corroding copper alloys can preserve organic material, such as wool and cotton, when in close association. As the alloy corrodes, copper ions build up in the organic material. High levels of copper ions act as a biocide, inhibiting the process of microbial decay, resulting in fragments of preserved material. The pH of surrounding soil affects how well clothing items are preserved. For instance, wool (keratin) degrades rapidly in alkaline conditions, whilst cotton (cellulose) degrades more rapidly in acidic conditions. Other materials, such as leather, are more resistant to decay. It is not unusual to find a body wearing only leather boots as the wool and cotton materials have degraded.

The Rising Sun badge and an Australia badge are set up for X-ray.

X-ray of the Rising Sun badge.

Anthropology

Obtaining a biological profile of an unknown body is an important step in the identification process. Males and females look different. This is known as sexual dimorphism, and is evident in the skeleton. This is most evident in the pelvis. The female pelvis is designed for childbirth, so is wide in comparison to the male pelvis.

It is also possible to tell age from the skeleton. When we are born our bones are not fused; this allows for growth. As we age, the ends of the bones (epiphyses) fuse to the bone shaft (diaphyses) at predictable times. The pattern of fused bones can help establish age. The last bone to fuse is the clavicle (collar bone), at around 30 years.

To age older individuals, patterns of age-related changes in the bones are used. The deterioration of the joint between the two pubic bones, known as the pubic symphysis, is well documented and can be used to estimate age to within a few years. Anthropologists can also estimate height by taking measurements from long bones. Old injuries, such as fractures, and pathological changes, such as osteoarthritis and dental disease, may also be helpful in establishing identity.

Isotope analysis

Isotopes of an element are atoms whose nuclei contain the same number of protons but different numbers of neutrons. Stable isotopes are those that do not decay or that have extremely long half lives. Strontium has four stable isotopes. One of these, ^{87}Sr, is formed from the radioactive decay of ^{87}Rb (Rb = rubidium, half life: 4.88×10^{10} years). In very old rocks, such as granite, the ratio of $^{87}Sr/^{86}Sr$ is high. In younger rocks, such as basalt, the ratio of the two isotopes is low. As rocks are weathered, strontium is released into plants and drinking water. Since strontium has a relatively large mass it does not fractionate (i.e. the ratios of the different isotopes remain constant).

Human teeth form during childhood and strontium from the biosphere is incorporated into the developing teeth. Therefore the ratio of $^{87}Sr/^{86}Sr$ in tooth enamel mirrors the strontium isotope composition of the geology of the area in which a person spent their childhood. Bone on the other hand changes – it 'remodels' in 7-10 year cycles. As a result, the strontium composition of bone reflects the geology of the area in which the person spent the last decade of their lives.

Archaeologists have compared strontium isotope ratios from tooth enamel and bone to investigate ancient migrations. The same techniques were also used by archaeological scientists to help identify the Plugstreet Soldier. As Australia is extremely geologically diverse, scientists from the University of Oxford were able to narrow down the area this man spent his childhood to two areas: the Sydney Basin or the Hunter Valley in New South Wales, Australia.

DNA – genetic analysis

Deoxyribonucleic acid is present in the cell nucleus. It is unique to every individual. DNA analysis has a number of applications in forensic science. One of them is the identification of unknown bodies. However, DNA is very susceptible to breakdown and it is often impossible to get DNA profiles from old or decomposed remains.

Instead of genomic DNA from the cell nucleus, scientists can use mitochondrial DNA (mtDNA), for identification purposes. Mitochondria are the organelles in the cell that are responsible for energy production. Their DNA is separate from genomic DNA and is passed from a mother to her children, so mtDNA can be used to trace maternal lineages. It has been used successfully in a number of high profile cases, including the identification of the last Empress of Russia and her children who were executed by firing squad in 1918.

DNA sampling procedures are discussed on site.

Males have both an X and Y chromosome as part of their genomic DNA. The Y chromosome can be used to trace paternal lineages, which may also be helpful in identification if no suitable mtDNA donors are available.

Both of these techniques have been used to help identify the missing of the Great War. As part of the identification process of the 250 men buried at Pheasant Wood, both mtDNA and Y chromosome profiles were obtained for all of the men. However, not all were identified, as families have to provide a DNA sample for comparison. In some cases it was not possible to obtain samples from a suitable donor.

Emma Brown is a doctoral student in Archaeological Sciences at the University of Bradford.

Many thanks to Rob Janaway, University of Bradford; Richard Osgood and Martin Brown of the MOD Defence Estates; the Mather family and the Australian Army.

Sylvia Knight

Cloud control

How to make a cloud

*Clouds come and go, rain comes and goes. There is nothing we can do about it – or is there? And what are the implications if we do? **Sylvia Knight** explains.*

Key words
clouds
evaporation
condensation
climate control

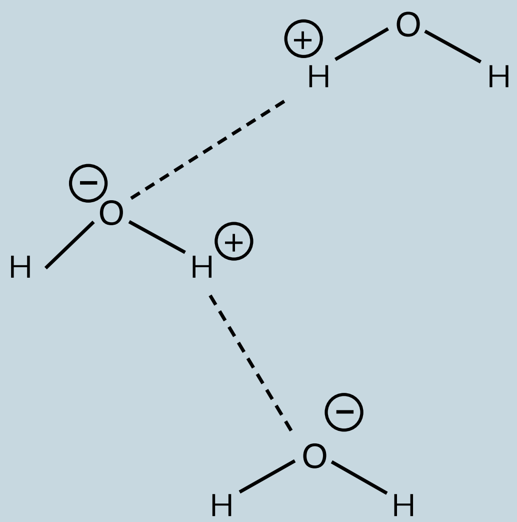
What is a cloud?

Clouds are made up of hundreds of thousands of tiny droplets of water – about 10 000 000 000 per m^3! They form from water vapour in the air, whenever the rate of condensation is greater than the rate of evaporation – usually this means when the air is cold enough. It is similar to what happens when warm moist air from your shower hits a cold mirror. In the atmosphere the same process is at work: when relatively warm moist air cools, the air becomes saturated, the rate of condensation becomes greater than the rate of evaporation and a cloud forms. The temperature at which this happens is known as the *dew-point temperature.*

1 μm = 0.001 mm

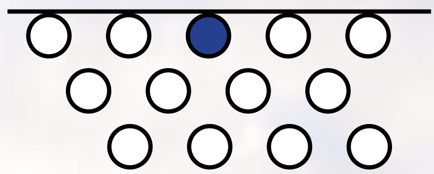
However, sometimes the air can be much colder than the dew-point temperature and still cloud droplets do not form. When relatively few water molecules form a tiny droplet, there are fewer neighbours attracting a molecule at the surface of the droplet holding it in place than there would be for a bigger droplet or a flat surface and the water molecule can evaporate more easily. In fact, the rate of evaporation from a droplet of radius 0.001 μm is more than three times as fast as from a droplet of radius 0.1 μm. It is therefore very difficult for cloud droplets consisting of just water molecules to form and grow.

The attraction between water molecules

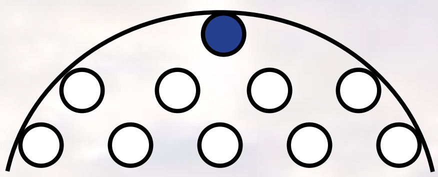


The dotted line represents the forces holding neighbouring molecules together

Water molecules have tiny negative charges on the oxygen atoms and tiny positive charges on the hydrogen atoms. These charges are much smaller than those on ions, but are strong enough to hold the molecules together more strongly than other molecules of similar size. These are the forces which hold water molecules together in droplets in clouds.



In a very large droplet or flat surface, there are many molecules binding a molecule near the surface, making it relatively hard for it to evaporate and leave the droplet.



In a small droplet, there are fewer molecules binding a surface molecule in place, so evaporation is easier.

How clouds form

Most cloud droplets get a 'head start' by forming on a particle in the atmosphere. This might be dust, soot, sea-salt or even phytoplankton. The particles are typically 0.1 µm or more in diameter. In this way, pollutants in the atmosphere are incorporated into clouds and can later be rained out of the atmosphere. The particles are called Cloud Condensation Nuclei (CCN). Cloud droplets grow – either as more water condenses onto each droplet, or by several droplets coming together and coalescing, until they are up to 9 mm in diameter. They then fall as rain, snow or hail.

Cloud seeding

The idea of cloud seeding is that by changing the number of CCN in the atmosphere, you can control how many cloud droplets there are. If the atmosphere is very clean, then adding CCN could cause a cloud to form. On the other hand, a cloud consisting of many small droplets is less likely to produce rain than a cloud with fewer, larger droplets.

Actually, most cloud-seeding techniques try to produce ice crystals rather than water droplets in the clouds. Once ice crystals have formed, they grow rapidly by taking water from any nearby water droplets because the intermolecular bonding is stronger in ice than it is in water. If the conditions are right, the latent heat released as the crystals form and grow can add energy to the cloud, increasing the convection going on and making the cloud grow much more rapidly than it would have done otherwise.

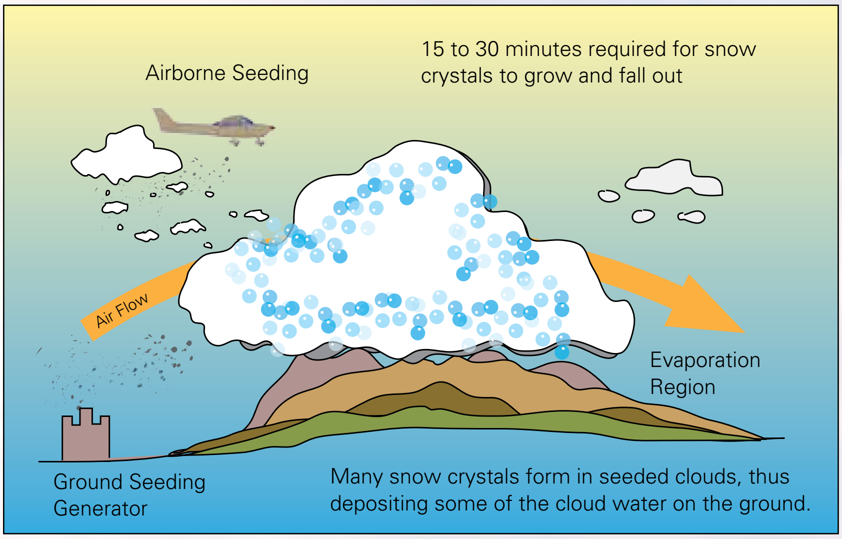
Typical substances used in cloud seeding include silver iodide, frozen carbon dioxide (dry ice) and salt. These are dispersed from aircraft, or fired into the atmosphere by ground based artillery.

A cloud-seeding aircraft is equipped with sprays along both wings.

Experiments

Cloud seeding experiments started in the mid 20th century. They continue today but there has been a lot of debate about how successful they are. There is a general consensus that winter cloud seeding over mountains can produce extra snow, and some studies suggest that cloud seeding in general can produce up to 30% more precipitation – rain or snow.

Dry ice crystals were dropped from a plane on this cloud in New York State in an early crop-seeding experiment, 1947.



Clouds often form over mountains, where rising air expands and cools. By adding silver iodide to the air, scientists hope to encourage ice crystals to form, so that they grow rapidly and produce more snow or rainfall than the cloud might have done otherwise. Some winter cloud-seeding projects over mountains in the USA have been running continuously since the 1950s, with the aim of supplementing water resources.

Ethical issues

Cloud seeding has led people to ask: who owns the weather? Does one government or authority have the right to cause it to rain more or less elsewhere?

Several governments have experimented with the cloud seeding. Between 1967 and 1972 the United States tried to 'make mud, not war' in Vietnam by intensifying the monsoon rainfall; an international treaty has since banned such actions. More recently, the USA has experimented with trying to affect the development of hurricanes by changing the cloud structure. This has similarly led to controversy. What happens if, by changing the intensity or path of a hurricane, a different set of people suffer adverse consequences?

Sometimes, clouds can be seeded inadvertently by aircraft. The exhaust from jet engines – mainly water vapour – cools rapidly. We sometimes see this as condensation trails (contrails) if conditions are right for clouds to form. However, if the aircraft flies through a cloud and conditions are just right, as the air expands and cools over the aircraft propeller or wing, ice crystals can be seeded. If these grow large enough and fall to the ground – probably melting into rain as they fall – they can leave clear skies behind, or a clear 'hole punch' in the cloud.

Contrails left by jet-engined aircraft flying through cold air.

This 'hole punch' cloud was formed by an aircraft flying through a cloud.

Cloud seeding at the Beijing Olympics

The organisers of the Beijing Olympics in 2008 used cloud seeding techniques to try to prevent it raining during the opening and closing ceremonies by forcing rain to fall before the events, clearing the skies, or away from the Bird's Nest Olympic stadium. Before and during the opening ceremony, 1 100 rockets containing silver iodide were fired into the sky. The ceremony was dry – but who knows whether that was because of the cloud seeding attempts. The organisers also had plans to induce rain to clear smog and other pollution during the games, if needed. Some reports suggest that China employs 40 000 scientists looking at weather modification and spent several million pounds on trying to manipulate the weather during the games.

Clouds over Beijing's Bird's Nest stadium, main arena of the 2008 Olympic Games

Cloud seeding and climate change

One suggested way of tackling (or at least masking) climate change involves spraying salty sea water into the air to encourage low clouds containing many, small cloud droplets to form. Clouds can have two impacts on climate. High level clouds act a bit like a greenhouse gas, absorbing heat from the Earth, whereas low clouds tend mostly to reflect the Sun's incoming visible radiation.

A cloud with many, smaller droplets is more reflective than a cloud with fewer, larger droplets (it looks whiter when viewed from space). So, if we can encourage low, reflective clouds to form, they will let less solar radiation into the atmosphere and it might not heat up as much as it would have done given only the increase in greenhouse gases. However, in 2010 the United Nations banned 'climate engineering' projects such as this one until they can be proven to have no unforeseen consequences, such as causing drought in some countries.

Stephen Salter of Edinburgh University designed wind powered ships like these which would spray salt water into the sky, seeding low level, very reflective clouds. These clouds could reflect incoming solar radiation, and cool the Earth, giving us time to reduce greenhouse gas concentrations in the atmosphere.

Sylvia Knight is Head of Education Services at the Royal Meteorological Society and a Climate Scientist

Make your own cloud

Making clouds form by cloud seeding may sound like an unusual idea, but in this experiment you can try it for yourself.

You will need:

- 0.5–1.5 litre clear plastic bottle with lid
- warm water
- matches
- small thermometer (to fit into the bottle – optional)

What to do

1. Put the thermometer into the bottle and screw on the lid. Note the temperature.
2. Squeeze the bottle and notice that the temperature rises as the air inside is compressed (squeezed) and the pressure increases.
3. Put a few drops of warm water into the bottle. Shake it around a few times to ensure there is plenty of water vapour in the bottle. As the water evaporates the amount of water vapour in the bottle increases.
4. If the water you are using is too hot you will see condensation on the inside of the bottle. This is not a cloud and it is best to try again with slightly cooler water.
5. Squeeze the bottle again. You should be able to see the temperature rise when it is squeezed and fall when you release the bottle as before. Although the air is almost certainly saturated with water vapour, you will not see any clouds forming.
6. Unscrew the lid of the bottle, leaving the lid in place for a moment. Carefully light a match, blow it out and hold the smoking end at the mouth of the bottle for a few seconds. Remove and replace the lid.
7. Squeeze and release the bottle a few times again as before. Then squeeze the bottle hard for a few seconds before suddenly releasing.

What you see

You should see a cloud forming in the bottle when you release it, as the water vapour now has small particles (of smoke, soot, ash) known as Cloud Condensation Nuclei to condense on.

What is happening?

Clouds can only form when the air is saturated with water vapour and when there are condensation nuclei present. Cloud seeding experiments introduce extra Cloud Condensation Nuclei to the atmosphere, to influence the number and size of raindrops in a cloud.

The equipment needed for the experiment

Condensation inside the bottle. This is not a cloud but a result of the water being hot.

A cloud has formed inside the bottle. This is not the same as condensation as it is not on the inside surface of the bottle, but in the air inside.

Vicky Wong is Chemistry editor of CATALYST.

Look here!

www.rmets.org/experiments for more meteorological experiments

Vicky Wong

Splitting light

Spectroscopy at work

Key words

spectroscopy

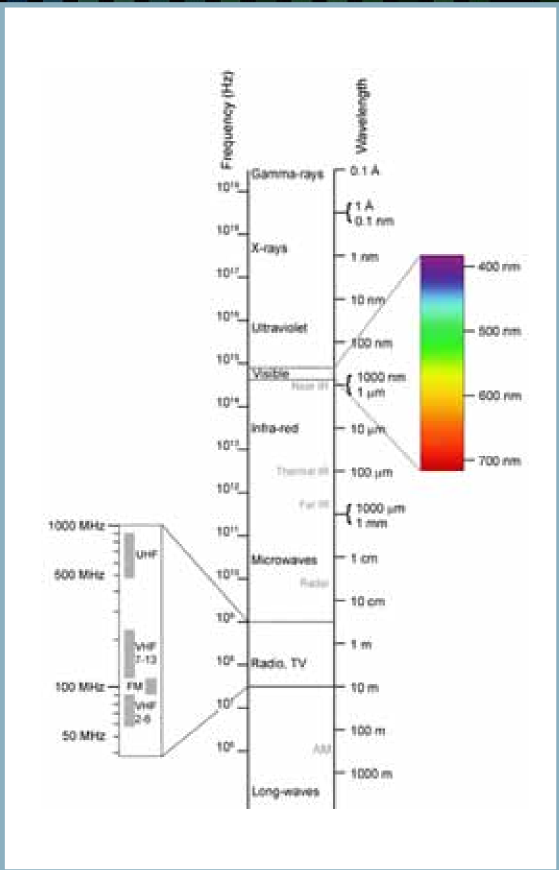
analysis

chemistry

element

Many substances absorb light at one wavelength and emit it at another. We make use of this in many ways, for example in glow-in-the-dark stickers. Compounds can also absorb and emit radiation that we cannot see, such as infrared, microwave and ultraviolet radiation.

Finding out which radiation is absorbed and emitted provides a lot of useful information about a compound. This is called **spectroscopy**. It is used in a very wide variety of applications, from helping chemists to work out the structure of a new molecule they have made, to testing for drugs, forensics testing and quality control.



The electromagnetic spectrum. Radiation from any wavelength on the spectrum can be used to find out information about matter.

Did you know?

Robert Bunsen invented his Bunsen burner not for heating laboratory equipment, but for use in flame tests and spectroscopy.

Case Study 1 Iodine in milk

Iodine is an essential part of a healthy diet as it is needed by the thyroid gland for making thyroid hormones but too much iodine can lead to thyroid disorders. Seafood, iodized table salt, milk and dairy products are common sources of iodine. It is important to find out precisely and reliably how much iodine is present in dairy products, even in low levels, to ensure people obtain adequate but not excessive amounts of this micronutrient.

A simple, precise and accurate automatic method for determining total iodine concentration in milk products based on atomic absorption spectrometry could improve studies of this essential micronutrient.

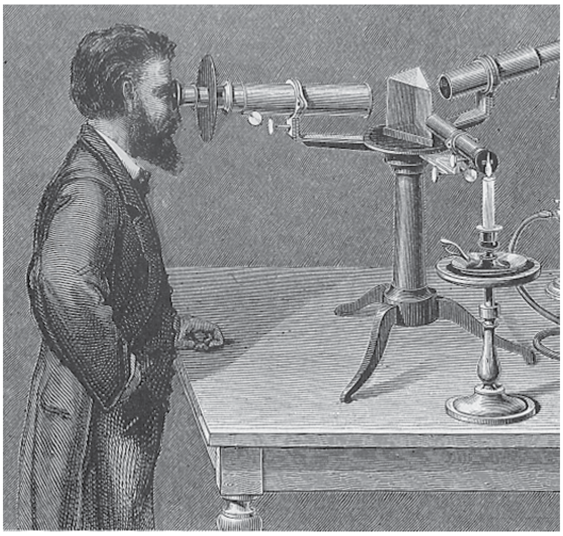
The method allows scientists to find out the concentration of total iodine in infant formulas and powder milk samples.

It is important to know exactly what is in formula milk for babies. Emission spectroscopy can help to identify the elements and compounds present.

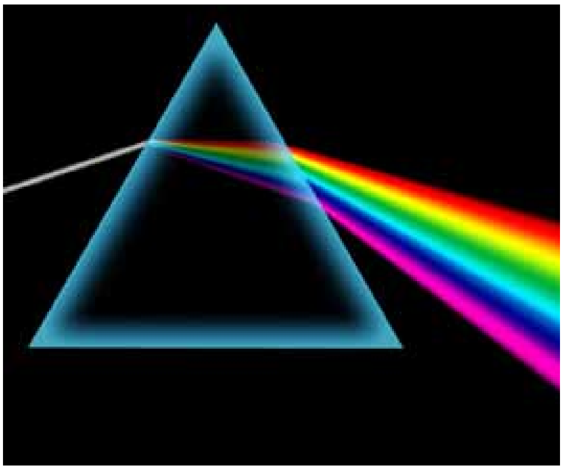
Emission spectroscopy

Spectroscopy began with the study of visible light spread out according to its wavelength by a prism or diffraction grating. This gives a spectrum or rainbow pattern. It was studied by Robert Bunsen (who invented the burner which bears his name) and Gustav Kirchhoff in the late 1850s.

Bunsen had observed that some elements give a coloured flame when they are heated – what we now know as the flame test. He was trying to use flame tests to analyse elements but found it was not accurate enough. Kirchhoff suggested to him that he use a spectroscopic method (to split up the light into a spectrum) rather than just the colours of the flames and this proved far more successful.



Gustav Kirchhoff working with his spectroscope. Note the prism used to split light up into a spectrum.



A prism splits white light into its different wavelengths – this is dispersion.

The emission spectrum of a chemical element or chemical compound is the spectrum of frequencies of electromagnetic radiation emitted by the element's atoms or the compound's molecules, in this case when they have been heated in a flame.

Each element's emission spectrum is unique. Therefore, spectroscopy can be used to identify the elements in matter of unknown composition.

Infrared spectroscopy

Infrared (IR) spectroscopy involves firing infrared radiation at a substance and measuring the radiation that is absorbed by the molecules. It is particularly useful for studying organic (carbon-containing) chemicals and has a huge range of applications.

Vicky Wong is Chemistry editor of CATALYST.

Case Study 2 Breath tests

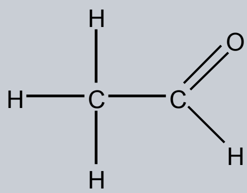
Trace chemicals can be detected in the breath using IR spectroscopy. This could open up a whole new area of medical diagnostics and health research.

The morning after eating, telltale odours of some foods such as onions and garlic can remain on the breath for many hours.

These smells are unpleasant but our breath can also carry other odours which are far more useful. Some diseases produce chemicals which are exhaled and it may be possible to use these for diagnosing those conditions. For instance, the presence of unusually large amounts of ethanal can be an indication of lung cancer; hydrogen cyanide may be detectable on the breath of cystic fibrosis sufferers with lung infections.

Using breath for diagnosis has the advantage that it is far more patient friendly than blood analysis, which involves insertion of a needle, or urine analysis, which some patients find embarrassing. It is much simpler simply to blow into a device.

Breath test diagnostics have been in development for many years, but researchers in the UK are now moving forward with a system that can detect propanone and other chemicals which are present at less than 10 parts per million. Propanone is produced during exercise when the body switches to so-called 'fat-burning' so this could be used in gyms to monitor how well a person has burned off body fat.



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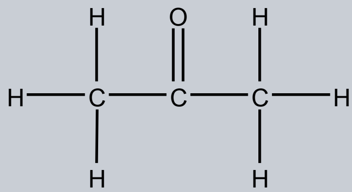

Propanone

Most people would prefer to breathe into a tube than to have a blood test.

The Big Picture on pages 10-11 shows emission spectra of 11 different elements, as observed by Bunsen and Kirchhoff.

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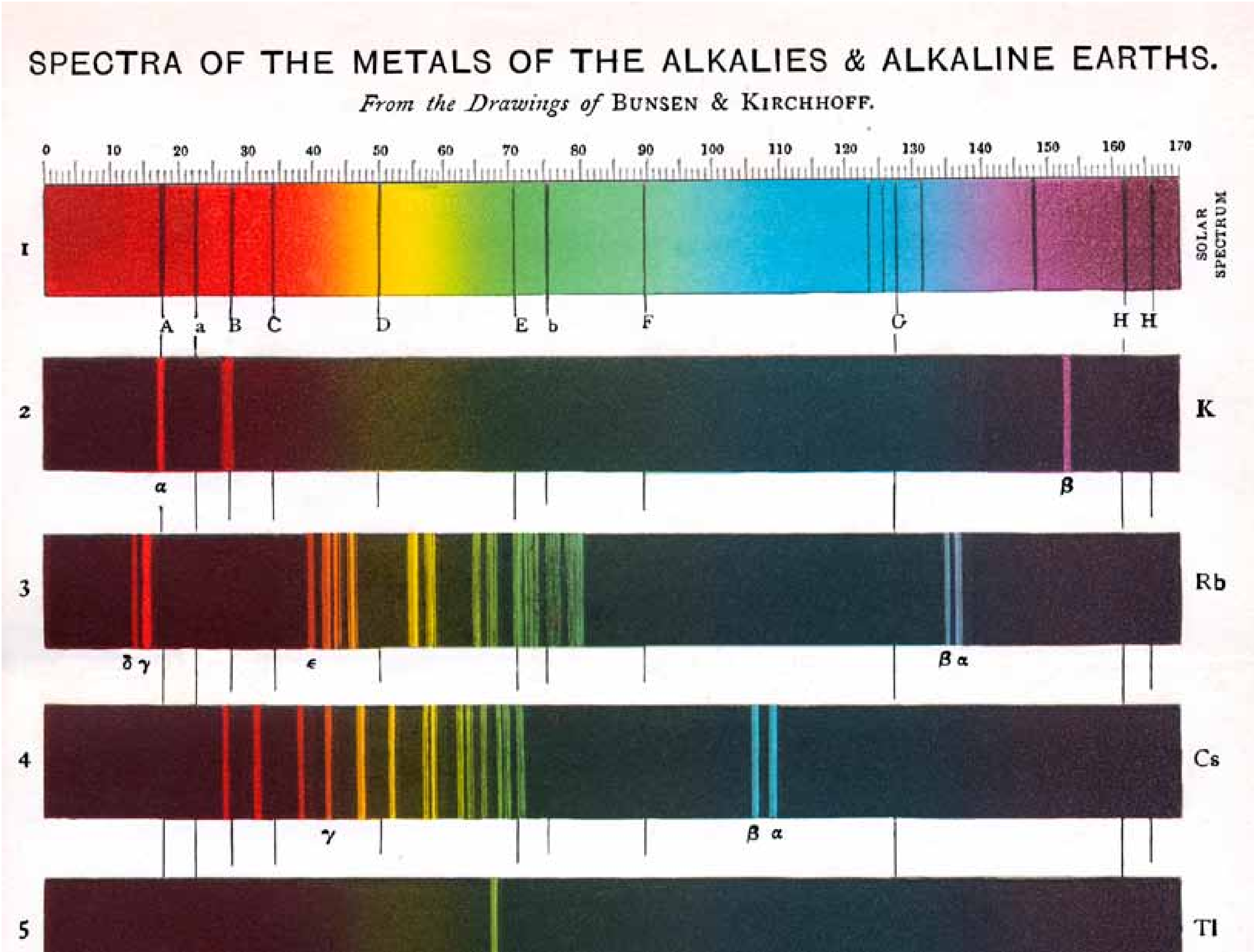
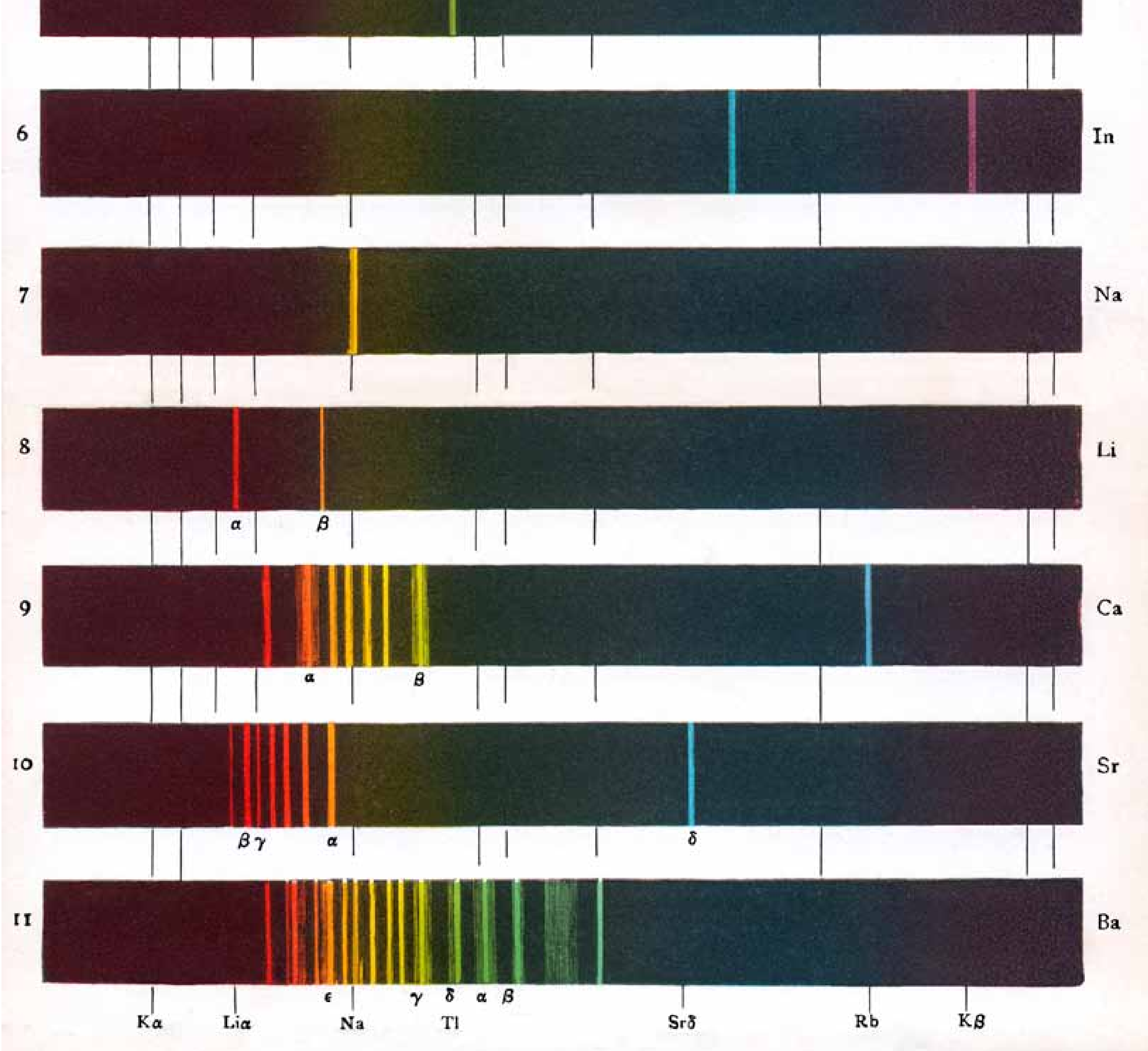
www.sep.org.uk/catalyst

Flame emission spectra of the elements of the first two groups in the Periodic Table, as discovered by Bunsen and Kirchhoff.





6
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β
Kα
Liα
Na
Tl
Srδ
Rb
Kβ

Try this

Make your own spectroscope

New discoveries are often made when a new piece of equipment is invented. The spectroscope was invented by Robert Bunsen and Gustav Kirchhoff. Back then, if you wanted a new piece of equipment, you tended to make it yourself and Kirchhoff made the first spectroscope in the late 1850s. He and Bunsen used it to discover the elements caesium and rubidium.

You can make your own spectroscope very simply from a cereal box and a CD. You can use it to see the variation in the spectra produced by different types of light bulb.

You will need:

- cereal box or similar
- CD
- sticky tape
- scissors
- ruler
- protractor (optional)
- light source e.g. light bulbs, candle flame

SAFETY: Take care with a candle flame

What you do:

At the open end of the cereal box, cut a slit wide enough for the CD. Arrange the CD in the slit at a 60° angle and then tape up the box.

About 3 cm from the CD cut a hole in the top of the box above the CD. The hole should be about 2 cm across.

At the far end of the box cut a slit about 4 cm long and 1 or 2 mm wide. Again, this should be opposite the CD.

Point the slit of your spectroscope at a light bulb. Look down through the hole onto the CD. You should see a spectrum of the light from the bulb. If you look at a different type of light bulb (energy saving, filament, fluorescent) you will see a different spectrum.

SAFETY: Do not look at the sun using your spectroscope.

Look here!

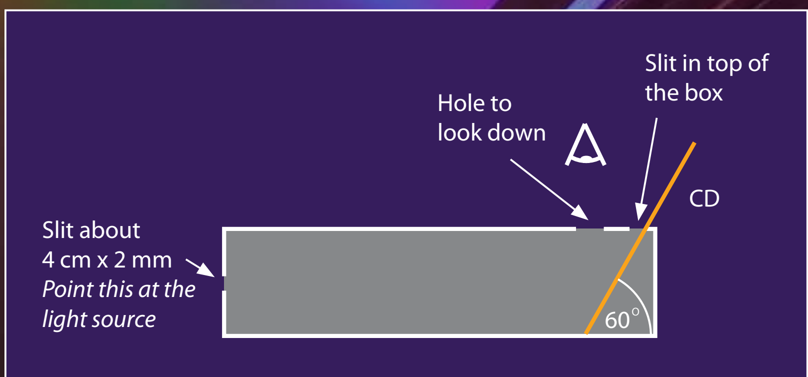
This website details some improvements you can make to your spectroscope.

http://tinyurl.com/37eahgn

What you see:

The spectrum from your spectroscope should look a bit like a rainbow. If the light source you are using produces a continuous spectrum (and a candle often does – although be careful not to set the box on fire) then you will see a complete rainbow. Most artificial light sources will produce distinct spectral lines, or, in other words, only some parts of the rainbow are present.

The cereal box spectroscope



A diagram of the spectroscope

Biophotovoltaics

Energy from algae

Alex Driver
Paolo Bombelli

Key words
photosynthesis
photovoltaics
energy efficiency
engineering design

Could these giant lily-pads be the green power station of the future? The image above is an artist's impression of what a biophotovoltaic power station might look like. ***Alex Driver*** *and* ***Paolo Bombelli*** *of Cambridge University explain.*

The Sun is the ultimate source of energy for almost all life on Earth and harnessing this energy is one of the great scientific and technological challenges. Traditional fossil fuels are considered to be the main contributor to the greenhouse effect; they are subject to a large political risk and destined to run out. Conversely, solar energy is virtually carbon-free, extremely abundant and available worldwide.

Nature has clearly demonstrated that it is possible to harness solar energy through the process of photosynthesis. The photosynthetic production of biomass is not a very energy-efficient process – plants use only about 0.25% of the energy of the sunlight that falls on them. Despite this, it is estimated that the Earth's photosynthetic organisms convert more than ten times as much energy per year as current human energy consumption.

A number of synthetic techniques have also been developed to try to emulate the photosynthetic process; the most successful of these are solar cells based on the photovoltaic effect in which sunlight releases electrons in a solid material, thus creating a useful voltage. Unlike photosynthetic organisms, solar cells are able to convert energy with a high efficiency (10-15%). However, the technology is based on the use of expensive, high purity semiconductor materials.

Conventional solar cells are based on silicon.

In order to exploit the advantages of both the biological and synthetic approaches, a technology is required which makes use of the high energy-conversion efficiency of the synthetic systems whilst keeping the merits of a low-cost biological approach. With the cooperation of four Cambridge University departments (see About the authors on page 15), a novel method for harnessing solar energy which does just this has been developed.

Biological solar cells

Biophotovoltaic (BPV) devices are biological solar cells that generate electricity from the photosynthetic activity of living microorganisms such as algae. When light falls on the algae, a series of reactions take place which split water into protons (hydrogen ions, H^+), electrons and oxygen. These are vital ingredients for transforming carbon dioxide and other inorganic materials into things like carbohydrates and proteins which allow the algae to grow. Biophotovoltaic devices exploit this charge separation to generate electrical energy. This is achieved by placing the algae inside one of two electrode-containing chambers separated by a membrane that only allows protons to pass through it, as shown in Figure 1. Electrons produced during photosynthesis flow through an external circuit in order to re-combine with protons and oxygen at the reductive electrode (cathode) to form water. The resultant current flowing in the external circuit can be used to power electronic devices.

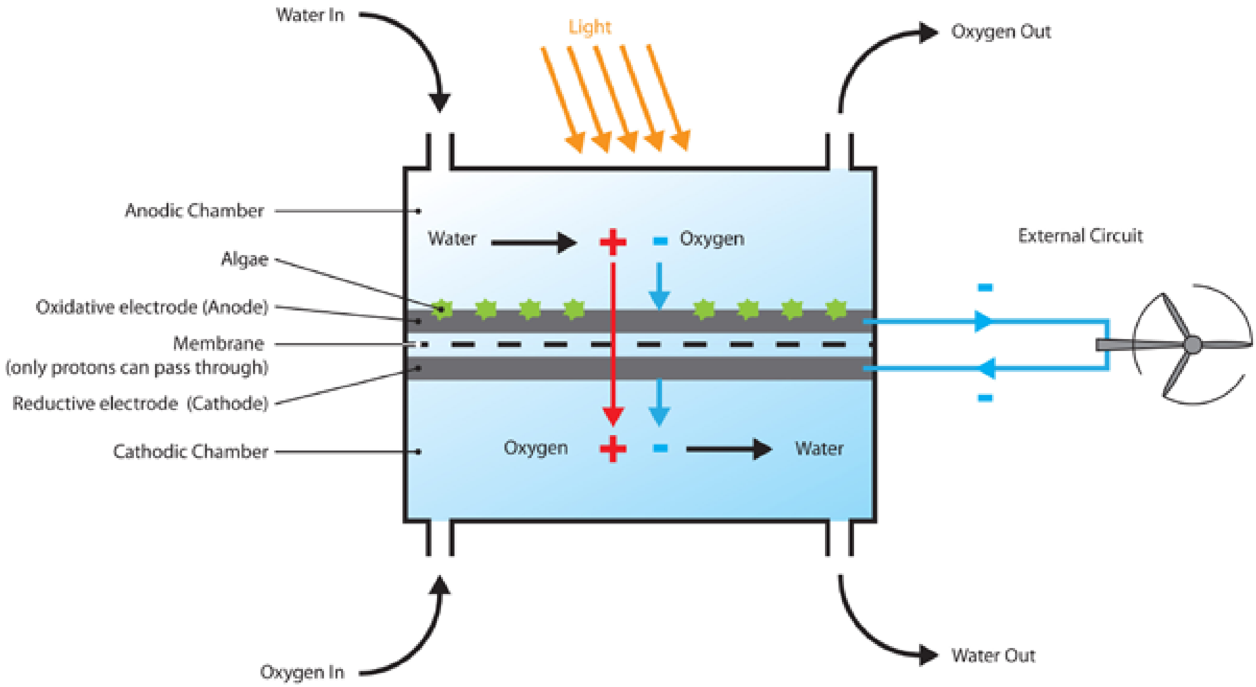
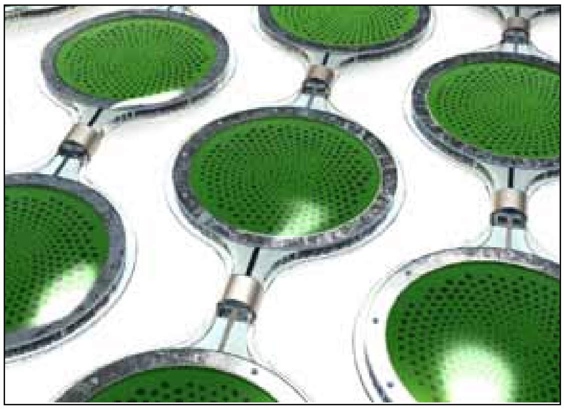


Figure 1 *A schematic diagram of a biophotovoltaic device*

Current research into biophotovoltaics exploits a wide range of techniques including electrochemistry, micro-fabrication, chemical synthesis, molecular biology and numerical simulation. The first BPV devices have recently been constructed and tested in the laboratory, but a great deal of research is required in order to develop biophotovoltaics into a commercially viable technology. Future research will focus on developing a fundamental understanding of the processes occurring within the devices. This knowledge will then be applied to the optimisation of both the synthetic and biological device components.



An array of biophotovoltaic solar panels

Manufacturing targets

Although they probably going to be less efficient, low-cost BPV devices are likely to become competitive alternatives to silicon-based photovoltaic cells within in the next 5-10 years. The long term target is to produce economical devices with low manufacturing costs and excellent energy conversion efficiency. With this in mind, the scientific team agreed to take part in a collaborative project with designers from the university's Institute for Manufacturing to look into the future to suggest a range of applications of BPV technology.

The designers had a brainstorming session with the scientific team, during which the scientists answered the designers' technical questions, and the group generated a range of ideas for possible products. These included a biophotovoltaic solar panel, a near-shore generator that harvests desalinated water, and a garden table that generates and stores enough energy during the day to power a light in the evening.

A floating biophotovoltaic generator, designed to produce desalinated water

Biological power

The team also came up with the idea of an offshore biophotovoltaic power station consisting of several vast floating 'lily pads' coated in algae. The power output per unit area of a BPV power station would ideally match that of an equivalently-sized offshore wind farm (5-6 watts per square metre) which should be enough to exploit this technology commercially. Such a power station would even generate energy during the night as a result of excess electrons being stored inside the plant cells during daylight hours.

Following this session, the scientific team asked the designers to build a prototype of the biophotovoltaic solar panel. They produced a 3D computer model of the device which they used to manufacture and assemble the components in the engineering department's workshop. The device, shown in Figure 2, operates on the principle outlined in Figure 1.

An array of these devices would be placed on a roof to provide a portion of the building's power requirements. The advantages of this device that are that it is environmentally friendly and easy to manufacture, at least compared with conventional solar panels. Algae, the bio-electrical catalysts, require only water and sunlight to survive and generate energy. The oxygen produced at the anode escapes into the atmosphere whilst the water produced at the cathode can be harvested or left to evaporate. No harmful chemical waste is produced during the process and once exhausted the devices should be easy to recycle.

Other possible uses of BPV technology include water desalination, the co-generation of chemicals (e.g. formic acid which can be used as a fuel) and the production of hydrogen.

The prototype and concepts have proved to be invaluable in communicating the potential of the technology to colleagues, potential investors and members of the public.

Alex Driver and Paolo Bombelli work at the University of Cambridge.

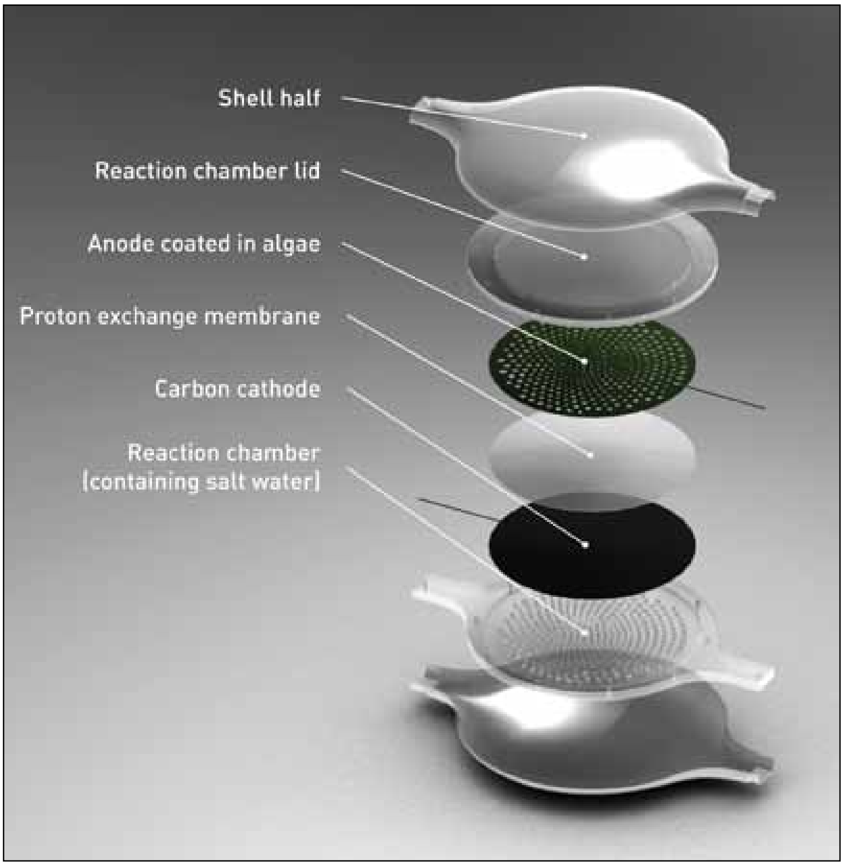


Figure 2 *A biophotovoltaic solar panel prototype, and an exploded view showing how it is contructed.*

About the authors

Alex Driver is a Research Associate at Cambridge University's Institute for Manufacturing. Alex has a background in mechanical engineering and industrial design and is currently researching the potential role of industrial design in scientific research.

Paolo Bombelli is a Research Associate at Cambridge University's Department of Chemical Engineering and Biotechnology. Paolo has a background in plant biology and photosynthesis. He has been working on the development of biological solar panels since 2002 and is currently investigating the wider application of biology in achieving renewable and sustainable sources of energy.

Scientific research is carried out, for the most part, by teams of individuals from a variety of different fields. The work on biophotovoltaics has been based in four departments and involved 14 scientists, designers and engineers. The University of Cambridge departments involved in this work are:

Department of Chemical Engineering and Biotechnology, Department of Biochemistry, Department of Plant Sciences, and the Institute for Manufacturing in the Department of Engineering

David Sang

Energy control

Wattbox: learning to manage home heating

Key words
space heating
thermostat
temperature control
energy efficiency

Too hot? Too cold? What's the heating like where you live? Coming soon is a new generation of intelligent heating controls which can learn how you live and deliver heating efficiently when and where you need it. That's the idea of Wattbox, newly developed at Leicester's De Montfort University.

A traditional thermostat (top left) and controllers for domestic central heating systems

Thermostats and controllers

In the UK, many households have a central heating system which uses a gas boiler to supply hot water to radiators for space heating. The boiler usually provides hot water, too.

Room temperature is controlled by a central thermostat which switches the heating on when the temperature falls below a certain level. Some homes have radiators with thermostatically-controlled valves so that the heating in individual rooms can be controlled separately. A programmable electronic controller, set by the householder, determines when the heating and hot water are on or off.

That sounds simple, practical and efficient. But is it? The UK Government, through its Warm Front programme, has tried to ensure that people in poorer homes are able to keep warm. To do this, they have provided better insulation and more efficient heating systems. However, a survey found that 25% of homes are persistently cold, despite the improvements. People living in cold homes are more likely to become anxious and depressed.

What is the problem? Many people find their heating controllers too complex to operate. A controller may have a combination of sliders,

More efficient heating systems:

- Use less limited resources (fossil fuels)
- Produce less greenhouse gas (carbon dioxide)
- Reduce fuel bills

switches and buttons and may require up to 30 steps to enter the desired pattern of heating times. Users complain that it is all too technical. Here's how they respond:

- Some leave the controls as originally set: "I never touch the controls."
- Others ask family members, friends or neighbours to alter the controls for them.
- Others abandon the automatic controls: "My husband switches it on when he gets up."

A survey in Norway found that many users didn't even turn down their heating when they go away on holiday. So some people are wasting energy while others are living in unnecessarily cold houses.

An engineering concept

Researchers at De Montfort University in Leicester set about tackling this problem. They wanted to devise an intelligent heating programmer which would determine the space heating requirements at any time, and which would also learn the pattern of energy use in the home, thereby reducing waste and increasing efficiency. They called their intelligent programmer 'Wattbox'.

Tenants Donna Howarth and Shaun White testing the Wattbox monitoring equipment

To begin with, the researchers identified three different levels of occupancy of a house:

- The occupants are awake and active: heating required between 19 and 23 °C.
- The occupants are asleep: heating required between 16 and 18 °C.
- The house is temporarily unoccupied: the temperature can be allowed to drop to 12 – 14 °C, avoiding dampness and allowing quick recovery when the occupants return.

But how to work out what the occupants are up to? One way is to monitor the use of electricity in the house. The graph in Figure 1 is typical; you can see that the occupants were active in the morning and evening (the tall spikes are the kettle being switched on). During the day, the occupants were out and at night they were asleep. At these times, only the fridge and freezer were using power.

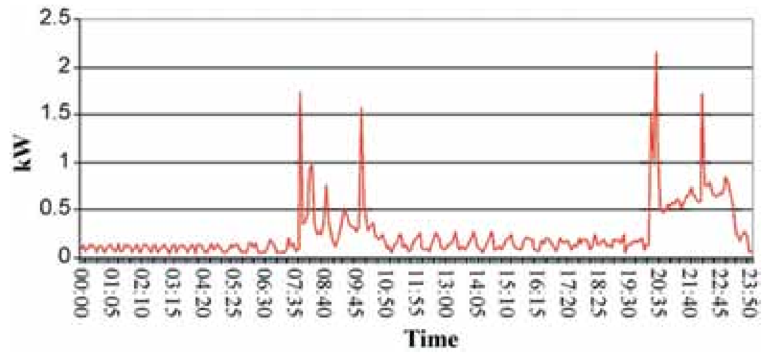


Figure 1 *How the use of electricity varied in one home over 24 h.*

Another way to tell how active the occupants are is to monitor the temperature of the hot water tank. Each time hot water is used, cold water enters at the bottom of the tank. Figure 2 shows how the temperature of the water in a tank dropped as it was used during the day; the water heater switched on at 7:00 pm to bring the temperature up to its original level. Rapid changes in the temperature at the bottom of the tank indicate when the occupants are active.

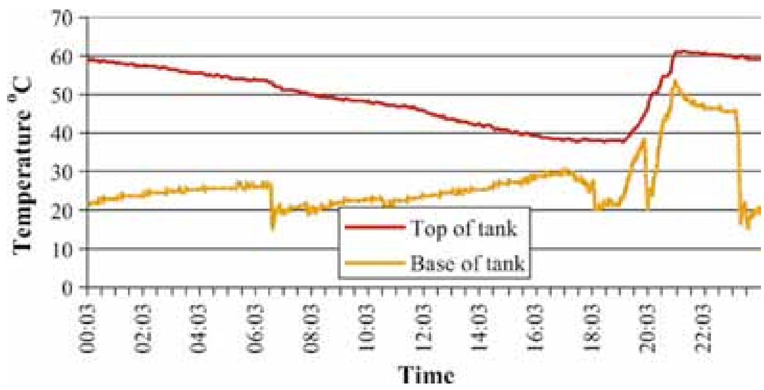


Figure 2 *How the temperature in a hot water tank varied over 24 h. When no water is being used, the temperature at the top slowly drops while the temperature at the bottom slowly rises.*

So by monitoring electricity use and water temperatures, Wattbox can work out what the residents are up to and control the space heating temperature accordingly. And once Wattbox has learned how the residents like their heating, they can forget about adjusting the controls and leave it to get on with the job.

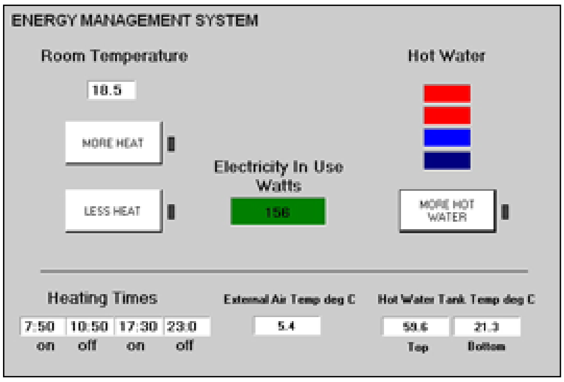
A prototype system

The researchers built a prototype system and installed it in a home. Initially, it had to be programmed with one of three 'standard' lifestyle options. These are shown in Table 1. But then it set about modifying this standard pattern according to the occupants' behaviour.

Option	Lifestyle	Chosen by
1	We are out of the home weekdays, otherwise at home	Office workers, families with children at school
2	We are at home most of the time	Retired people, home workers, invalids. families with young children
3	We do not have a regular pattern of being at home	Shift workers, students

Table 1 *Three lifestyle options which users of Wattbox can select*

The controller allowed the users to increase the level of heating ("More Heat" button), or reduce it ("Less Heat"). In this way, the controller could learn the occupants' preferred pattern of heating and adjust the level of heating it automatically provided.



The user interface of the prototype control system

Assessing the prototype

How well did the prototype system work? This was assessed in April 2008. For two weeks, the test home used a heating system with a traditional controller. Then, for another two weeks, the system was controlled by the Wattbox.

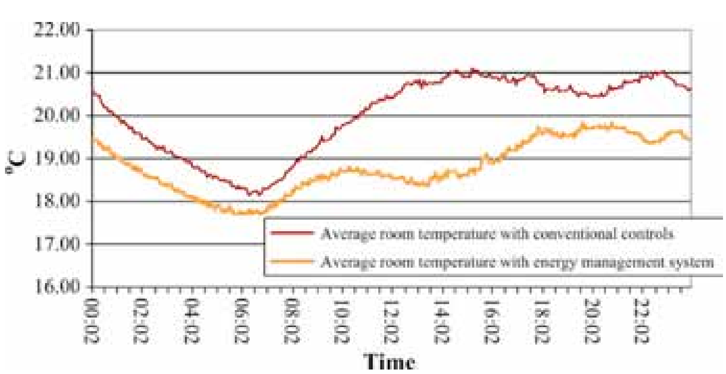


Figure 3 *Testing the Wattbox - average room temperature before and after introducing the prototype*

The graph (Figure 3) shows how the use of the Wattbox kept the room temperature under better control, so that less energy was used on space heating. To make the comparison of the two systems a fair test, several factors had to be taken into account, including the outdoor temperature, energy gain from sunshine, and heat coming from electrical appliances.

How much energy did Wattbox save? Results showed that it cut daily consumption by about one-seventh, a total of almost 20 kWh of gas per day. That means 4 kg less of carbon dioxide poured into the atmosphere, and a saving of about 80 p per day.

The Wattbox was developed at the Institute of Energy and Sustainable Development at De Montfort University, Leicester, by a team including Dr Peter Boait, shown here. His colleague Jim Oswald has recently obtained a US patent for its design, opening up a large future market for the product.

Watt next?

The Wattbox team now have several patents for their device. They are working on a programme of further trials, with many more households taking part.

When the Wattbox is in more general use, it is likely to have wireless signalling from the electricity meter, providing it with data on electricity use. It will be fitted in a kitchen, above a worktop, where the user will get immediate feedback on their electricity use. This is the same principle as the 'smart meters' which are now becoming more common. Householders who have a visual display showing their electricity consumption are more likely to switch off unnecessary appliances.

Another advantage of Wattbox is that it will help householders make better use of low-carbon technologies such as solar hot water (which works intermittently because of the variable level of sunlight), heat pumps and micro-CHP (Combined Heat and Power).

David Sang is physics editor of Catalyst. Thanks to Dr Peter Boait of De Montfort University for his help with this article.

Paul Graham

Andrew Philippides

How smart is an ant?

Spend an hour or two watching a colony of ants and you will see hundreds, even thousands, of ants working diligently and cooperatively, perhaps to kill and carry a large prey item, build a large nest structure or develop and use road-like networks for foraging. It is evident that collectively, colonies of social insects can do amazing things (Figure 1) and scientists invest lots of time trying to work out how ant colonies organise themselves so neatly and effectively. In this article, ***Paul Graham*** *and* ***Andrew Philippides*** *set out to answer the question: just how smart is a single ant?*

Many ants = 1 super-organism

To explain collective behaviours, ant-colonies are thought of as super-organisms, where each ant is like a single neuron in a large collective brain. In this analogy, an individual ant is seen as a simple automaton. But each ant has a brain and here, we are interested in how intelligent an ant is when she is separated from her nest-mates. To assess the intelligence of a single ant, we investigate how theytheir performance in a task which is fundamental to their survival and the survival of the colony:, how they navigate back to their nest after finding food.

To find new sources of food, animals must safely explore novel places while remembering something of their outward journey so that they can return efficiently to their nest having found food. The mechanism used by ants is called *path integration*.

Key words

insect behaviour

memory

intelligence

experiment

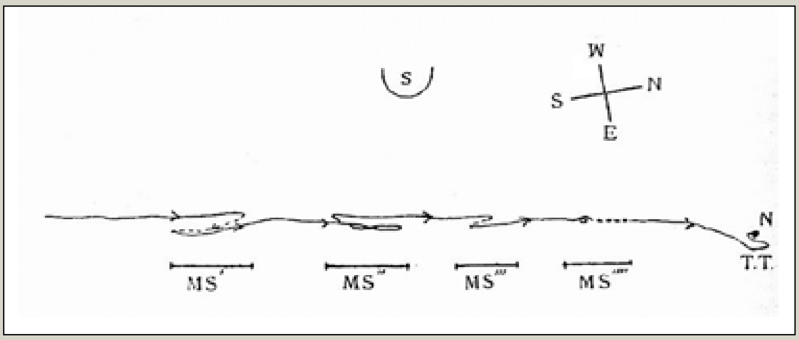
Box 1 How do we know the mechanisms of ant path integration?

To perform path integration, an insect must know continuously the direction she is traveling in and also how far she travels during each segment of the route, i.e. she needs a compass and a measuring tape. For distances, ants keep track of the number of strides they have taken. We know this because scientists have manipulated the lengths of ants' legs as they try to find their nest. In path integration experiments, scientists move ants from the food to a new test ground and then see how far they walk before they stop and begin to search for their nest entrance.

If you take ants to an unfamiliar place as they try to get home with food, they will walk the distance that would normally take them back to their nest before then starting to search. However, if you lengthen their legs with pig bristle, they will take the same number of strides but cover a longer distance before they think they are near home and start searching. From this simple demonstration we can conclude that ants measure distances by counting their steps.

An ant of the species Cataglyphis fortis with pig bristles glued to its legs

For a compass, ants use the sun. Felix Santschi discovered this in the early twentieth century. He observed the paths of homing ants as he blocked their view of the sun with a board, whilst simultaneously reflecting a view of the sun with a mirror. In this way, the sun appeared to come from a different direction. The figure shows an ant path recorded by Santschi. Each labeled (MS) section is part of the path recorded as Santschi changed the apparent direction of the sun. In each case, the ant immediately reverses its path direction, showing clearly that it relies on the sun's position for a sense of direction.



When path integrating, ants keep track of the direction and length of every section of their journey (see Box 1). To make use of this information, ants must mentally add together these route segments so that they always have an estimate of the direct route back to their nest, effectively doing vector geometry (Figure 2).

Always knowing the fastest path home is particularly useful when the ant finds food or when she is trying to escape a predator. The fact that ants can perform path integration tells us about the processing power of their tiny brains. Not only can they do something similar to counting, their brains are wired up to perform calculations which approximate to trigonometry.

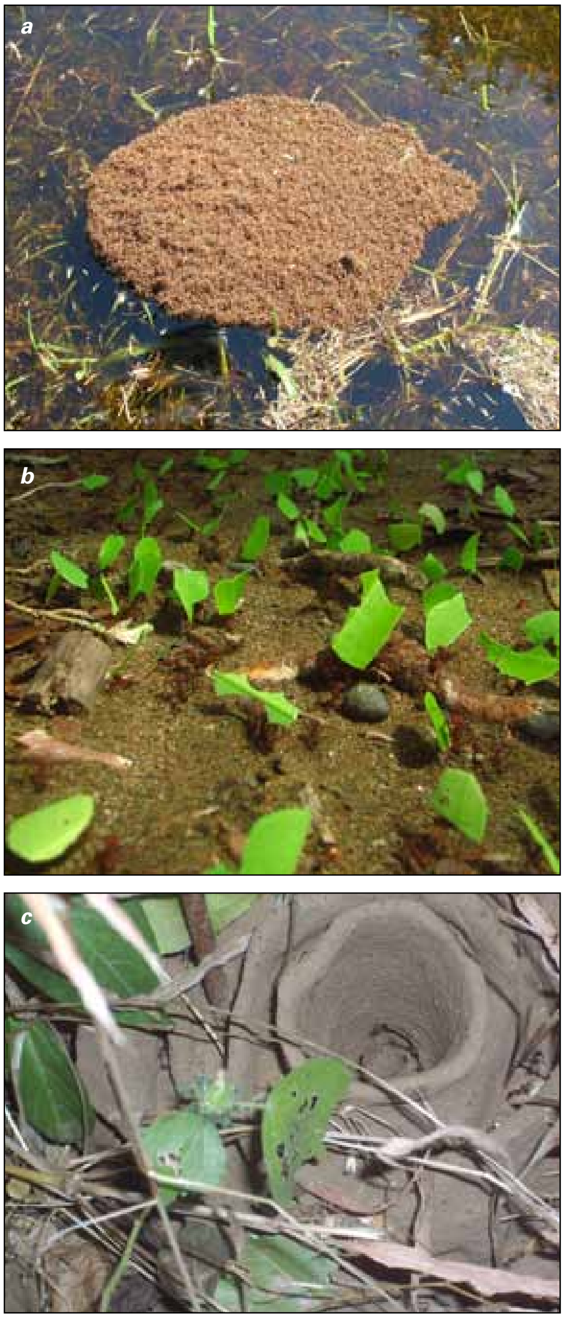


Figure 1 *The amazing cooperative behaviours of ants.*
a) Fire ants cluster together on the surface of water.
b) A foraging highway of Leafcutter ants.
c) The beautiful architecture of a Harvester ant nest.

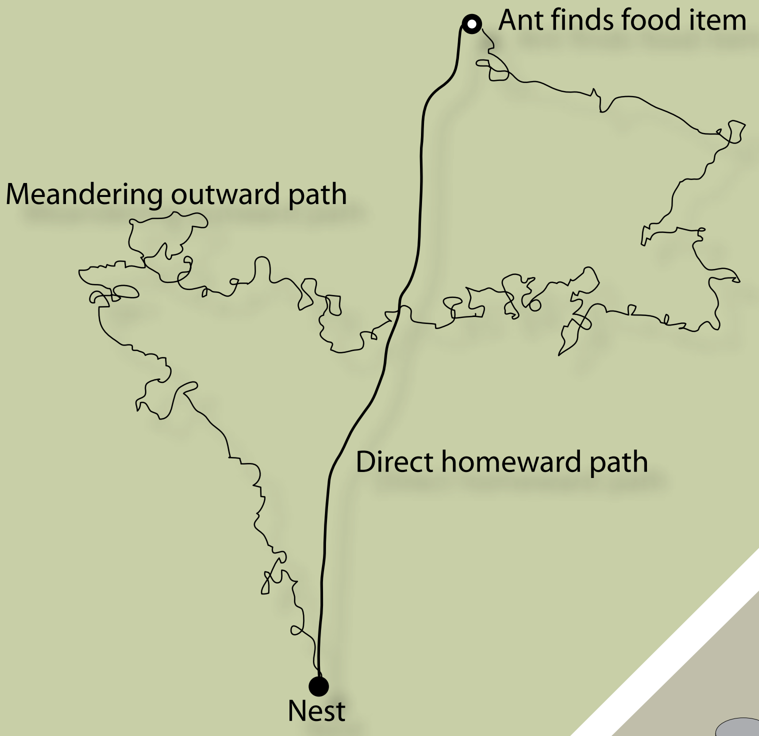
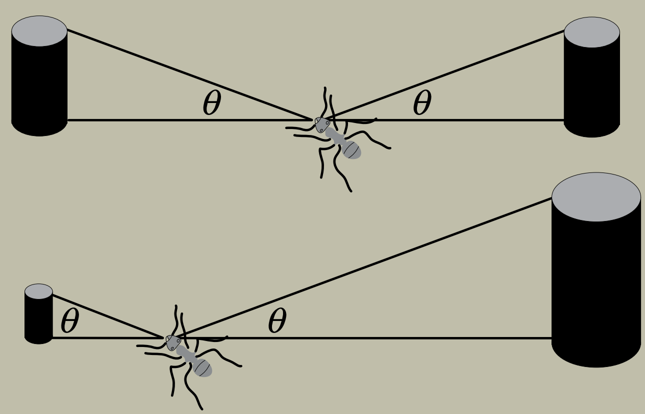


Figure 2 *The long and winding path of a desert ant as she searches for food in the desert. When she finds food (○), after a path of over 100 m, she takes a direct path back to her nest.*

Box 2 How do we know how ants use visual landmarks?

The basic method for investigating how ants use snapshots is, as with path integration experiments, based on the fact that when an ant thinks she is very close to her goal, she will start a special search behaviour. To understand what ants have learnt about visual landmarks, we observe how changes to the landmarks influence where ants search. The diagram represents a simple experiment. Ants are trained to find food between two identical landmarks. If you change the landmarks so that one is small and one large, ants will search for food closer to the small cylinder, where both landmarks appear to be the same size. Unlike humans, ants don't see in 3D and, to an ant at the location close to the small cylinder, the world looks identical to a snapshot which was stored from the feeder during training.



The ant learns that food is half way between two identical cylinders (above). When the cylinders are changed (below), she searches at the point where they appear to be the same size.

Learning landmarks

Path integration allows ants to explore new places whilst being connected to their nest, but it is not perfect. As an ant travels longer and longer distances, small errors from each path section can add up and result in her missing the nest when she returns, meaning she will have to spend time and energy searching for her nest entrance. Fortunately, when an ant has become familiar with her environment she can avoid this problem, because, just like humans, ants are capable of learning an important location by remembering the visual landmarks close to it.

When an ant is at a place that she wants to return to (perhaps the nest or a food source), she memorises the appearance of the world from that place. We liken this to 'taking a mental snapshot'. When she wants to get back to the important place all she has to do is recall this mental picture and try and make the world look like the remembered snapshot (Box 2). This is an elegant strategy for navigation. At no point does an ant need to calculate where she is. She simply moves in whatever direction makes the world look more similar to her memory. However, it still requires brain-power because ants have to have a photographic memory.

Smarter than the average insect

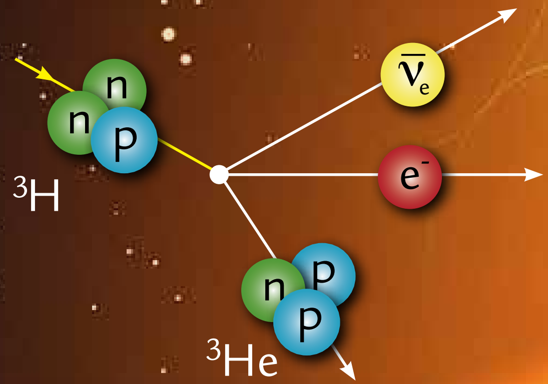
All animals, including humans, have to move through the world. Despite the fact that colonies of ants can work together to provide specialist highways to travel along, individual ants also use individual strategies to explore new territory. Studying these behaviours allows us to understand the impressive feats animals can achieve with tiny brains. Using path integration and memorised snapshots requires ants to be able to do calculations similar to trigonometry and also to have a photographic memory. So, how smart is an ant? At least when it comes to finding her way home, pretty smart.

Paul Graham and Andrew Philippides study the navigational abilities of insects at the University of Sussex. They are interested in how small brained animals can produce clever behaviour and whether we can replicate that behaviour in robots.

Tiny particle, giant detector

Neutrinos are fundamental particles. They are tiny – a neutrino has a mass about one-millionth of the mass of an electron – and they have no electric charge. So how can we detect these elusive particles?

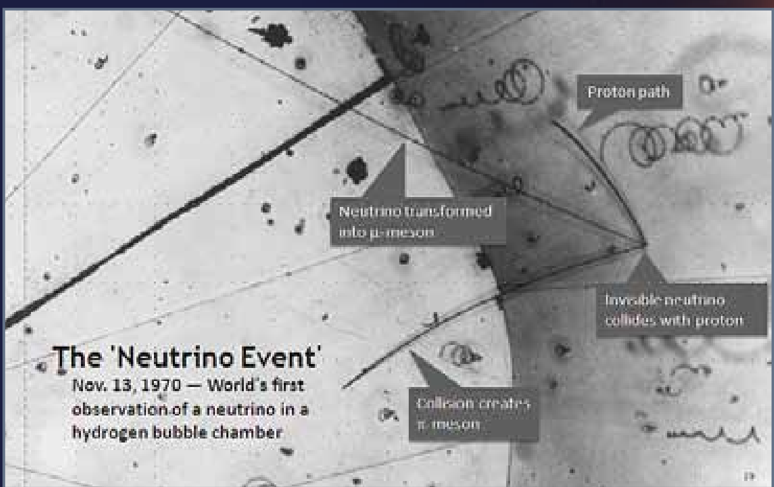
The answer is to use a giant detector. The one shown here is from the Katrin experiment at Karlsruhe in Germany. This is designed to give an accurate measurement of the mass of a neutrino.



Neutrinos are emitted when a radioactive nucleus undergoes beta decay. Here, a tritium (hydrogen) nucleus emits a beta particle (an electron, e^-) and an antineutrino ($\bar{\nu}_e$).

The neutrino detector was built in southern Germany but, to reach its final site, it spent two months travelling along rivers and by sea. Here it is seen passing through the town of Eggenstein-Leopoldshafen.

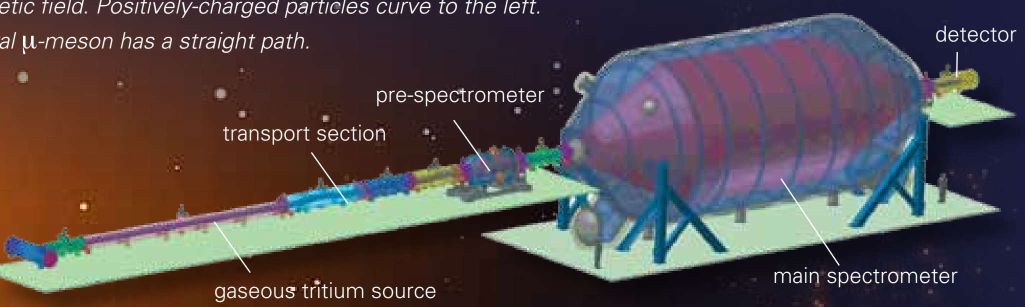
The Katrin detector is lowered into place.



In this photograph, a neutrino entered from lower right and struck a proton. The resulting particles are identified from their paths in the magnetic field. Positively-charged particles curve to the left. The neutral μ-meson has a straight path.

Did you know?

In the time it takes you to read this sentence, millions of billions of neutrinos coming from the Sun will have passed right through you – they interact only very weakly with matter.



The complete Katrin experiment: tritium ^3H is a beta emitter; neutrinos travelling along the tube are detected in the giant spectrometer on the right.