Catalyst

Secondary Science Review

Volume 27
Number 2
December 2016

When the ice shakes

Earthquakes and volcanoes in Iceland

SEP
Science Enhancement Programme

Catalyst

Volume 27 Number 2 December 2016

The cover image shows Thorbjorg Agustsdottir of the Cambridge volcano seismology research group. She is installing a seismometer on Vatnajökull ice cap in central Iceland to record seismic unrest due to the subglacial volcano Bárðarbunga. Photo: Agust Thor Gunnlaugsson

Contents

Earth-shattering science

Volcanoes and earthquakes are two natural phenomena that go together. On pages 8-12, Cambridge seismologist Jenny Jenkins explains how measuring the tremors associated with volcanic activity can help to predict where the next eruption will occur. The 'Try this' experiment on page 13 illustrates how buildings can be engineered to reduce the risk of earthquake damage.

How would you live after a major disaster which wiped out all the major systems that keep civilisation going? On pages 17-19, Lewis Dartnell explains how you could manage to provide yourself with food and drink when the supermarkets are empty.

One solution might be aquaponics, combining vegetable growing with fish farming. Caroline Wood explains this low-impact technology on pages 14-16.

Students: We have now created a website specially for you where you can browse hundreds of articles from past issues of Catalyst and find out how to subscribe.
www.catalyststudent.org.uk

Published by the Gatsby Science Enhancement Programme
Gatsby Technical Education Projects
The Peak
5 Wilton Road
London SW1V 1AP

ISSN 0958-3629 (print)
ISSN 2047-7430 (electronic)

Design and Artwork: Pluma Design

Subscription information

Catalyst is published four times each academic year, in October, December, February and April. A free copy of each issue is available by request to individuals who are professionally involved in 14-19 science teaching in the UK and who are registered with the National STEM Centre. Teachers should visit www.nationalstemcentre.org.uk to find out how to register.

Individual annual subscriptions (4 issues) are available from Mindsets for £12.00. Bulk subscriptions are also available from Mindsets, ranging from £7.00 to £12.00 per subscription, depending on the number ordered.

Visit www.mindsetsonline.co.uk/catalyst for further details, or email catalyst@mindsetsonline.co.uk.

The Catalyst archive

Over 300 articles from past issues of Catalyst are freely available in pdf format from the National STEM Centre (www.nationalstemcentre.org.uk/catalyst).

Zoë Ayres
Julie Macpherson

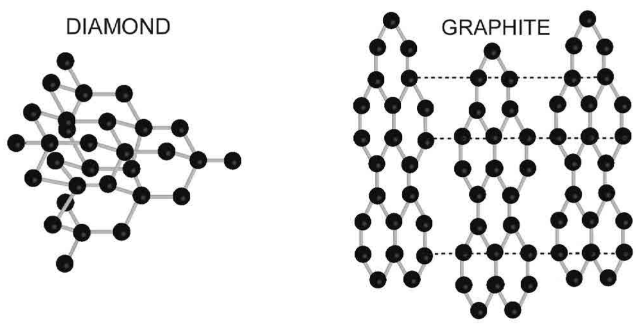
Diamond
More than just a gemstone

Key words
diamond
bonding
hardness
synthetic

When asked to think of diamond, a sparkling, colourless gemstone typically comes to mind, mined from deep within the Earth. Diamond, however, can be grown in the laboratory, with small changes in growth conditions resulting in diamonds with a range of colours and vastly different properties. UK scientists, led by the University of Warwick, are exploiting these extreme properties for a range of exciting new technologies.

Structural differences

Both diamond and graphite (found in pencils) are made of carbon, but they exhibit vastly different properties. For example, graphite is soft, whilst diamond is the hardest material known to man. This is due to that fact that each has a unique arrangement of carbon atoms. In graphite, each carbon atom is bonded to three others, to form flat sheets, with the carbon atoms arranged hexagonally. The sheets can move easily over one another. In contrast, in diamond, each carbon atom bonds to four others creating a rigid three dimensional tetrahedral crystal structure.



Two structures of carbon. (Black dots represent carbon atoms.)
Left: tetrahedrally bound carbon atoms in diamond.
Right: carbon bonding in graphite, where the flat layers are clear to see.

The rigid structure of diamond is not just responsible for its extreme hardness; it also allows heat (and sound) to travel very quickly through the lattice. Diamond is in fact the best thermal conductor of any three dimensional material. For this reason, synthetic diamond is used to dissipate heat in electronic devices and to transmit clear sound in audio systems.

Changing the recipe

By growing diamond in the laboratory, the properties of diamond can be altered to our advantage. For example, we can add different elements into the crystal lattice provided they fit. For this reason only elements either side of carbon in the periodic table are considered. Adding boron during growth turns the diamond from electrically insulating (where all the electrons are tied up in bonds) to electrically conducting. This process is called doping. As the energy levels in the diamond structure are modified during doping, the way the material interacts with light changes too. Adding boron turns the diamond from colourless to blue, and eventually black. Making diamond conductive allows scientists to fabricate superior electrodes to metals. By doping with nitrogen, the diamond is turned yellow.

CVD-grown wafers of diamond (transparent, left) and boron doped diamond (black, middle, right).

Scientific applications

Laboratory grown diamond is finding use in many exciting scientific applications. On an industrial scale, microscopic synthetic diamonds are routinely used for cutting and abrasive applications, taking advantage of the fact that diamond is extremely hard (scoring 10/10 on the Mohs hardness scale). Diamond coated cutting tools, are used for the manufacture of car and aeroplane parts, and to dig through the earth for oil, machining faster and for longer than other non-diamond based tools.

As diamond can withstand high pressures and temperatures and is optically transparent, diamond also finds use as optical windows in pressure cells and high power laser devices.

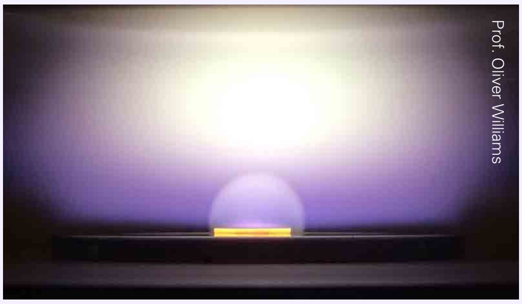
How to grow diamond

Natural diamond is grown over billions of years, in the upper mantle of the Earth, under extremely high temperatures (>1000 °C) and pressures (> 10 GPa). In the laboratory three main methods exist to produce diamond on much shorter time-frames:

Detonation Diamond: Carbon-containing explosives, in a metal chamber, are detonated, producing temperatures and pressures similar to those found within the Earth's mantle. The diamond produced is typically tiny (nanometres in size) and used primarily in abrasives.

High Pressure High Temperature (HPHT): High temperatures (1500 °C) and pressures (55 000 times our atmosphere) are applied to carbon dissolved in a metal solvent using large scale hydraulic presses. Large diamonds are obtained using HPHT.

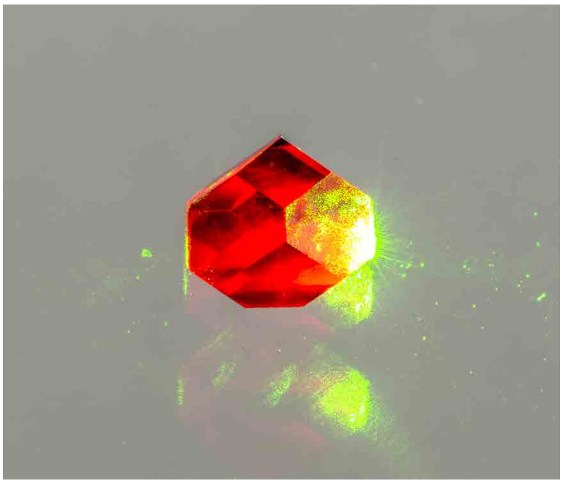
Chemical Vapour Deposition (CVD): Diamond is grown using a plasma, a carbon containing gas, such as methane, and hydrogen. The carbon containing molecules are broken down in the plasma, and deposited onto a substrate to form wafer-like structures. CVD is conducted at much lower pressures than HPHT. CVD can produce diamond wafers over 10 cm in diameter.



Looking inside a CVD diamond growth reactor. The silicon substrate (yellow: 50 mm in diameter) on which the diamond is growing is clearly visible surrounded by a high temperature plasma.

Sensors produced from boron doped diamond (BDD) electrodes can also be used for sensing chemicals in solution environments. For example, monitoring the *p*H of our oceans is extremely important as a means of detecting the effects of climate change. Due to the high-pressure, high salinity (corrosive) environment presented by deep sea monitoring, most materials cannot survive for long periods of time. As BDD electrodes can be made *p*H sensitive, they offer the possibility for continuous *p*H measurement in this challenging environment. Furthermore, as diamond is made of carbon, it is biocompatible and can be placed in the human body without rejection. Research is now underway into using diamond electrodes for a whole host biomedical applications.

Synthetic diamonds are also finding uses in the latest quantum technologies. By introducing defects into diamond during the growth process, such as nitrogen-vacancy (NV) centres (where two neighbouring carbon atoms are replaced by a nitrogen and the other is left vacant) magnetic fields can be detected. The production of a NV defect results in energy levels in the diamond which enable the absorption of high energy green light from a laser but emit lower energy red light (due to energy loss). The intensity of the emitted red light can be strongly influenced by the presence and strength of a magnetic field. Hence NV defects in diamond can be used to sense a wide variety of magnetic fields ranging from small variations in the earth's magnetic field to detecting magnetic fields in the human brain.



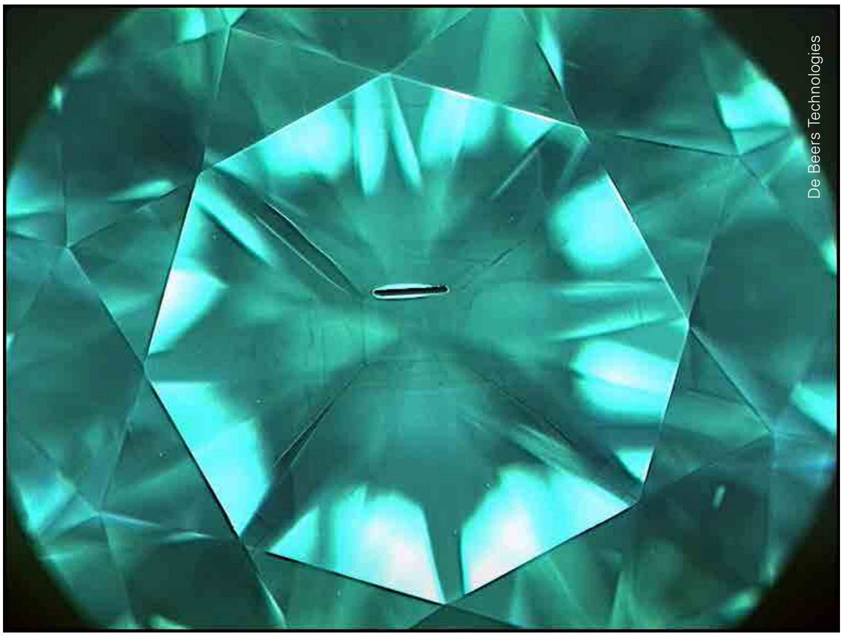
Green light shone onto a diamond crystal containing NV defects. The diamond emits red light. (Photo copyright Dr Jon Newland)

What is the cost?

Natural diamonds can sell for millions of pounds, so how much does it cost to grow synthetic diamond? Equipment can be costly due to the energy required to reach the temperatures necessary to grow diamond. The size and quality of the diamond produced is also a key factor. Microscopic, imperfect synthetic diamonds for cutting and abrasive applications are relatively inexpensive (sold for a few dollars per gram). Making large, perfect crystals is much more difficult, requiring longer growth times (thus more energy) to ensure defects are kept to a minimum. For example, single crystal plates, grown by chemical vapour deposition (CVD) and approximately millimetres in size, can be bought for a few hundred pounds. Synthetic diamonds cut and polished appropriately for gemstone use are also cheaper than those mined naturally. Synthesis offers the ability to grow diamond to order for the application of interest. Finding appropriate diamond for applications requiring large scales would be impossible with natural diamond, mined from the ground, but is now routinely possible through synthesis.

Spot the difference?

Synthetic and natural diamonds are both made of four-bonded carbon, so the question is, can we tell the difference? To the naked eye, the two are indistinguishable, but if we look closely enough using modern scientific equipment, differences can be identified. Natural diamonds are typically over 1 billion years old and require volcanic events to occur before they are moved close enough to the Earth's surface for humans to find. In that time, small impurities and defects can form. These form a fingerprint, allowing the origin of the diamond to be determined. When grown in the laboratory, the defects formed are different, and distinctive growth patterns can be determined. Placing the diamond under ultraviolet light can reveal the hidden patterns presented by the defects in diamond.

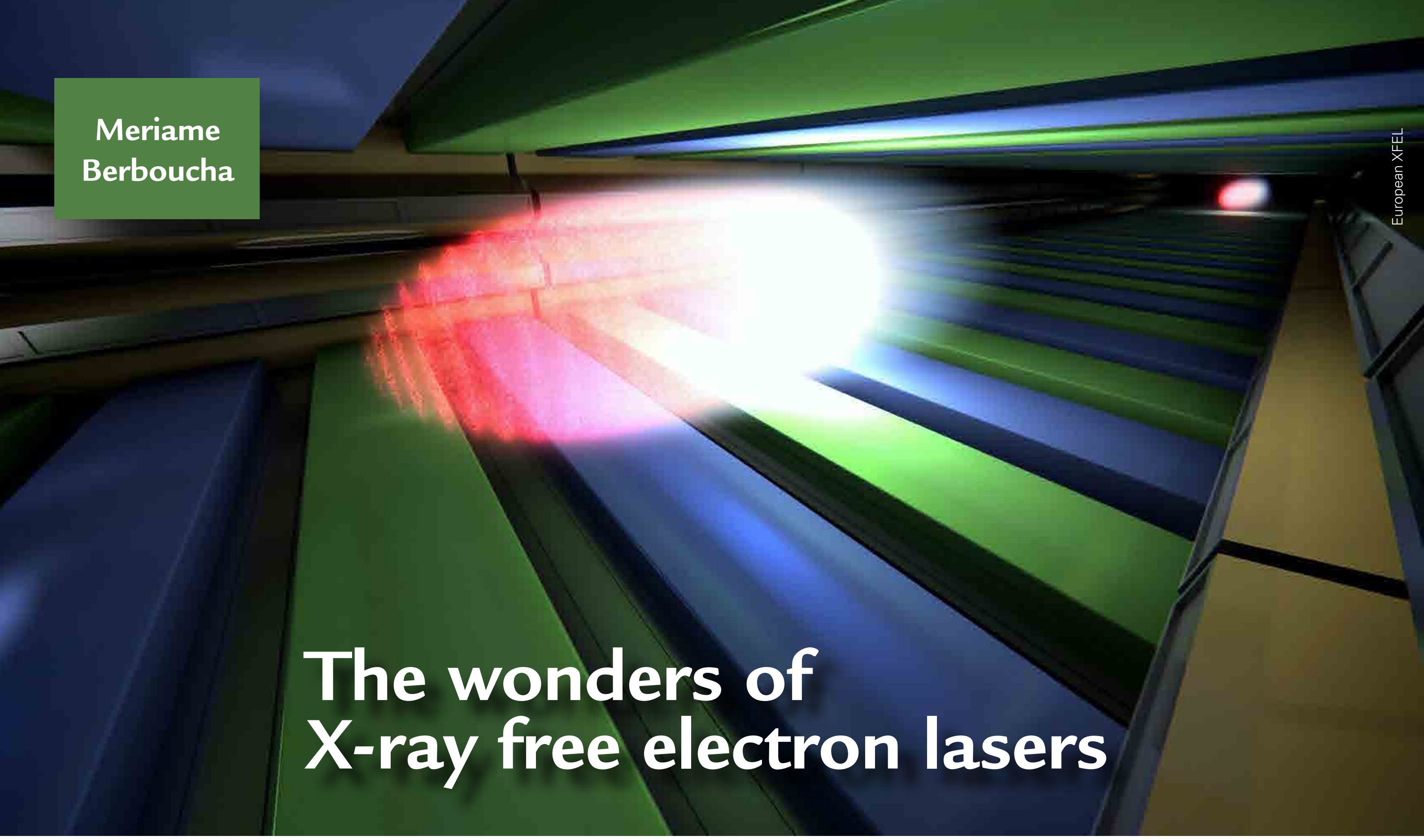


De Beers Technologies

Synthetic HPHT grown diamond illuminated using DiamondViewTM UV technology. Cubic and octahehdral growth regions are revealed that are absent in natural diamonds.

*Zoë Ayres is a postgraduate student and **Julie Macpherson** is a Professor of Chemistry at the University of Warwick, working together to investigate boron doped diamond electrodes for sensor applications.*

Meriame Berboucha



The wonders of X-ray free electron lasers

Simulation of a laser flash generated in an XFEL undulator

Key words
laser
X-rays
electrons
radiation

*Unravelling the complex molecular structure of proteins and viruses, taking snapshots of atoms and molecules during chemical reactions – these are just some of the many things we can do with an **X-ray free electron laser**. With this, we can reveal the fundamental processes occurring in materials, living things and technology, helping us find out more about the world we live in.*

Laser light

You will be familiar with lasers used in laser pointers and in supermarket checkouts. These produce beams of visible light. There are several special things about this light:

- It is collimated – the beam is very narrow so that it spreads out only very slowly.
- It is monochromatic - all the waves have the same frequency.
- It is coherent - all the waves are in phase with each other.

What is an X-ray free electron laser?

An X-ray free electron laser (XFEL) is a type of laser that is typically hundreds of metres long. It uses 'wiggling' electrons to generate laser light with very short wavelengths.

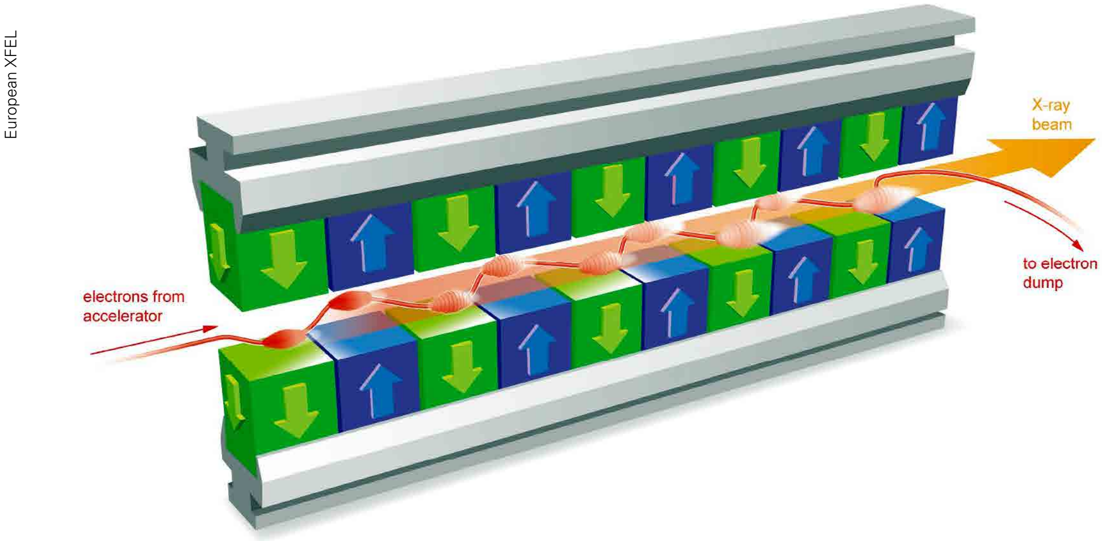
So how does an X-ray free electron laser work? An XFEL begins with an electron beam. The electron beam is generated by 'boiling' off electrons from a metal with a laser. These electrons are then accelerated in special cavities known as resonators. In a resonator microwaves transfer energy to the electrons causing them to speed up to close to the speed of light. These resonators are superconducting which means that when they are cooled down to a very cold temperature (-271°C) they have zero electrical resistance. As a result, all the electrical power from the resonator is transferred to the electrons.

Now that the electrons are up to higher energies they pass through a magnetic structure with alternating north and south poles called an undulator where the electrons wiggle from side to side, almost as if they were on a tight slalom course. The 'wiggling' electrons are accelerating because they are changing direction and so they emit radiation, in this case X-rays.

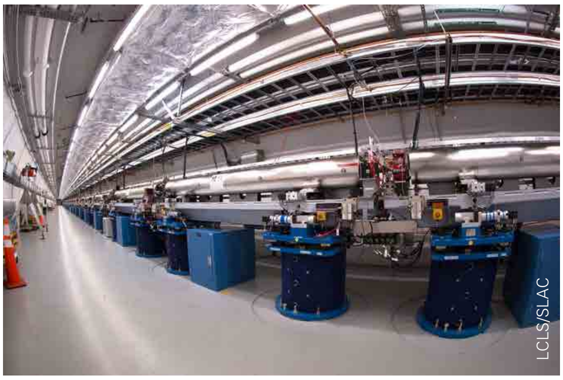
The X-rays are much faster than the electrons and as the radiation overtakes the electrons they interact with the electrons and cause some of the electrons to accelerate and others to slow down. This leads to bunching where the electrons are organised into a series of thin disks. This is a very important property because the electrons in a given disk emit light that is coherent like the visible light from a laser. These disks normally take a bit of time to form and so the undulators are typically hundreds of meters long.

A final magnetic field is used to deflect the electrons from the electron-X-ray beam into a dump, leaving a train of ultra-short and ultra-bright pulses of X-rays. These X-ray flashes have similar properties to the light from a laser, namely, it is coherent and (almost) monochromatic. One of the great things about X-ray free electron lasers is that they are tuneable over a wide range of frequencies so we can use them for a wide range of science.

'Laser' stands for Light Amplification by Stimulated Emission of Radiation



In the undulator of an XFEL, magnetic fields force the electrons to wiggle from side to side. This causes them to emit X-rays. The electrons bunch together into flat discs so that the radiation they produce is coherent, like the light from a laser.

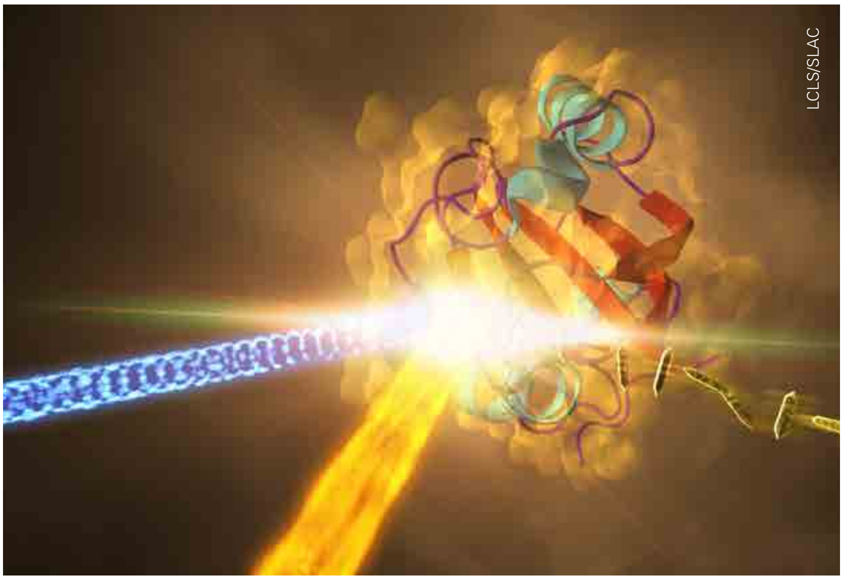


The undulator hall at LCLS, SLAC National Accelerator Laboratory, California, USA. Each undulator contains 224 magnets with alternating poles which force the electrons to wiggle and produce X-rays.

What use is an XFEL?

XFELs can be used to answer some fundamental questions and allow us to probe the very small scales of our world. This is because the wavelength of X-rays is very short (typically a billionth of a metre!) and so we can see very small objects. Also, each pulse only lasts for quadrillionths of a second which is short enough to study samples before they are damaged by the very bright light. Here are just some of the things we can find out about the world we live in with XFELs:

Photosynthesis and other chemical reactions – researchers have been using XFELs to study photosynthesis, one of the most important chemical reactions on Earth. They can take snapshots of these processes and turn them into science-y movies! Additionally, we can gain understanding of the crucial steps required for chemical reactions to occur which could, for instance, improve our ability to produce fuels and other industrial chemicals in more efficient and controllable ways.



This is an illustration of a protein from photosynthetic bacteria that changes shape in response to light. It was investigated during an experiment at LCLS, SLAC National Accelerator Laboratory, California, USA.

Electronics – scientists are looking into ways of controlling the magnetic and electronic properties of certain electronic materials with ultrashort pulses of light. As a result, we could have very fast, low-energy computer memory chips.

Matter in extreme conditions – we can create extremely hot and dense conditions which can help us understand the environment inside the cores of stars and planets. This will allow us to have a better understanding of fusion, aiding our quest of achieving fusion on Earth and generating clean, unlimited power to all of its inhabitants.

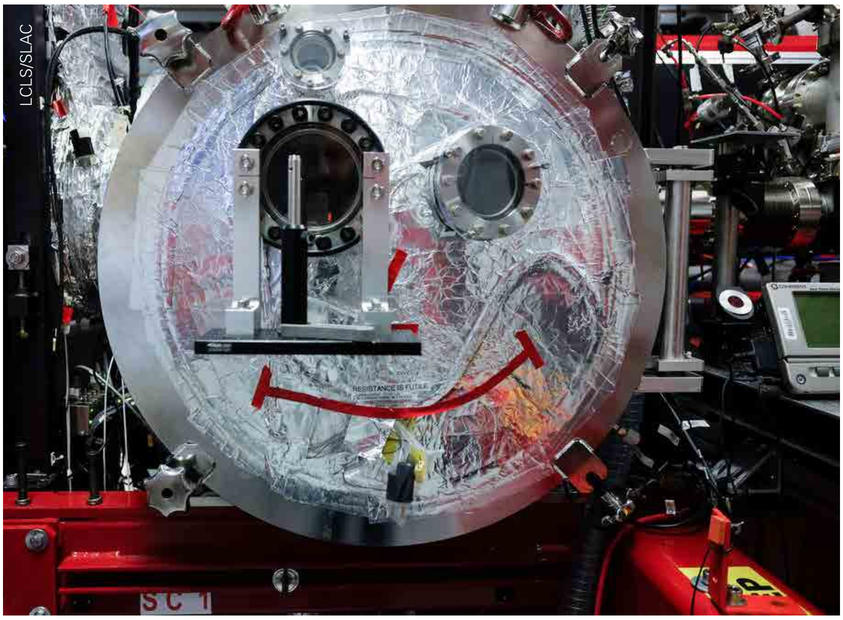
Inside us – we can determine the structures of proteins and as a result study biological structures, in particular those vital for disease and its treatment. This could lead the way to drug development and better treatment for diseases.

World's biggest XFEL

The largest XFEL in the world is located in the beautiful state of California in the U.S. at SLAC National Accelerator Laboratory. Linac Coherent Light Source (LCLS) is about 4 km long in total – that's the size of 40 football pitches length-ways!

Bird's eye view of SLAC, where the highlighted region in the diagram is LCLS. The experimental hutches are the rooms to the far right of the image. The linear accelerator (linac) is on the far left and is the largest linac in the world.

LCLS has six specialised experimental hutches where the X-ray laser is used for a wide variety of experiments. LCLS can image samples down to the size of atoms and see processes that occur in less than one tenth of a trillionth of a second! Consequently, LCLS is embarking on ground-breaking research not only in physics but also in chemistry, biology and various other fields. Research done at LCLS has allowed scientists to discover how DNA guards itself against damage from ultraviolet light and map the structure of an enzyme that is relevant to the African sleeping sickness disease, just to name a few of the things discovered at LCLS. Scientists from all over the world use the LCLS facility to carry out their research and add to the body of scientific knowledge. Science is a global field and can only progress with the collaboration of minds all around the world.



One of the experimental vacuum chambers in the Coherent X-ray Imaging (CXI) experimental hutch. Here, X-ray crystallography experiments have allowed scientists to image biological samples without damaging them because of the very short pulse duration.

The X-ray Correlation Spectroscopy (XCS) experimental hutch is used to carry out experiments that observe dynamical changes of large groups of atoms. The SLAC director, Chi-Chang Kao (far left) and LCLS director, Mike Dunne (far right) can be seen in this picture.

LCLS is currently undergoing an upgrade where LCLS-II will build from the success of LCLS. It will go from producing 120 X-ray pulses a second to 1 million pulses a second which will be 10 000 times brighter! This upgrade will allow scientists to perform experiments that are currently impossible enabling us to make discoveries that shall advance technology and our quality of life further and hopefully help produce new energy solutions. Thus, exciting times lie ahead of us in the field of X-ray free electron lasers – look out for more discoveries in the next few years!

Meriame Berboucha is a final year undergraduate student of Physics at Imperial College London. In the summer of 2016 she was the first international student to win an internship at the Linac Coherent Light Source, SLAC, California, USA.

Meriame explains her work at the end of her internship at LCLS, SLAC.

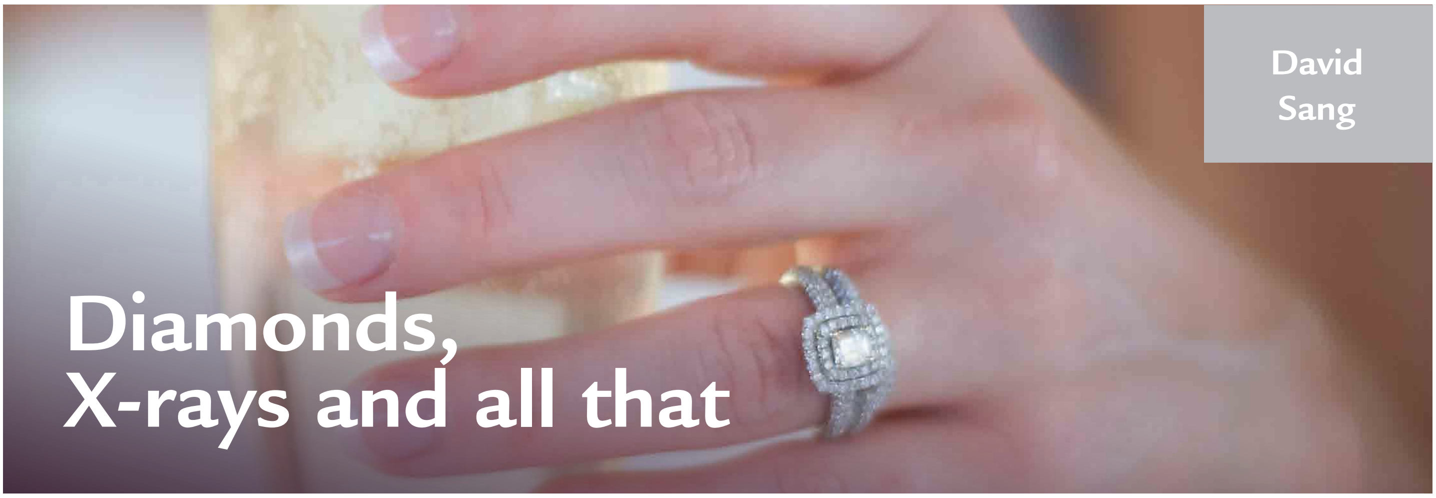
Look here!

Watch a short film about LCLS-II: *https://www.youtube.com/watch?v=t7jUZwhZdd0*

A European collaboration is building an XFEL: *http://www.xfel.eu*

Find out more about Meriame's career in Physics: *http://meriameberboucha.weebly.com*

David Sang



Diamonds, X-rays and all that

Light refracted by a diamond catches the eye.

It is sometimes said that diamonds don't show up on X-ray images. That's not true, as diamond smugglers can be caught in X-ray checks. However, it is true that, in the early days of X-rays, diamond rings could be distinguished from synthetic or 'paste' stones used in costume jewellery using X-rays. This is because of the chemical differences between the two.

Ernie the puppy swallowed a diamond ear-ring.

Paste is a form of glass, made by mixing together compounds containing lead, silicon, potassium, boron and arsenic. These elements mostly have high atomic masses and so they show up strongly in X-ray images. Diamond is different. It is pure carbon (see the article on pages 1-3 of this issue of Catalyst) and carbon atoms have an atomic mass of just 12. This means that they cast only weak X-ray shadows.

Jewellers traditionally check diamonds by eye but today more scientific techniques are need to distinguish fakes.

Crystal structure

X-ray crystallography was used to show up the underlying atomic structure of diamond. Each carbon atom is tightly bonded to four others in a tetrahedral structure. This tight bonding means that vibrations travel rapidly through the crystal structure of diamond. Two consequences:

- The speed of sound in diamond is 12 000 m/s, twice as fast as in steel and nearly 40 times as fast as in air.
- Diamond is an excellent thermal conductor, with five times the thermal conductivity of copper.

Its high thermal conductivity explains why diamond is known as 'ice'. Touch a piece of paste jewellery to your top lip and it feels warm. Repeat with a genuine diamond and it feels cold as the warmth of your lip is conducted away.

Diamonds and light

Diamond has a very high refractive index (2.42, compared with 1.5-1.6 for most types of glass). It is also highly dispersive – it refracts blue light significantly more than red light. This gives diamond its quality known as 'fire' which you will notice if you see a cut diamond moving in the light.

Computer modelling determines how best to cut a stone from a rough diamond. Hand polishing is still used to give the most brilliant surfaces.

Jenny Jenkins

Daði Harðarson

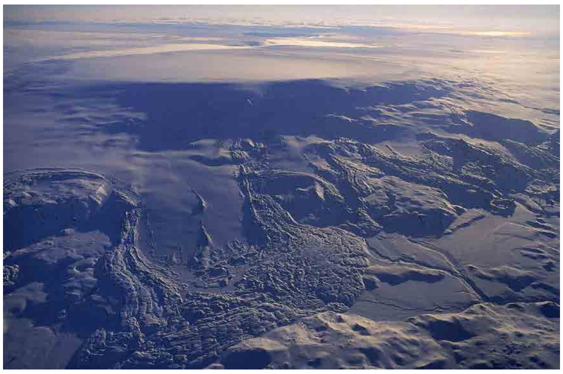
Explosive Earth

Earthquakes and volcanoes in Iceland

The eruption of Bárðarbunga volcano in Iceland, July 2014

Key words
volcano
earthquake
seismology
prediction

Bárðarbunga is a massive volcano located in central Iceland. It sits under 800 m thick ice of the largest glacier in the country. In July 2014 Bárðarbunga erupted but instead of lava erupting out of the top of the volcano the molten rock moved underground for nearly 50 km, and came to the surface on a sandy river flood plain.



The volcano of Bárðarbunga beneath the glacier

The eruption was spectacular, forming huge fire fountains as the molten rock was thrown over 150 m high into the air, glowing yellow-red due to its high temperature (over 1000 degrees). Lava was not erupted from a single central vent, but all the way along a crack in the Earth called a fissure. This was the largest eruption in Iceland in over 200 years with as much energy released as dropping a Hiroshima-sized bomb, not just once but every 2 minutes, hour after hour, day after day for 6 full months before the eruption finally stopped. By the time it was finished a massive area of 84 km^2 was covered by the fresh cooling lava flow – large enough to cover the whole of Manhattan. However this eruption was not very explosive or even particularly dangerous, since it happened in a deserted area of the Icelandic highlands.

Molten rock is known as magma when it is underground and lava when it comes to the surface.

Ragnar_Th_Sigurðsson

The fire fountain eruption of Bárðarbunga

Ragnar_Th_Sigurðsson

The extent of the lava flow from Bárðarbunga

For several weeks before the eruption, scientists knew Bárðarbunga volcano was restless and there was molten rock moving deep beneath the surface. We tracked the molten rock using tiny earthquakes as it moved from the volcano out to where it eventually erupted.

Tracking molten rock underground using earthquakes

When magma moves underground it cracks and fractures a path, forcing its way through the solid rock, causing thousands and thousands of tiny earthquakes. These are not the kind of earthquakes reported on the news that knock down houses and cause lots of damage, in fact they are so tiny a person can't even feel them. For earthquakes that small even to know they are happening we need very sensitive instruments called seismometers, which measure tiny changes in the motion of the ground.

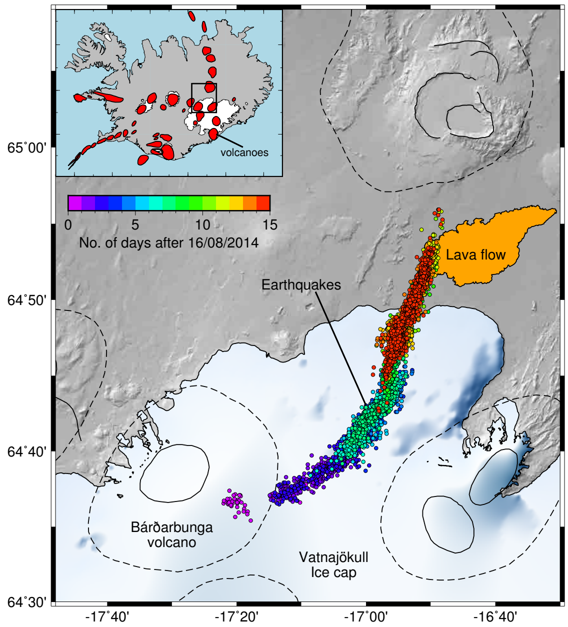
Setting up seismometers near the volcano

By recording the same earthquake with many different seismometers we can calculate where the earthquake must have originated. When an earthquake happens, seismic energy is released, causing the ground to shake. Vibrations spread outwards from the centre in all directions, just like when you drop a stone in a pond and see the ripples spreading out. By measuring how long it takes these seismic waves to reach different seismometers we can tell which ones are close to where the earthquake started and which are further away, and can pinpoint a location for the earthquake. Locating multiple earthquakes in this way can show us where molten rock is moving underground as it cracks its way forward.

Seismometers in Iceland

In Iceland around Bárðarbunga volcano the University of Cambridge had a network of around 70 seismometers used to record earthquakes. When the unrest at Bárðarbunga first started, teams of scientists rushed out over the rugged terrain using off-road vehicles to put out extra instruments, even flying up onto the glacier by helicopter to bury some in the ice.

From about two weeks before the eruption started our seismometers recorded over 30 000 tiny earthquakes. These earthquakes moved northwards over time allowing us to track the molten rock as it moved underground from under the volcano out to the eruption site. When the melt eventually came to the surface it erupted right in the middle of our instruments. This was very useful for getting really accurate locations of where the earthquakes come from. Unfortunately it also meant that two of our seismometers had to be quickly removed, to save their precious data from the advancing lava flow.



Earthquake locations tracking the underground movement of magma

Rescuing a seismometer as the lava flow approaches

Can we predict a volcanic eruption?

Predicting exactly when a volcanic eruption will happen is very difficult, because there are so many different factors which control how an eruption may develop, many of which are poorly understood. Even as molten rock was tracked using the locations of the earthquakes its movement produced, scientists didn't know how far it would go before coming to the surface to erupt or when that would be. Indeed it was possible that no eruption would happen and the melt would stay in the ground where it would slowly cool and solidify, becoming an igneous intrusion.

Scientists couldn't say exactly when the magma would stop moving, but knowing whether it would erupt beneath the ice of the glacier or would travel far enough away that it could erupt outside the ice would have resulted in completely different styles of eruption. Being able to tell authorities what type of eruption is likely to occur and what sorts of hazards they need to be prepared for is extremely important, even if it's not possible to say exactly when it will happen.

An igneous intrusion is rock formed from magma which has cooled underground without erupting to the surface.

The photograph on pages 10-11 shows an aerial view of lava flowing when Bárðarbunga erupted.

Daði Harðarson

Catalyst
www.catalyststudent.org.uk

A light aircraft carries scientists and their measuring equipment over the lava flow as Iceland's Bárðarbunga volcano erupts.

The earthquake magnitude scale – how big is a big one?

The size of an earthquake is defined by the magnitude scale. Big damaging earthquakes are usually magnitude 6 or larger, whereas the tiny earthquakes caused by magma movement are only around magnitude 1. This might not sound a lot smaller than a magnitude 6 but the earthquake magnitude scale is logarithmic. This means each time earthquake magnitude increases by one, 32 times more energy is released. So a magnitude 6 earthquake doesn't release 6 times as much energy as a magnitude 1, but around 33.5 million times as much.

Different eruptive styles

Molten rock in Iceland is usually very runny and fluid, which means gases in the magma can easily escape, leading to effusive fire-fountain style eruptions which are not very explosive or dangerous. But when an eruption happens under ice, everything changes.

Eruptions that happen beneath glaciers bring very hot magma into contact with very cold ice. The ice instantly melts or turns to steam and expands. In contrast, the hot magma is suddenly cooled and solidified into volcanic glass which is instantly shattered into tiny fragments by the expanding steam and thrown into the air. These tiny fragments of volcanic glass are what form volcanic ash. Glacial melt water can also cause catastrophic glacial outburst floods.

Lava can emerge from many points during an eruption.

Therefore the difference between an eruption happening underneath a glacier or at the surface can mean a change between an ash heavy explosive eruption and major flooding, or a gently effusive fire fountain type eruption. By tracking the magma movement from Bárðarbunga we could try and determine which of these scenarios was more likely.

Jenny Jenkins is a seismologist at the University of Cambridge studying the deep structure of the Earth beneath Iceland.

Just a handful of volcanic dust

Volcanic ash produced in sub-glacial eruptions doesn't seem very dangerous, it just looks like a handful of fine grey dust. But when ash in the air gets inside aeroplane engines it can become a major hazard. Plane engines can reach very high temperatures causing the volcanic ash to melt forming magma droplets. These droplets can get stuck to plane turbines and re-solidify, which can potentially stall the engine. Thus planes cannot fly through heavy ash eruptions.

This happened during another eruption in Iceland in 2010 when the volcano Eyjafjallajökull (pronounced: AY-JAH-FYAT-LA-YOK-KULT) exploded. Just like Bárðarbunga, Eyjafjallajökull sits beneath a glacier, but unlike Bárðarbunga the magma erupted out of the centre of the volcano beneath the ice, creating a very ash-heavy eruption. Winds blew ash from Iceland over European airspace which was forced to close. Over 100 000 flights were cancelled, leaving around 10 000 000 people stranded or unable to fly, and costing the aviation industry around $1.7 billion.

The Eyjafjallajökull eruption in 2010 caused widespread flight cancellations.

Look here!

Find out about volcanoes, earthquakes, and Iceland and what it's like to be a volcano seismologist on the Cambridge Volcano Seismology group webpage: *http://tinyurl.com/zyp4m9c*

Sturdy structures

Earthquake resistant buildings

In areas where there are frequent earthquakes, engineers try to design earthquake-proof buildings which sway with the motion of the earthquake, rather than cracking and breaking. What kind of structures make for stable earthquake-proof buildings?

You will need:

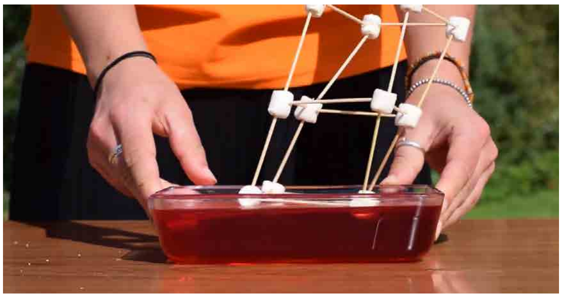
- a deep baking dish or tray approximately A4 size
- a pack of jelly
- some cocktail sticks
- a bag of mini marshmallows

What you do:

Make the jelly and pour into the dish. Leave to set. Make some 3-dimensional structures using cocktail sticks, joining corners together using marshmallows.

Place your structures on the solid jelly and slide the dish from side to side to simulate an earthquake to test how well different structures stand up.

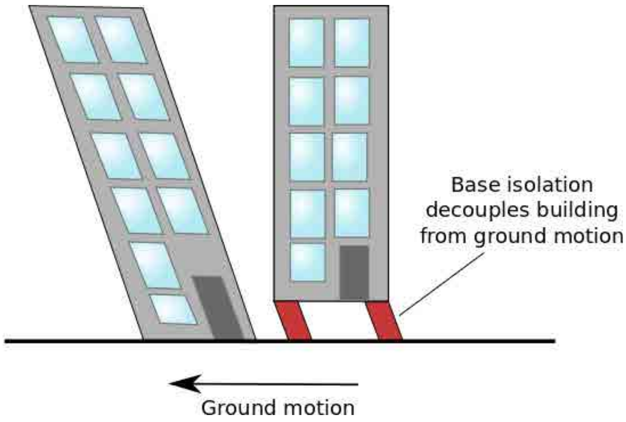
Are tall or short structures better? What shapes make the most stable structures?



What's happening?

You should find that short structures are much more stable than tall structures. This is because even though short and tall buildings shake at the same rate, the shaking motion is magnified as buildings get taller. The strongest structures are often pyramids or tapered shapes which are wider at the base and get thinner towards the top. Triangles provide very stable shapes: adding cross-bracing to form triangles can make shapes like cubes stronger.

Engineers design buildings with detached bases which are not completely fixed onto the ground. Instead they sit on top of systems of ball bearings or springs which act as shock absorbers, so that the building is free to move slightly. Then the building does not have to shake with the earthquake but can stay in the same place, and not all of the shaking is transmitted up through the building.



Why is it important?

When an earthquake occurs near a town or city it can cause lots of damage. Often it is not the magnitude of the earthquake that determines how much damage will be caused but the design of buildings. Japan experiences large magnitude earthquakes regularly but due to investments in building design and high building standard regulations most of the time there is very little damage. In contrast much smaller magnitude earthquakes can be devastating for countries with less money to spend on infrastructure. This is why the design of inexpensive earthquake-resistant buildings is so important – earthquakes don't kill people, poorly designed buildings do.

Vicky Wong is Chemistry editor of Catalyst.

Look here!

For more information about buildings with detached bases: *https://www.youtube.com/watch?v=kzVvd4Dk6sw*

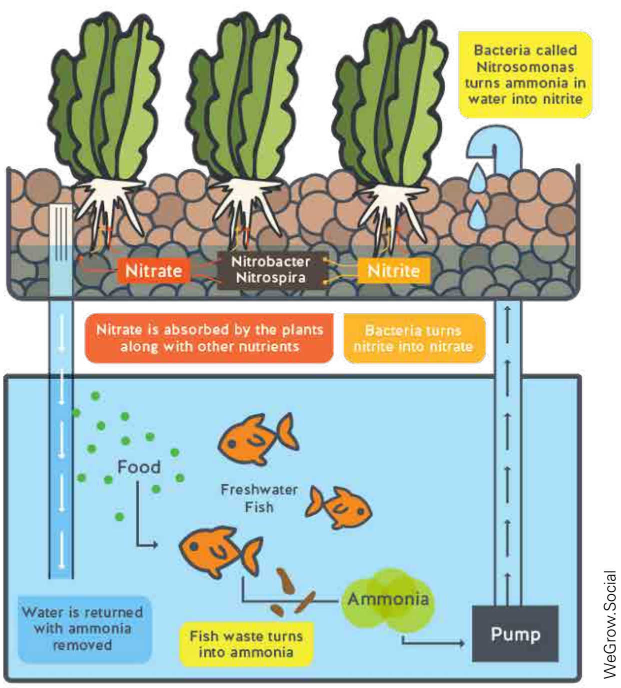
Caroline Wood

Aquaponics

Feeding the world – with fish poo!

Key words
aquaponics
aquaculture
hydroponics
nitrogen cycle

Living organisms have an essential need for nitrogen to build proteins and nucleic acids (such as DNA). Most modern, intensive agricultural systems rely on heavy inputs of nitrogen fertilisers. Producing these requires large amounts of fossil fuels, and so there is an urgent need for more sustainable methods to source nitrogen for crops. Aquaponics is a potential solution that could help minimise the environmental costs of producing enough food to feed the growing population.



A basic aquaponics system

What is aquaponics?

Put simply, aquaponics is the combination of aquaculture (farming aquatic animals or plants) with hydroponics (growing plants without soil). A problem with conventional aquaculture, such as commercial fish farms, is that waste excretions from the animals accumulate in the water and can reach toxic levels. In aquaponic systems, the water containing these excretions is fed to hydroponically grown crops to provide a source of nitrogen (see diagram, left). Instead of using soil, the crops are either grown in a substrate, such as gravel or coconut fibre, or suspended so that their roots grow into pipes or a tank containing running water.

However, the plants cannot use the waste products directly and so require an intermediate organism to break them down first. Hence, the waste water from the fish enclosure is first pumped to a tank containing the bacteria *Nitrosomonas* and *Nitrobacter* which convert the wastes to nitrite and then nitrates as part of the nitrogen cycle (the processes which transfer nitrogen between living organisms and the environment). The water is then pumped to the plants, which filter out the waste products. Afterwards the water is returned to the fish tank, creating a self-sustaining cycle. Because the water is effectively recycled, the plants in an aquaponic system need considerably less irrigation than conventionally grown crops (as low as 2%). Growing the crops hydroponically also reduces the risk of soil-borne plant diseases, reducing the need to apply toxic chemicals.

The basic principles of aquaponics have been practised for thousands of years: one of the earliest examples is the chinampas (floating islands) developed by the Aztecs. Here, plants were grown on stationary or moveable islands in the lake shallows, and were fed using waste water dredged from the canals of the surrounding cities.

Where will it work?

A key advantage of using aquaponics is that it can be adapted to a wide range of climates and agricultural systems. It is particularly popular in Asia and Australia, and is growing in popularity in the USA and in Europe. Because of the low water demands, aquaponics can even be done in urban spaces or land that would otherwise be unproductive, such as rooftops or warehouses (see Box right). There is also a huge variety of plant/fish combinations that can be used. Green leafy vegetables, such as lettuce, spinach and herbs grow particularly well in aquaponics systems, as these typically have low-medium nutrient requirements. Plants that need higher levels of nutrients (e.g. tomatoes, cucumbers and peppers) can also be grown however these may require a higher density of fish.

Crops growing using aquaponics at the WeGrow.Social Project at the University of Sheffield

One of the most popular fish species for aquaponics systems is Tilapia, a fast-growing, edible fish that can be harvested for food. In Britain, where the climate is too cold to use Tilapia outside a greenhouse, freshwater fish such as carp, rainbow trout and perch are used instead or ornamental fish such as goldfish. As for the bacteria, *Nitrosomonas* and *Nitrobacter* are naturally abundant in the environment and will generally seed themselves into a standing body of water.

The Bristol Fish Project

The Bristol Fish project is one example of an urban-based aquaponics system, being located inside a warehouse formerly used for spraying paint on cars. Alice-Marie Archer, founding director of the project, says, "We work with critically endangered *Anguilla anguilla* (European eels) as part of international conservation efforts and we plan on growing wasabi and watercress. As a community-supported farming model, people can get involved at different levels with the day to day farming. We also teach aquaponics so that other communities can start their own projects."

Newly installed tanks at the Bristol Fish Project; elvers (young eels) ready to grow

Challenges and opportunities

Given that aquaponics could help us to grow more food without fertilisers, why is it not more commonplace? Hamish Cunningham, a Professor at the University of Sheffield explains that because aquaponics is a 'three-way balanced ecosystem', it can be tricky to get all the elements exactly right. The basic inputs are water, oxygen, light, fish food and electricity to pump and oxygenate the water. However, many other factors can affect the system, including the air and water temperature, the pH, the humidity level and the water flow rate.

It takes real skill and knowledge to keep an aquaponic system working effectively. Currently, aquaponic farms require regular maintenance to check the physical conditions and the health of the fish and plants. As part of the WeGrow.social team, who are investigating new methods to grow sustainable food locally, Hamish is developing ways to automatically monitor and control the conditions in aquaponics systems. One of their latest creations is the WaterElf, a micro-controller with built-in sensors that can monitor various parameters including the pH, temperature, water depth, light and humidity levels. If the conditions change, the WaterElf can activate 16 electrical sockets, which can be connected to fans, pumps, lights, etc., to make sure the conditions stay within a certain range. Technology such as the WaterElf could eventually allow aquaponics systems to be grown with minimum supervision.

The WaterElf - a device that automatically monitors conditions in aquaponic systems

Another factor to consider is the cost: currently, it is no cheaper to use aquaponics than conventional agricultural methods, mainly due to the need to supply fish food. But scientists are investigating whether waste food could be used to feed the fish instead. One potential method uses the larvae of black soldier flies. As Hamish explains, "The larvae are voracious eaters and consume food waste very quickly, producing a protein which is appropriate for fish diets." The initial cost of setting up an aquaponics system can be high but it is possible to construct systems using recycled materials, such as former shipping containers or even old bathtubs.

Finally, lack of knowledge and awareness is also a barrier to aquaponics becoming more commonplace. However aquaponics farmers are starting to form virtual hubs where they can advise one another and exchange ideas. Meanwhile, there is an increasing number of aquaponics demonstrations and courses which the public can visit to see how it works.

Growing resilience

In a world facing increasing uncertainty due to climate change, rapidly growing populations and environmental degradation, aquaponics could help to increase the resilience of our food supplies. "One of the most interesting and useful things we can do is to start growing more food locally so that we have supply chains that are under our control and more predictable in the face of chaos and confusion," says Hamish. It has already been demonstrated that aquaponics can be a powerful means to help communities improve food security.

Eman Nofal collects vegetables from her rooftop garden in the Gaza Strip, part of an aquaponics scheme developed by the United Nations.

One example concerns the Gaza Strip, an area of great conflict and poverty between Israel and Egypt. Here, the Food and Agriculture Organisation of the United Nations has been installing rooftop gardens connected to fish tanks. These have helped to provide a source of fresh vegetables and protein for some of the most impoverished families and are particularly suitable for female-headed households as they require little physical effort to maintain.

Given the many challenges that humanity faces, it's likely that we will need a whole range of approaches to secure the harvests of tomorrow, rather than a single magic 'silver bullet'. But aquaponics certainly looks like a promising method that deserves to be taken up more widely.

Caroline Wood is a postgraduate research student in the Department of Animal and Plant Sciences, University of Sheffield.

Look here!

Have a look at Aquaponics in action:

Bioaquafarm: 'The biggest aquaponic trout farm in Europe', near Bristol: *http://bioaquafarm.co.uk/*

The Incredible Aqua Garden, Todmorden, West Yorkshire: *https://incredibleaquagarden.co.uk/*

Humble by Nature, near Monmouth in the Wye Valley in South Wales, and run by the BBC presenter Kate Humble: *http://www.humblebynature.com/*

Lewis Dartnell

Why do we eat what we eat?

Let's imagine, as a thought experiment, that the world as we know it ends. There's a global catastrophe. Civilisation has collapsed and the vast majority of humanity has died. But you've fallen in with a community of other post-apocalyptic survivors.

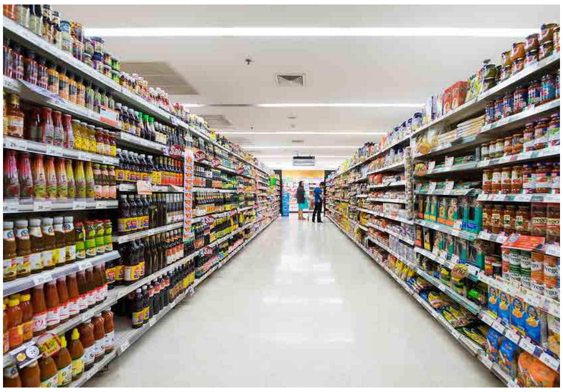
What now...?

What science and technology would you most need to know -- not just in the immediate aftermath but in the long-term, to go about rebuilding a new society for yourselves from scratch? Could you reboot civilization? What would be the one book you would want handed to you as a post-apocalyptic survivor that told you all the most important knowledge from history about how to make and do things for yourself?

This is the book that I've written. The conceit behind *The Knowledge: How to Rebuild our World from Scratch* is that it's a quick-start guide to civilisation itself. As a scientist, I wanted to explore all the behind-the-scenes fundamentals of how our world works, and what discoveries and inventions enabled civilisation to advance over history. I thought the best way to explore how civilisation works and all that we simply take for granted in our modern lives was to imagine that suddenly none of it was there any more. In this article, we'll focus on food – why do we eat what we eat?

Early days

If the majority of humanity were to suddenly perish, the survivors won't need to immediately begin making everything they need. There'll be of stuff left lying around from the dead civilization. There'll be a 'Grace Period' during which the survivors could forage for what they need.



Help yourself before someone else gets there.

With food, you're not going to need to start farming straight away. Simply go into a supermarket and help yourself to all the preserved food lining the shelves. How long do you think a single supermarket could support one person? To work this out, I multiplied I together all the food stocked in an average supermarket and dividing it by the amount you would need to eat per day to stay alive. And the answer comes out that a single supermarket could support one person for 55 years!

The end of civilisation – from the movie Resident Evil

The fundamental point I'm trying to make here is that the reason all of us living in the developed world today no longer fear starving to death is that we've developed technologies to effectively preserve food. We developed the canning process in the early 1800s, and later learned how to exploit the gas laws to create little pockets of artificial winter in a refrigerator. This preservation and stockpiling of food has enabled us to build modern civilisation. We worked out how to stop bacteria or mould eating our food before a person was ready to eat it.

Fancy a drink?

Ensuring clean drinking water will be another of your top priorities. How can you use science to know for a fact that the water you are about to put to your lips and drink isn't going to kill you -- that it's not contaminated with typhoid or cholera or other waterborne diseases? When you're scavenging through the post-apocalyptic world, all you need to do is to find some ordinary kitchen bleach, and if you dilute this down enough -- DO NOT DRINK CONCENTRATED BLEACH! -- you can use it to chemically disinfect water. Diluted swimming pool chlorine will work just as well. These are the chemicals sodium hypochlorite and calcium hypochlorite. Chlorine will kill germs in the water, to make it safe for you to drink, in fact, municipal tap water is disinfected using chlorine.

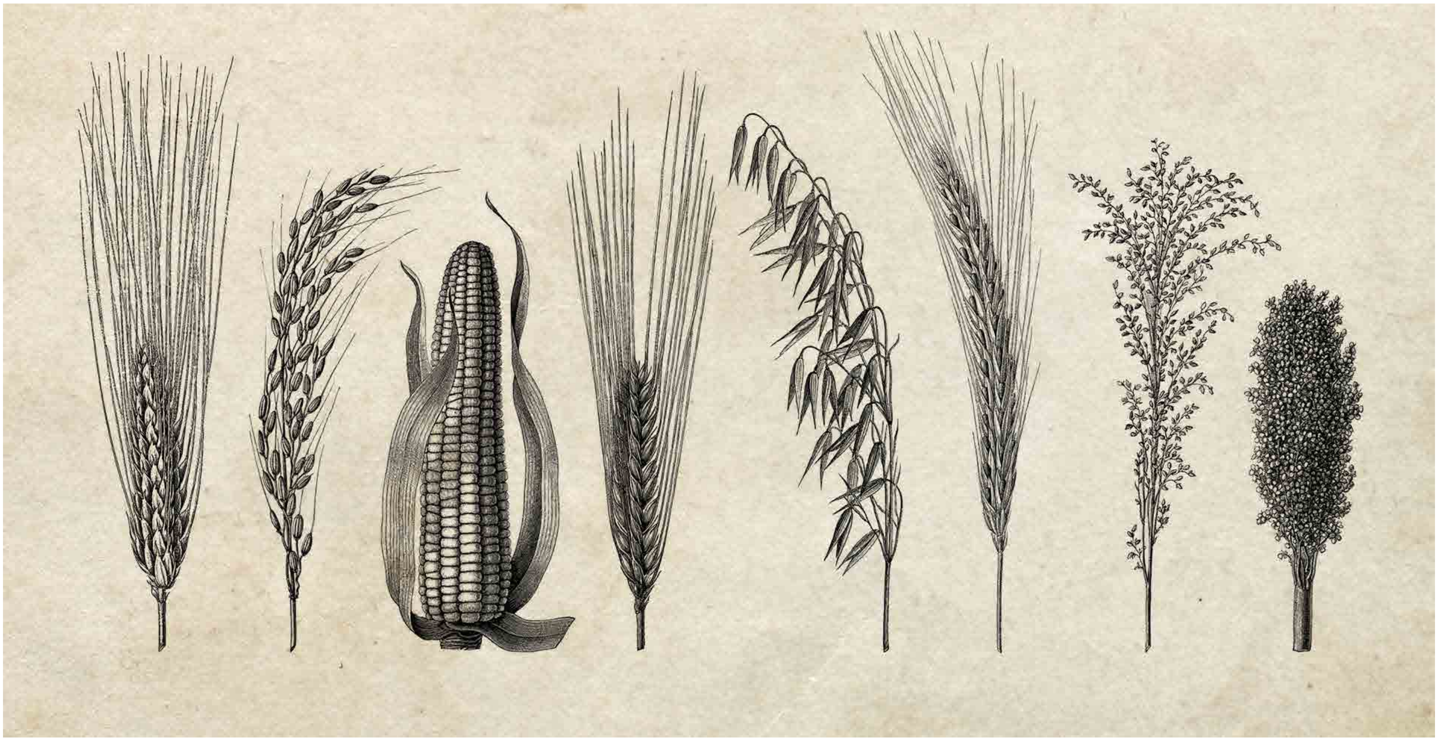
But there's an even simpler method you can use to disinfect water. This technique is known as SODIS, or solar disinfection. Put your suspect water inside an empty plastic bottle , and leave it out in the sunshine. The water is very shallow, so ultraviolet rays can shine through and kill any microbes. A day or two later the water will be safe to drink.

Alongside food and water, fire has been a fundamental part of the modern human lifestyle. Amongst other things, it is used to cook our food -- again, to kill microbes so that we don't get ill.

Solar disinfection of water, seen here in practice in Indonesia

Get growing

As the Grace Period draws to a close, and you've eaten all the canned food left lying around, you're going to have to have worked out how to grow your own crops. And it turns out there is a really deep, fundamental question about everyday life. Why is it that every day of our lives for breakfast we munch a slice of toast or bowl of cereal – we eat wheat, rice, corn, or oats? And not just for breakfast – these are the staple crops for all our meals. Why is it that over 10 000 years ago with the very beginnings of agriculture our ancestors chose to cultivate these crops, rather than the thousands of other plant species in the natural world?



Let them eat grass – a selection of cereal crops.

These are all examples of cereal crops -- the most important group of plant species throughout human history. Wheat, rice, and maize have supported every civilisation across Europe, Asia and the Americas. The fact that cereal crops serve as staples means that throughout the history of civilisation, humanity has supported itself by eating grass. The cereal crops are all fast-growing and nutritious species of grass. We are no different from the cows or goats or sheep that we leave out to pasture.

But humanity has a problem. We didn't evolve with multiple stomachs like a cow to be able to effectively digest that grass, so rather than applying our stomachs to the problem, we've had to apply our intelligence. The two most important inventions for helping us digest grass have been the water wheel and the windmill.

These are ways for harnessing natural energy sources: hydropower and windpower. The crucial part of both of these is the pair of cylindrical slabs of stone -- the mill stones -- that are forced to turn over each other. We put our grain in between them and grind that down into flour. We then take the flour and we bake bread with it, using fire to help break down and release the nutrients. The millstone is like a technological extension of our own molar teeth – it does the same thing as our own bodies but much more effectively -- and the oven that we use for baking bread or the pot we use for boiling rice is like an artificial stomach that we use to help release the nutrients for our bodies.

Save your muscle power – use a windmill.

An instinct for preservation

Growing crops to eat is only the first problem. You then need to preserve that nutrition to stop it decomposing before you're ready to eat it. Humanity has used a variety of strategies. You can dry grain to stop it going mouldy, and a similar trick works well for thin slices of meat. Salting also works well. For fruit you can turn it into jam, with a high sugar concentration, and pickling with high acidity is good for vegetables. In all of these preservation techniques what you're essentially doing is modifying the environment within the food so that bacteria or mould cannot grow, but the nutrients remain for human consumption – by making it too dry or too salty or too acidic for microbial survival. And there's a really interesting reason why we preserve with high acidity (i.e. pickling) but never high alkalinity: alkalis cause any fats in food to turn into soap, which would taste awful.

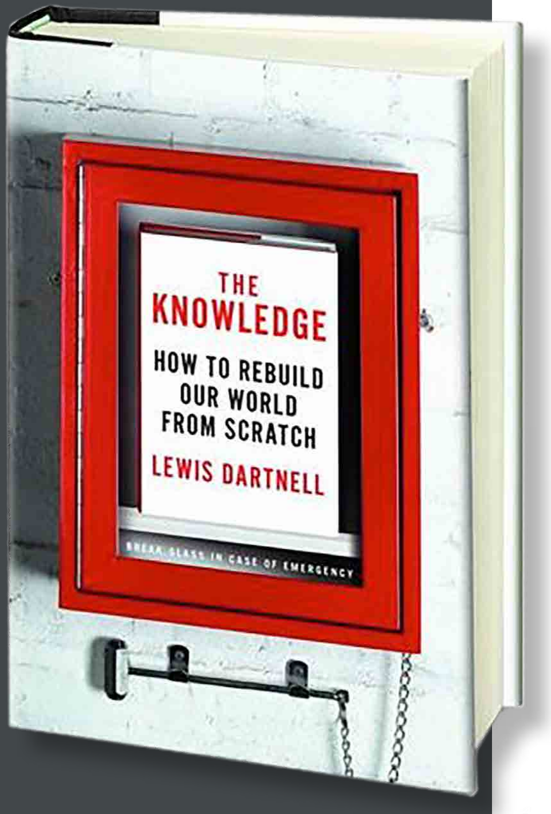
So the next time you bite down into a juicy burger, complete with a wheat-based bun, pickled gherkins and sweet ketchup, think about the thousands-of-years-old technologies that it represents!

Prof. Lewis Dartnell is an astrobiology researcher at University of Westminster, and author of The Knowledge.

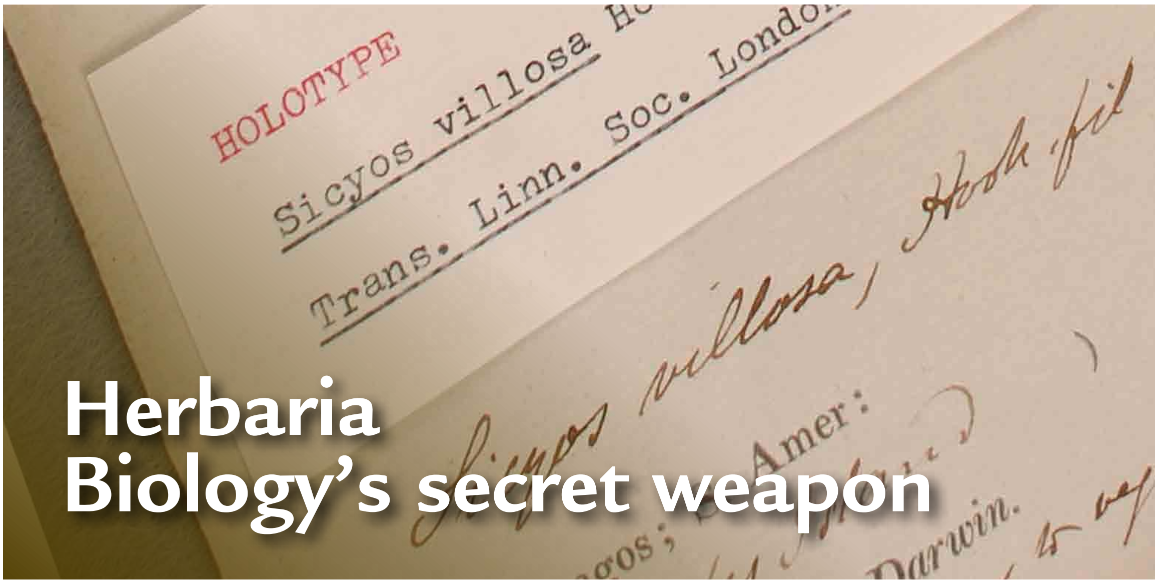
Look here!

Lewis Dartnell is author of *The Knowledge: How to Rebuild our World from Scratch*.

You can explore lots of videos, articles and how-to guides, and buy the book, at *www.the-knowledge.org*



Christine Bartram



Herbaria
Biology's secret weapon

The hidden halls and passageways of more than 3000 herbaria worldwide are home to millions of pressed and dried plant specimens collected over three centuries. The plants, labelled with information and stuck on to sheets of paper, preserve a 300-year biological timeline of plant-life and its global diversity. At Cambridge University Herbarium we even keep the plants collected and dried by Charles Darwin on the Beagle Voyage.

These collections are crucial to science as a physical record of the plants that scientists study, a way of permanently connecting their research with the plants they use in their experiments. Under optimum conditions a herbarium specimen should last for hundreds of years.

Imagine the scene: 1840s Ireland, the entire potato crop has perished. One million men, women and children, reliant on potatoes as their staple food, starve to death. A further million people flee the country. Researchers across Europe, eager to understand why this disaster is happening, press and dry plant material infected with the blight pathogen *Phytophthora infestans* and carefully preserve it on herbarium sheets. They cannot know that their specimens will be used 170 years later...but in 2014 scientists extracted DNA of *Phytophthora infestans* from 39 of those nineteenth-century herbarium samples. Using new developments in DNA sequencing technology, the entire genome of the destructive pathogen was reconstructed from herbarium specimens and a number of current questions about the population biology of the *Phytophthora infestans* pathogen were answered.

On the Beagle voyage (1831-36) Charles Darwin gathered from the Galápagos Islands a number of tomato plants now preserved as herbarium specimens at Cambridge. The tomatoes are tiny, unlike our modern, much-bred, larger fruits. The scientists who extracted *Phytophthora infestans* DNA from herbarium specimens have now turned their expertise to Darwin's preserved tomatoes and will compare their molecular structure with living tomato plant material growing in the same places where Darwin collected his specimens.

The Galápagos tomato, Solanum chessmanii

While on Galápagos, Darwin also collected a single specimen of *Sicyos villosa*. This member of the *Cucurbitaceae* family (which includes squashes and cucumbers) is now extinct. Known only from Darwin's specimen, which comprises just one large leaf and a few seeds, it too is preserved at Cambridge. Some of this plant's close living relatives are also dying out. *Sicyos australis*, for example now only grows on smaller islands around New Zealand where domestic squashes and cucumbers, with the viruses that infect them, have not been introduced. In years to come we may gain more knowledge about the extinction of *Sicyos villosa* by exploring DNA from the single preserved leaf. At the moment this would mean taking a 2cm section from the leaf, a bit sad when it is the very last one of its kind.

Sicyos villosa *collected by Charles Darwin in December 1835 on Charles Island in the Galápagos. When he saw it the plants were abundant and lush. It is now extinct.*

Cambridge scientists currently studying petal spot evolution in populations of the South African Cape Daisy *Gorteria diffusa* have placed specimens of the flowers in the herbarium. Future scientists will be able to see the published results of their work but they can also check out the exact plants used in the experiments by visiting the herbarium and then accurately repeat those experiments. They can also collect even more data on the species from where the previous material was gathered.

A flower of the Cape Daisy, Gorteria diffusa

Climate change

Herbaria are now informing many climate change studies. For example, we know from looking at Cambridge herbarium specimens that some plants flower earlier than they did just 30 years ago. Also at Cambridge there are thousands of plants collected and dried before the Industrial Revolution in 18th century Europe. Study of their stomata in comparison with the stomata of the same species today reveals changes to their numbers, which may be in response to climate change and air pollution.

Herbarium specimens can be used to study the evolution of plant breeding systems and the interactions between plants and insects such as bees. A current PhD project in Prof. Beverley Glover's Cambridge laboratory aims to increase understanding of how plants evolve to improve pollinator activity by investigating the morphology (the structural features) of the anthers of *Solanum*. This large and diverse genus includes commercially important crop plants such as potatoes, aubergines and tomatoes. Anthers from hundreds of herbarium specimens and from living material are measured, DNA sampled, and coated with gold for scanning electron microscopy to see how cell structure may be evolving.

Christine Bartram is Chief Herbarium Technician at Cambridge University Herbarium, The Sainsbury Laboratory.

Look here!

Cambridge is fortunate to have a large university herbarium with over 1 000 000 specimens. But many other universities, gardens and museums, even small museums, have fascinating collections too. To find your nearest see *Index Herbariorum* at *http://sweetgum.nybg.org/science/*ih/ and type in your nearest town and country. Individual entries give addresses, plant specialisms and the name of who to contact. They are great places to visit!

Visitors to the Cambridge Herbarium study plant specimens.

See the back page of this issue of Catalyst for more about how scientists can learn about evolutionary processes by studying Gorteria.

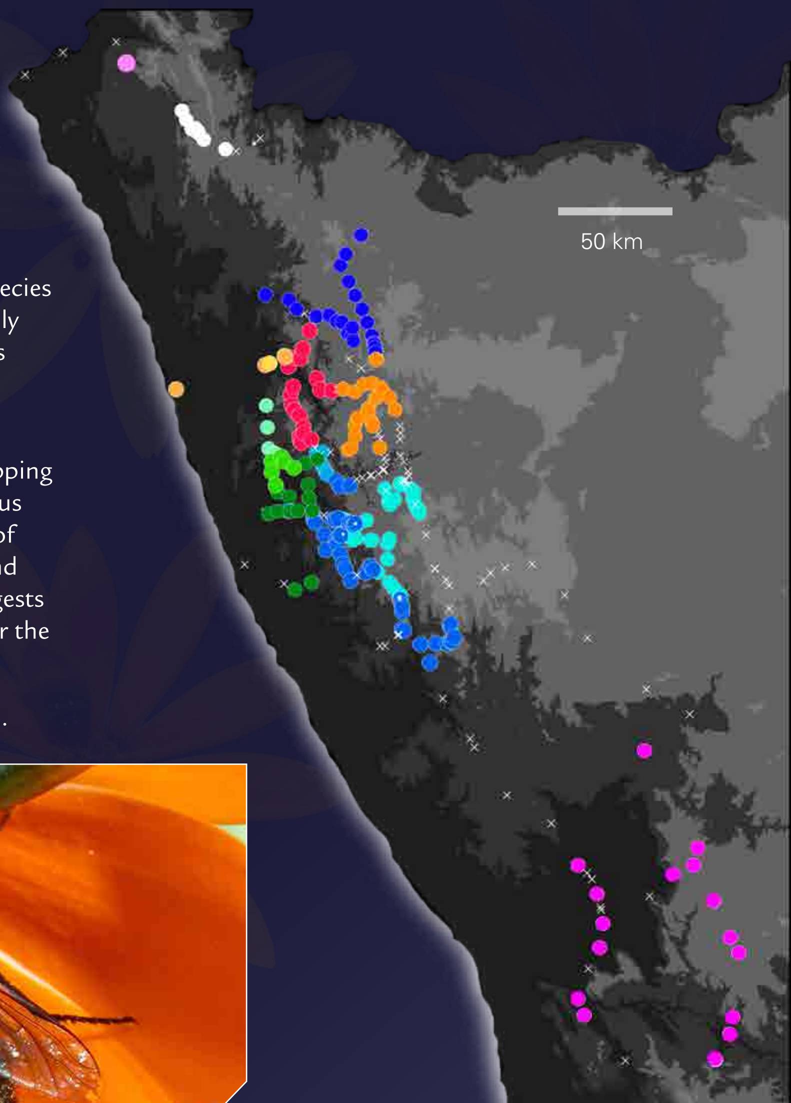
The world's most variable flower

The picture (left) shows variation in Gorteria diffusa, *the South African annual daisy. The flowers attract male bee flies of the species* Megapalpus capensis. *The flies are thought to be attracted to the marks and spots at the base of the petals. Here, they attempt to mate with the spots which they appear to recognise as females. In doing so, the males become covered in pollen. This makes* Gorteria diffusa *the only non-orchid to exhibit sexual deceit pollination.*

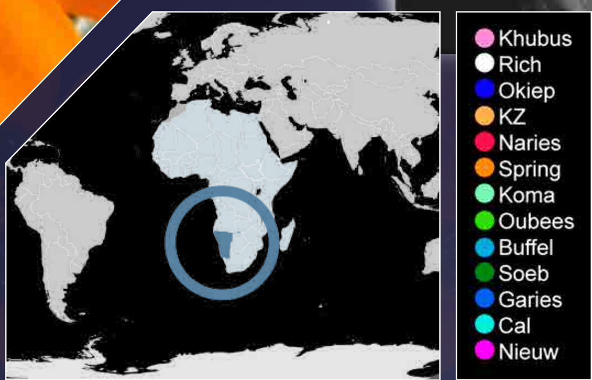
Scientists from the University of KwaZulu-Natal used the species to test the pollinator-shift model, which attempts to partially explain the huge variety of flower types. This model suggests that flower types differ because they are evolving to attract different pollinating insect species.

They found 13 separate flower types which had non-overlapping distributions in the Namaqualand region of South Africa plus one other in a region called the Little Karoo (see map). 11 of these variants were studied and in every case they were found to be visited by the fly *Megapalpus capensis*. This strongly suggests that the pollinator-shift model is not a good explanation for the existence of these many types.

Studies continue into the cause of this remarkable variation.



A male bee fly hopes to mate with a female; instead, it becomes covered in pollen.



Main illustration and map from The evolution of floral variation without pollinator shifts in *Gorteria diffusa*, Allan G. Ellis and Steven D. Johnson, American Journal of Botany 96(4): 793–801. 2009.