



Science in School

The European journal for science teachers



Design inspiration The secrets of shark skin

INSPIRE
Supporting
African science:
the role of fruit flies

TEACH
A particle accelerator
in your salad bowl





SUPPORTING AFRICAN SCIENCE: THE ROLE OF FRUIT FLIES 35

Not only is the fruit fly a valuable model organism, but it is also helping to put Africa on the scientific world map.



HOW DO BIRDS FLY? A HANDS-ON DEMONSTRATION 38

Dissect a chicken from the supermarket to discover the unusual pulley system that enables birds to fly.



DESIGN INSPIRATION: THE SECRETS OF SHARK SKIN 19

Shark skin is adapted for energy-efficient swimming in remarkable ways, some of which are now being copied by designers and engineers.



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CELLULOSE: FROM TREES TO TREATS

The same molecule that keeps mighty trees standing also led to the first multicellular life forms – and can even be used to make sweet treats.

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EDITORIAL

Hannah Voak
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The new academic year is in full swing. You have welcomed back your students and familiarised yourself with new faces. Now we would like to welcome you back with this issue of *Science in School* – and to say hello to new subscribers who have joined us over the summer.

It was a pleasure to meet both our new and long-standing readers and contributors at the international Science on Stage festival at the end of June, when teachers from all over the world came together to exchange ideas about science teaching. Your enthusiasm and innovation was incredibly motivating, and highlighted the importance of us helping you to share ideas with your peers across Europe.

In this issue, we take a closer look at the natural world. Below the waves, we discover the secrets of shark skin and how it is inspiring new technologies, including a swimsuit (page 19). On land, we consider Earth's most abundant large molecule, cellulose (page 8). And in the air, we answer the simple question 'how do birds fly?' with a hands-on dissection of a chicken (page 38).

On a smaller scale, we investigate the element molybdenum (page 30). Essential for living organisms, it is also thought to have been crucial to the 'last universal common ancestor' – taking us back billions of years to the earliest stage of evolution. To watch evolution more directly, we explore a unique experiment that has tracked the changes in *E. coli* over 67 000 generations – the equivalent of some one million years in human reproduction (page 24).

Much as monitoring populations of microbes can tell us about the evolution of other species, the tiny fruit fly can help answer fundamental questions about animal development. For researcher Isabel Palacios, however, this valuable model organism is key to connecting researchers in Africa to the rest of the global scientific community (page 35).

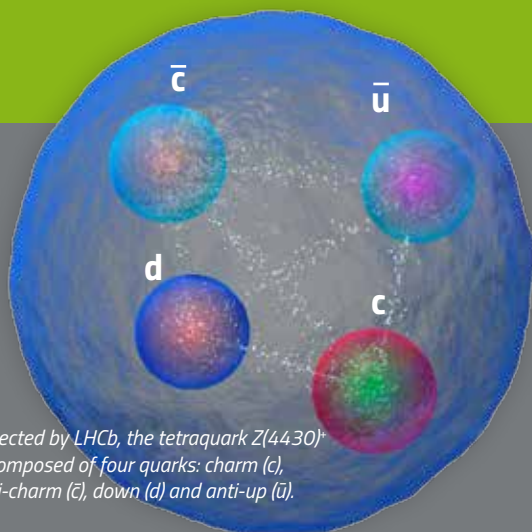
In the broadest sense, the natural world encompasses our entire Universe. So why not calculate the distance between Earth and the Moon using radio signals (page 44), build your own particle accelerator (page 49) or learn about the ripples in space-time caused by gravitational waves (page 13)?

Finally, we wish you all the best for the year ahead, and look forward to hearing how you use these articles in your lessons. Send us an e-mail to tell us (editor@scienceinschool.org) – we always welcome your feedback.

Hannah Voak

Interested in submitting
your own article? See:
www.scienceinschool.org/submit-article

Exotic particles, fusion-device ashtrays and lunar missions



Detected by LHCb, the tetraquark $Z(4430)^0$ is composed of four quarks: charm (c), anti-charm (\bar{c}), down (d) and anti-up (\bar{u}).

CERN Exotic quark arrangements



One of the four experiments in CERN's Large Hadron Collider is LHCb, set up to help us understand what happened in the immediate aftermath of the Big Bang – what are the slight differences between matter and antimatter, and how did the matter in our Universe escape annihilation? LHCb does this by studying a type of particle called the beauty quark and its antimatter counterpart, the anti-beauty quark. LHCb's detectors also enable scientists to search for rare and unstable combinations of quarks.

The Standard Model of particle physics describes quarks being bound together by the strong interaction to form hadrons: either quark-antiquark pairs or three quarks. The strong interaction is transmitted from one quark to another via messenger particles known as gluons, and is predicted to be so strong as to prevent quarks existing in an unbound state. Since 2014, however, LHCb has observed particles with four quarks (tetraquarks) and even five quarks (pentaquarks), known as exotic particles. Furthermore, under conditions of extremely high energy, quarks and gluons have in fact been shown to exist freely in a plasma. By investigating both the plasma and exotic particles with LHCb, scientists hope to shed light on the nature of the strong interaction and the processes by which matter interacts.

To learn more about LHCb, see:

Landua R (2008) The LHC: a look inside. *Science in School* **10**: 34-45. www.scienceinschool.org/2008/issue10/lhchow

Based in Geneva, Switzerland, CERN is the world's largest particle physics laboratory. See: www.cern.ch

EMBL New site in Barcelona



At a ceremony in Barcelona on 10 April 2017, the European Molecular Biology Laboratory (EMBL) and the Spanish government signed an agreement for a new EMBL site to be hosted in the city. EMBL Barcelona will be located on the campus of the Barcelona Biomedical Research Park, and researchers at the site will explore how tissues and organs function and develop, and how preventing failures in those processes may help to tackle disease. Alongside cutting-edge research, the site will house state-of-the-art imaging facilities, making pioneering technologies available to scientists worldwide.

Scientists at EMBL Barcelona will tackle key challenges around human health. Many health issues, such as cancer, diseases of the immune system and birth defects, involve flaws in how cells arrange themselves and interact at the tissue level. Research in tissue biology raises the exciting prospect of being able to make, control and heal tissues and organs – approaches that could provide new means of treating such conditions.

For more information, visit the EMBL news website. See:

<https://news.embl.de> or use the direct link: <http://tinyurl.com/yb8vuj3m>

EMBL is Europe's leading laboratory for basic research in molecular biology, with its headquarters in Heidelberg, Germany. See: www.embl.org



The internal structure of a mouse pancreas, imaged with a selective plane illumination microscope like those that will be used at EMBL Barcelona.

Science in School is published by EIROforum, a collaboration between eight of Europe's largest inter-governmental scientific research organisations (EIROs). This article reviews some of the latest news from the EIROs.

ESA Robotic lunar missions to prepare future human exploration



Image courtesy of ESA

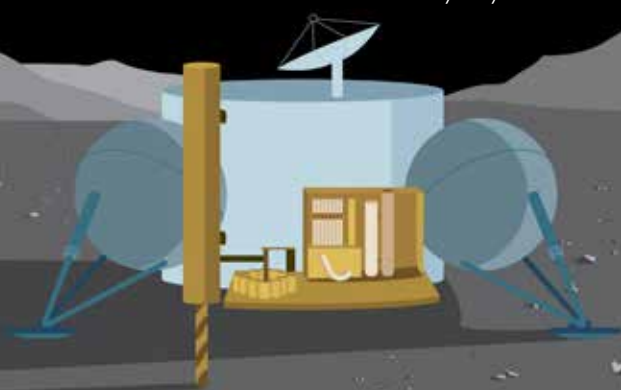
Our understanding of the Moon and its scientific importance has been transformed recently by new missions and new analyses of samples from the Apollo missions that took place between 1963 and 1972. Now the European Space Agency (ESA) is working with Russia to send robotic missions to the lunar surface in preparation for the next phase of human space exploration, which will see humans venture back to the Moon.

The availability of resources on the Moon is fundamental for humans to survive there and will be a focus of the Russian-led robotic missions. Luna-27, the main mission of the ESA-Russia cooperation, will land near the Moon's South Pole and search for frozen water and other potential resources. If there is enough water, it could become a source of oxygen and hydrogen to support life and provide rocket fuel to take us further into the Solar System.

ESA will provide a precision landing system for the Russian Luna-27 lander and a system to drill the lunar soil, take samples and analyse them to establish their potential as future resources. ESA will also provide communications and navigation support for all the missions using their ground-station network, supporting the landing and operations of both European and Russian scientific instruments.

ESA is Europe's gateway to space, with its headquarters in Paris, France. See: www.esa.int

Illustration of lunar soil drilling and sample analysis system



ESO The biggest eye on the sky



Artist's rendering of the ELT in operation

Image courtesy of ESO

The European Southern Observatory (ESO) is building the world's biggest eye on the sky – the Extremely Large Telescope (ELT) – with a gigantic main mirror of 39 metres diameter. The ELT is being built on the Cerro Armazones mountain in the Atacama Desert of Chile, where astronomers benefit from skies that are clear, dry and free of light pollution. Construction work has started on the huge dome, which will enclose the telescope, and contracts are being issued to several industrial partners for the production of sensors and actuators.

The ELT is a truly international project. So far, an Italian firm is responsible for building the dome; German and French companies are manufacturing some of the mirrors that the telescope will use; and institutions from all over Europe are designing the spectrographs and cameras that will help astronomers uncover more about our wonderful Universe.

Visit the ESO website for more information. See: www.eso.org/public/unitedkingdom/news/eso1716/ or use the direct link <http://tinyurl.com/yd43zf7j>

ESO is the foremost intergovernmental astronomy organisation in Europe and the world's most productive ground-based astronomical observatory, with its headquarters in Garching, near Munich in Germany, and its telescopes in Chile. To learn more about ESO, see: www.eso.org



Four new beamlines will be built and commissioned from 2018 to 2022.

Image courtesy of ESRF / S Candé

ESRF

Four new beamlines approved, opening new frontiers in X-ray science



Last June, the European Synchrotron Radiation Facility (ESRF) council gave the green light for the construction and commissioning of four new beamlines between 2018 and 2022. The beamlines, where the X-ray beam from the synchrotron is carried to the experimental end station, are designed to exploit the enhanced performance of the Extremely Brilliant Source (EBS), a project that was launched in 2015 to build a new storage ring in the existing synchrotron tunnel.

The 67th meeting of the ESRF council was held in Lund, Sweden, on 27 June 2017 and brought together

representatives from ESRF's 22 partner nations. The four new beamlines will underpin research addressing the major challenges facing our society, including:

- Defining the next generation of biomaterials and new sustainable materials
- Developing new drugs
- Unravelling the complex mechanisms of living organisms
- Reconstructing historical artefacts and fossils in 3D.

Situated in Grenoble, France, ESRF operates the most powerful synchrotron radiation source in Europe. See: www.esrf.eu

EUROfusion

Selecting the perfect ashtray for fusion



Did you know that fusion devices such as tokamaks and stellarators have ashtrays? These ashtrays, known as divertors, collect the waste from fusion experiments – helium ash – and are crucial for successful fusion operations.

In fusion experiments, plasma (in which the fusion reaction occurs) reaches 150 million °C, and deuterium isotopes ('heavy hydrogen') fuse to form helium and release energy. But the process causes helium to react with solids and produces helium ash, which can interfere with the experiments. To avoid this, the divertor redirects waste particles out of the plasma with the help of magnetic field lines.

While it sounds simple, a good divertor is actually extremely complex to design and produce, because it needs to operate inside the fusion device at temperatures ten times hotter than the Sun. In 2016, a group of experts from EUROfusion evaluated ten different divertor concepts that could be used

Image courtesy of EUROfusion



An internal view of the reaction vessel of the Joint European Torus (JET)

in future fusion experiments. After a year-long evaluation process, six concepts from across Europe have been selected. And these, the fusion experts say, provide a solid foundation for improving divertor designs in future fusion experiments.

For more information, visit the EUROfusion website. See: www.euro-fusion.org/2017/05/six-exhaust-systems-make-the-cut/ or use the direct link <http://tinyurl.com/y9rq7nxj>

EUROfusion manages and funds European fusion research activities, with the aim to realise fusion electricity by 2050. The consortium comprises 30 members from 26 European Union countries as well as Switzerland and Ukraine. See: www.euro-fusion.org

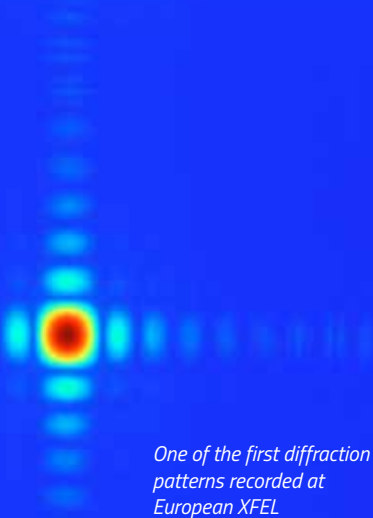
European XFEL Operation begins



Over the summer, European XFEL – the world’s biggest X-ray laser – entered its operation phase. The facility, which began commissioning in October 2016, produced its first X-ray light in May and went into official operation in July. After several months of continuing to build infrastructure and install instruments, the X-ray laser is now ready for its first users.

On 1 September, science ministers of the member states joined other guests from politics, the diplomatic corps and academia to officially open the facility. The first instruments available for experiments are the ultrafast chemistry-oriented FXE instrument and the SPB/SFX instrument oriented towards structural biology. A panel of international experts selected the first experiments over the summer. The other four instruments at the facility are still under assembly.

European XFEL is a research facility currently under construction in the Hamburg area in Germany. Its extremely intense X-ray flashes will be used by researchers from all over the world. See: www.xfel.eu



One of the first diffraction patterns recorded at European XFEL



EIROforum combines the resources, facilities and expertise of its member organisations to support European science in reaching its full potential.

To learn more, see: www.eiroforum.org

For a list of EIROforum-related articles in Science in School, see: www.scienceinschool.org/eiroforum

To browse the other EIRO news articles, see: www.scienceinschool.org/eironews

ILL Neutrons supporting the fight against diabetes



Image courtesy of ILL / M. Burat

Medical research at ILL is determining the biological mechanisms underpinning various chronic conditions.

Health is a leading area in which the impact of neutron science and technology has high visibility, with neutrons providing a very effective analytical tool for investigating the properties of matter at both the atomic and molecular scales. The use of neutron scattering methods in medical research at the Institute Laue-Langevin (ILL) has significantly progressed our knowledge of the biological mechanisms underpinning various chronic conditions, including diabetes. Ultimately, this research has the potential to improve both quality of life and life expectancy.

A key consequence of type 2 diabetes is the death of pancreatic insulin β -cells, the cells responsible for producing the hormone insulin, which regulates glucose levels in the body. The production of islet amyloid polypeptide (IAPP), a hormone secreted by β -cells, increases substantially during the development of type 2 diabetes. Small-angle neutron scattering experiments at ILL are enhancing our knowledge of how IAPP works, and recent observations have led to a new hypothesis about the interaction between IAPP and cell membranes. Further investigations into the role of IAPP in type 2 diabetes will help to develop drugs that are better tailored to tackle β -cell depletion in the pancreas.

For more details, read the full press release on the ILL website. See: www.ill.eu/press-and-news/press-room/press-releases or use the direct link: <http://tinyurl.com/ycxno9k7>

Based in Grenoble, France, ILL is an international research centre at the leading edge of neutron science and technology. See: www.ill.eu



Cellulose: from trees to treats

The same molecule that keeps mighty trees standing also led to the first multicellular life forms – and can even be used to make sweet treats.

By Ute Römling

What is the most abundant large molecule on Earth? Perhaps a synthetic polymer? In fact, we are most likely to come across this molecule in the natural world – walking through a forest, for example. That's because the molecule is cellulose – the substance produced by plants for structural support.

Earth's plants produce at least 100 billion (10^{11}) tonnes of cellulose each year – hundreds of times greater than the amount of plastics produced in the same time. As well as being hugely abundant, the cellulose produced by plants is extremely useful. You might be reading this article printed on a piece of cellulose-based paper, for example, and we dress in T-shirts and jeans made of cotton, another example of cellulose. Our furniture at home consists mostly of wood, which itself is mostly cellulose; some of us even live in wooden houses. Many people also use wood as an energy source to heat their homes,

“You might be reading this article printed on a piece of cellulose-based paper.”

perhaps due to the timeless appeal of a real fire. And as a biofuel, wood is a key renewable energy resource.

What is cellulose?

Despite its giant molecular size, cellulose is a surprisingly simple molecule: it is built up solely from molecules of the sugar glucose. Sometimes several thousand glucose molecules make up a single macromolecule (giant molecule) of cellulose. Glucose itself is made



- ✓ Biology
- ✓ Biochemistry
- ✓ Biomolecules
- ✓ Microbiology
- ✓ Food technology
- ✓ Ages 14–19

REVIEW

This article would make excellent background reading, and could be linked to a lesson on the structure and function of biomolecules. The fact that cellulose is produced not just in plant cell walls but also by some bacteria could provoke some discussion and/or research on biofilms, and also on the nature of bacterial virulence. Students could be tasked with researching uses of bacterial cellulose, e.g. for medical use and in foods, and presenting the information to the remainder of the class, or as a small homework project. In addition, some comprehension questions could be set, such as:

- How is cellulose important in tunicates?
- What is the role of cellulose in bacteria that live in saline springs?
- Describe and explain the role of a biofilm.
- What is meant by the term ‘virulence’?

Dr Shelley Goodman, teacher of applied science, UK

Wood is made up mainly of cellulose, the world's most abundant molecule.

by plants from carbon dioxide and sunlight, via the process of photosynthesis.

A cellulose macromolecule consists of a bundle of individual glucan chains. Each glucan chain is made up of cellobiose molecules, which consist of two linked glucose molecules (figure 1). The linear glucan chains associate with each other through hydrogen bonds, and the large number of these weak linkages gives cellulose its special properties. For example, they help cellulose to exclude water, and thus retain its structural properties even in wet conditions. In addition, they make the molecule resistant to chemical attack by acids and alkalis (Ross et al., 1991).

Cellulose: not just a plant thing

These useful properties mean that cellulose is found elsewhere in the living world, not just in plants. Some

fungi have a cell wall made of cellulose (although in most fungi, this wall is made from chitin, another abundant macromolecule). Algae, some amoeba and even some invertebrate animals (mostly marine invertebrates known as tunicates) also produce cellulose. In sea squirts, for example, cellulose helps the larvae to metamorphose into adults and is also part of the ‘tunic’, a kind of exoskeleton. In social amoeba, these single-celled life forms build up to become multicellular, mushroom-like organisms when nutrients are scarce, with cellulose used in the stalk and spores.

Perhaps surprisingly, some bacteria can also produce cellulose (Ross et al., 1991; Zogaj et al., 2001). Genome sequencing has revealed that this ability is present in a wide range of bacterial species, from the evolutionarily ancient thermophilic bacteria to those that associate with plants or colonise our gastrointestinal

tract (Römling & Galperin, 2015). This last group includes two well-known gastrointestinal bugs, *E. coli* and salmonella (*Escherichia coli*, *Salmonella typhimurium*).

So why do bacteria need to produce cellulose? This molecule, which is so strongly associated with rigid structural properties in plants, helps bacteria to adapt to a surprisingly wide range of specialised environments. Cellulose helps bacteria that live in association with plants to attach to the plant’s surfaces – and in the case of pathogenic bacteria, to bind tightly to host cells and cause disease. Some bacteria living in saline springs (including thermophilic species and cyanobacteria) produce cellulose that seems to protect the bacterial cells from desiccation and other environmental threats such as ultraviolet light and even disinfectants.

“Cyanobacteria may well have been the origin of plants’ ability to produce cellulose.”

Cyanobacteria, in fact, may well have been the origin of plants’ ability to produce cellulose. Through evolution, these bacteria became incorporated within plant cells as chloroplasts, bringing with them the genetic information needed to produce cellulose; these genes are now found in the genome of plants (Nobles et al., 2001). But how did this happen? The endosymbiotic theory suggests that, about one billion (10⁹) years ago, free-living photosynthetic cyanobacteria were captured by the ancestors of today’s algae, providing a tremendous advantage to the new combined organisms, which evolved and diversified to form the many photosynthetic species of plants and algae. This theory is supported by the fact that, although today’s chloroplasts

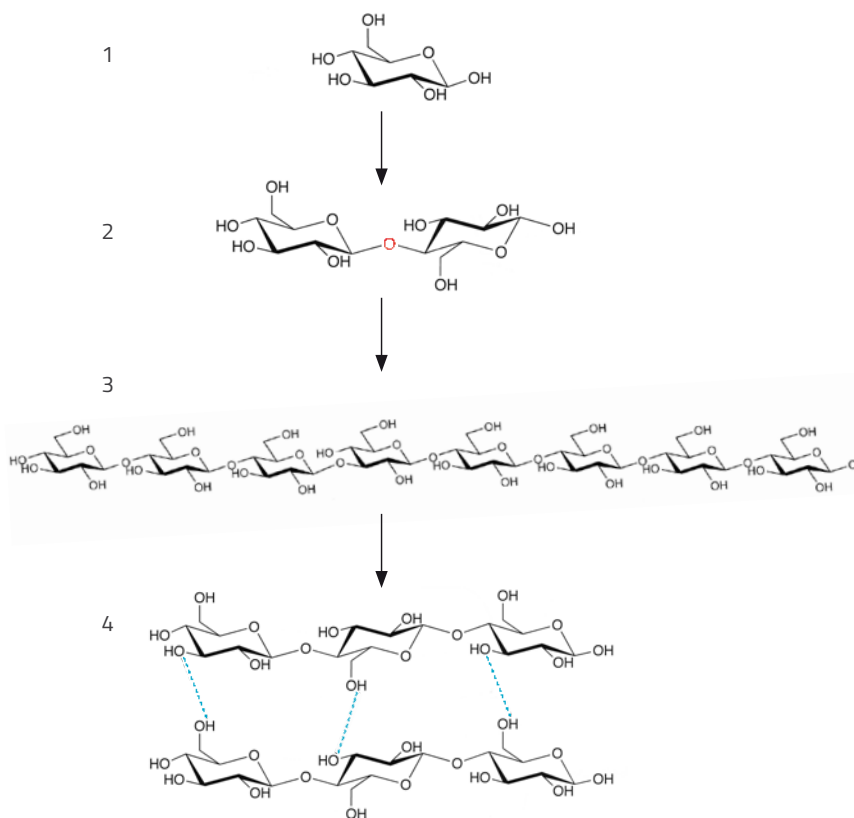


Figure 1: The chemical structure of cellulose, which is built up from molecules of glucose. 1: glucose molecule; 2: cellobiose (two glucose molecules linked by oxygen, shown in red); 3: glucan chain; 4: part of a cellulose macromolecule showing hydrogen bonds (in blue) linking the glucan chains. (Adapted from worthington-biochem.com, megazyme.com)

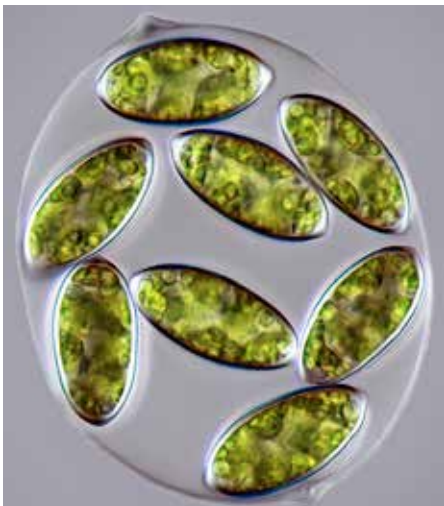
Image courtesy of Stefan Siebert Photography

The sea squirt Ciona intestinalis, which has an exoskeleton that contains cellulose



Image courtesy of Rogelino Moreno / Flickr

The gastrointestinal pathogen Salmonella typhimurium produces cellulose biofilms as an extracellular matrix.



Cellulose is found in the cell wall of the unicellular algae Oocystis solitaria.

have lost most of their original genes, the ancestor gene for cellulose synthase (the enzyme needed to make cellulose) has been transferred to the plant genome and still shows a striking similarity to its counterparts in modern cyanobacteria.

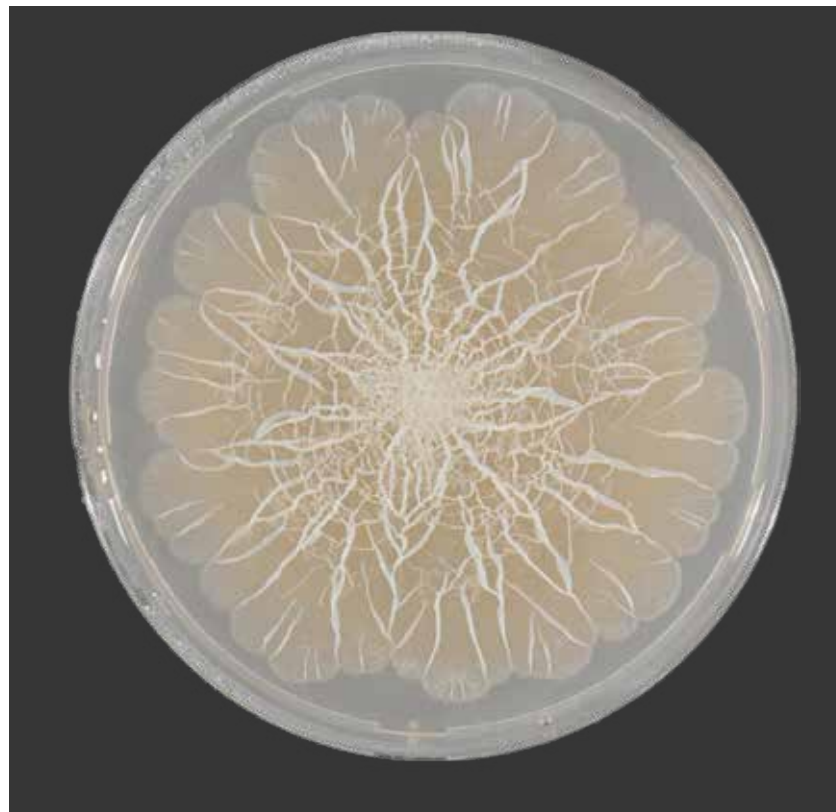


Image courtesy of U Römling

Biofilms: making connections

One of the main reasons that bacteria make cellulose is to produce 'biofilms' – cellulose films that form a matrix outside bacterial cells and help their multicellular communities to stick together. These bacterial communities were the earliest form of multicellular life on Earth, dating back to around 3.1 billion years ago. Today, there are many

micro-organisms that show a similar multicellular lifestyle, which functions remarkably like tissue formation in higher organisms and is thought to make more efficient use of nutrients.

Cellulose films can also help bacteria to interact with higher organisms such as fungi, plants and animals. When highly pathogenic bacteria infect an organism, biofilms provide a mechanism for

the bacteria to control the virulence (severity) of the infection. In chronic infections, however, when the bacteria deregulate their biofilm matrix, there is low degree of virulence, allowing the host and bacteria to continue to coexist (Pontes et al., 2015; Ahmad et al., 2016).

Bacterial cellulose: a future supermaterial?

Bacterial cellulose has some very special features that make it different from plant cellulose, and these are only just beginning to be explored. Here are some of them: it is especially pure; it has a high surface area and water retention capacity; and it is a natural nanomaterial. Bacterial cellulose has considerable promise in terms of its economic value, and some bacterial cellulose products are already being produced commercially. For example:

- ‘Nata de coco’ is a popular, low-calorie sweet from the Philippines. It is made almost completely from bacterial cellulose produced by fermenting coconut milk.
- Kombucha tea, a traditional Asian fermented tea drink, is made using a pellet of bacterial cellulose with a variety of bacteria and yeast strains embedded in it. Promoted as a health drink, it is becoming popular worldwide.
- In medicine, bacterial cellulose is used as a wound dressing, particularly for chronic wounds, because it is mechanically strong and can retain water. As it is also biodegradable and biocompatible, bacterial cellulose has many other potential medical uses: in drug delivery, for example, or in rebuilding damaged tissue, where it can provide a biodegradable, non-immunogenic ‘scaffold’ that living cells adhere to.

This ancient natural material could be well on its way to becoming a supermaterial of the future – revealing another way in which bacteria can help, rather than harm, us.

Image courtesy of Römling & Galperin (2015)



Fermented kombucha tea, which is becoming popular, is made using a pellet of bacterial cellulose.

- Römling U, Galperin MY (2015) Bacterial cellulose biosynthesis: diversity of operons, subunits, products, and functions. *Trends in Microbiology* **23(9)**: 545-557. doi: 10.1016/j.tim.2015.05.005
- Ross, P, Mayer R, Benziman M (1991) Cellulose biosynthesis and function in bacteria. *Microbiological Reviews* **55**: 35-58
- Zogaj X et al. (2001) The multicellular morphotypes of *Salmonella typhimurium* and *Escherichia coli* produces cellulose as the second component of the extracellular matrix. *Molecular Microbiology* **39**:1452-1463

Resources

- Find out about starch, another macromolecule built up from glucose molecules:
- Cornuéjols D (2010) Starch: a structural mystery. *Science in School* **14**: 22-27. www.scienceinschool.org/2010/issue14/starch

References

- Ahmad I et al. (2016) BcsZ inhibits biofilm phenotypes and promotes virulence by blocking cellulose production in *Salmonella enterica* serovar Typhimurium. *Microbial Cell Factories* **15**: 177. doi: 10.1186/s12934-016-0576-6
- Nobles DR, Romanovicz DK, Brown RM Jr. (2001) Cellulose in cyanobacteria. Origin of vascular plant cellulose synthase? *Plant Physiology* **127**: 529-542
- Pontes MH et al. (2015) Salmonella promotes virulence by repressing cellulose production. *Proceedings of the National Academy of Sciences of the United States of America* **112**: 5183-5188. doi: 10.1073/pnas.1500989112

Dr Ute Römling is professor of medical microbial physiology at the Karolinska Institutet in Stockholm, Sweden. She studied biochemistry at the Technical University of Hannover, Germany, but considers herself to be a self-educated microbiologist. She has been involved in science education throughout her professional career.



Image courtesy of Midori / Wikimedia Commons



Cubes of nata de coco (made from bacterial cellulose), served with fruit

Illustration showing a LISA satellite, part of a future gravitational wave detection system to be sited in space.

Image courtesy of AEI / MMI / exozet

Gravitational waves: a taxonomy

Gravitational waves were predicted by Einstein – but where do they come from, and what different types might there be out in the cosmos?

By Nicolas Arnaud

The scale of gravitational waves is tiny and huge at the same time. While the ripples they cause are so slight as to be almost undetectable, their wavelengths can be vast: much, much larger than the more familiar electromagnetic waves – ranging from radio waves to X-rays – used by astronomers to view space.

So what are gravitational waves? These ripples in space-time are produced whenever any mass accelerates. However, gravitational waves from sources on Earth are unlikely ever to be detectable, because objects on Earth are simply not massive enough or do not accelerate fast enough. Instead, we have to look for signals coming from sources in the cosmos, where masses and movements are on the astronomical scale. Recently, detecting gravitational waves produced by massive celestial objects has finally become possible, so they can

potentially be used as an extra tool for observing events and objects in space – an exciting prospect for today's astronomers.

The gravitational wave spectrum

Like electromagnetic waves, gravitational waves travel at the speed of light. And like the electromagnetic spectrum, the gravitational wave spectrum is extremely broad, with the different parts classified according to frequency. In general, gravitational wave frequencies are much lower than those of the electromagnetic spectrum (a few thousand hertz at most, compared to some 10^{16} to 10^{19} Hz for X-rays). Consequently, they have much larger wavelengths – ranging from hundreds of kilometres to potentially the span of the Universe.

The frequency range of a gravitational wave signal provides information about its source: the lower the frequency, the larger the mass involved. It also tells scientists which type of detector to use to look for which source, as the detector size should be comparable to the wavelength of the signal. Figure 1 shows the full range of gravitational waves, with the sources that produce them and the different frequency ranges in which detection can take place.

Giant Earth-based interferometers like LIGO (laser interferometer gravitational-wave observatory) and Virgo (featured in Arnaud, 2017) are designed to detect gravitational waves at the top end of the frequency range, from a few tens of hertz to a few kilohertz. In addition, the LISA^{w1} (laser interferometer space antenna) project – a group of space interferometers – is planned for launch in about a decade. Using similar design principles to terrestrial detectors, LISA will cover gravitational wave frequencies in a lower range (1–10⁻⁵ Hz). Low-frequency gravitational waves would affect the precise regularity of the electromagnetic wave flashes detected



REVIEW

- ✓ Physics
- ✓ Astrophysics
- ✓ Objects in space
- ✓ Gravity
- ✓ Relativity
- ✓ Ages 16–19

After the recent exciting detection of a third gravitational wave, this article gives an excellent overview of what gravitational waves are, how they are generated in space, and how gravitational detectors work. It is a very nice and topical article, at just the right time.

Comprehension questions on this topic could include:

- What are gravitational waves?
- Why is it so difficult to detect gravitational waves?
- How do gravitational wave detectors work?
- Describe the gravitational spectrum, and discuss how it differs from the electromagnetic spectrum.
- Which space objects trigger gravitational waves? Describe these objects.
- For gravitational wave detection, a minimum of two detectors must be used. Why?
- There are a several detectors on Earth. What are their names and where are they located?

Gerd Vogt, physics teacher, Higher Secondary School for Environment and Economics, Austria

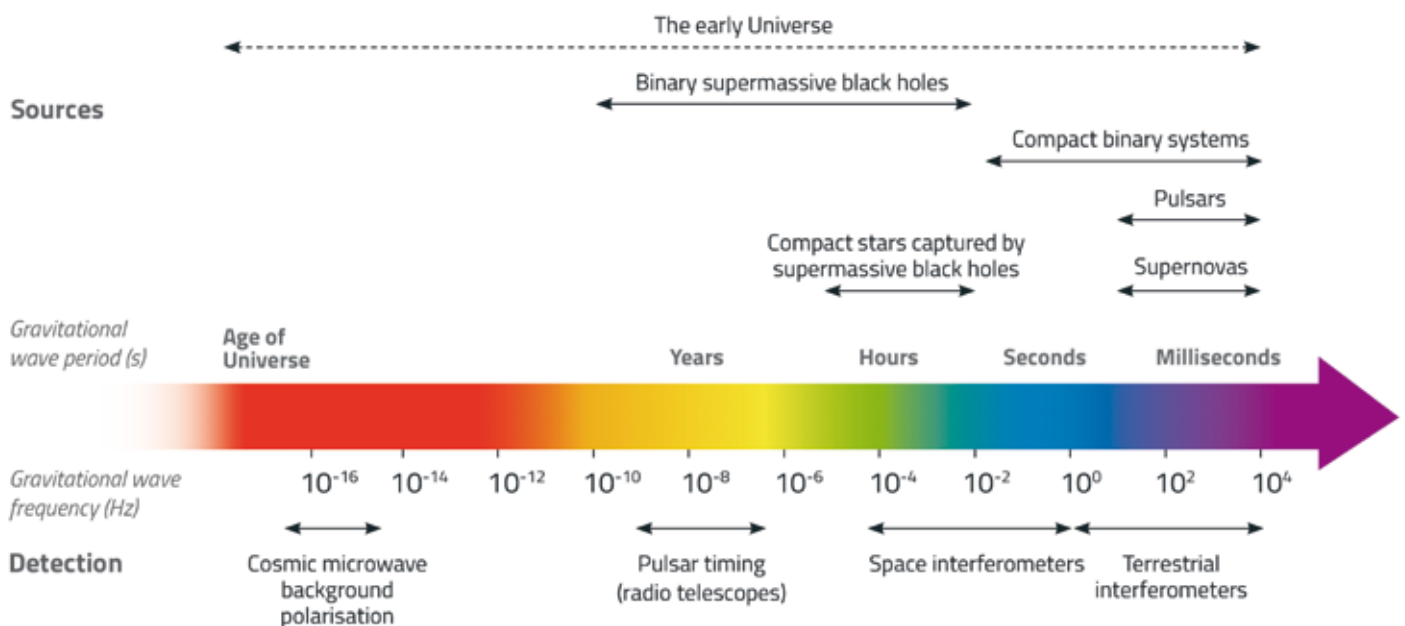


Figure 1: The gravitational wave spectrum. The horizontal axis shows the frequency (and the wave period, which is the inverse of frequency) on a logarithmic scale, with the colours representing the corresponding wavelengths (red = longer; blue = shorter). The detectors shown are those existing or planned, while the sources are those known to exist and expected to produce detectable gravitational waves. (Adapted from: <https://lisa.nasa.gov>)

“Gravitational waves have wavelengths ranging from hundreds of kilometres to potentially the span of the Universe.”

from pulsars, providing another means of detection, this time in the range of 10^{-6} – 10^{-9} Hz. Finally, gravitational waves emitted in the early Universe could have left a faint imprint on the cosmic microwave background. This signal is being sought, for example by

the Planck satellite, in the gravitational wave frequency range of 10^{-15} – 10^{-17} Hz. The wavelengths associated with these extremely low frequencies would be on the scale of the Universe itself.

Sources of gravitational waves

Among the diversity of gravitational wave sources, let's briefly look at three sources that produce waves with frequencies in the range accessible to terrestrial detectors.

Supernovas

When a giant red star runs out of its nuclear fuel, the balance between the

nuclear reactions (which pushes matter apart) and gravity (which pulls matter together) is destroyed. The star collapses until it reaches the density of nuclear matter (about 10^{17} kg/m³), which triggers a shockwave that ejects the external layers of the star. This phenomenon, called a type-II supernova, produces a strong burst of neutrinos plus an emission of light that can last for days. A burst of gravitational waves is also emitted, but these would only be detectable if the supernova event occurred within our own galaxy or very nearby. Such events are very rare (a few per century) but they do happen: supernova 1987A was observed 30 years ago.

Image courtesy of ALMA (ESO / NAOJ / NRAO) / Alexandria Angelich (NRAO/AU/NSF)

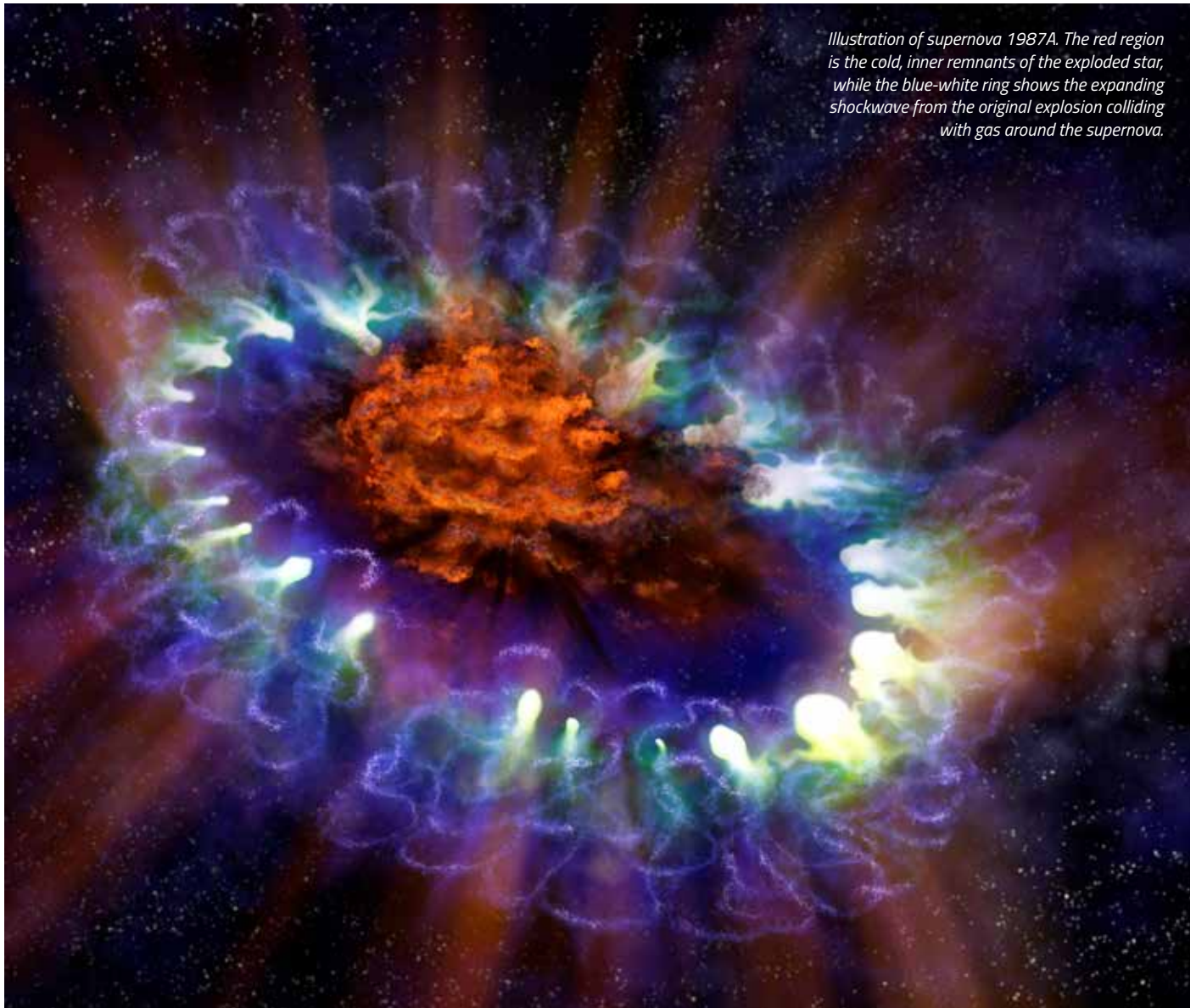


Illustration of supernova 1987A. The red region is the cold, inner remnants of the exploded star, while the blue-white ring shows the expanding shockwave from the original explosion colliding with gas around the supernova.

Image courtesy of LIGO, NSF, Aurore Simonnet (Sonoma State University)

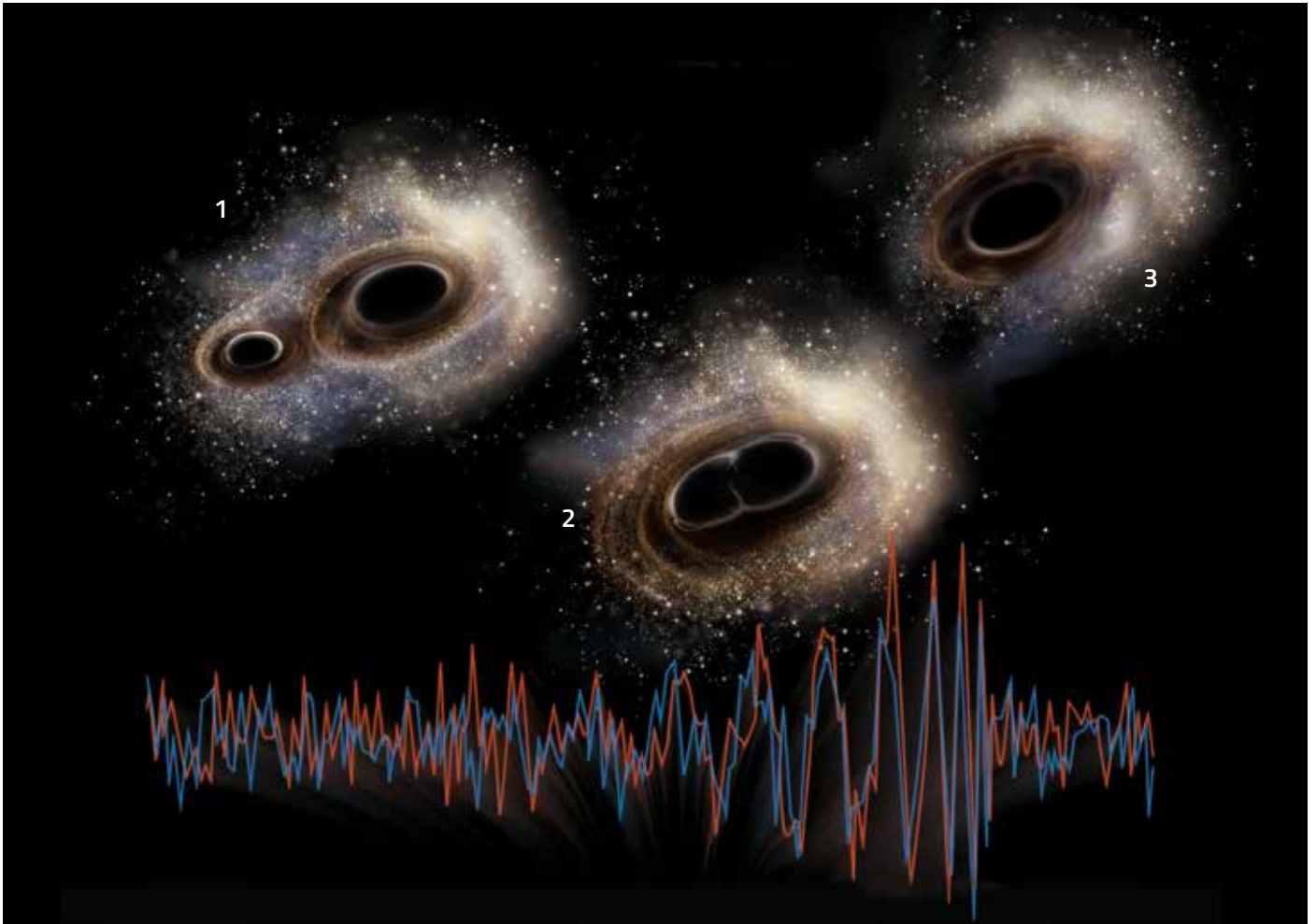


Illustration showing (below, in red and blue) the traces of the first gravitational wave detection by the two LIGO observatories. These traces are aligned with the progress of the black hole merger that produced the waves in three phases (top images): 1 – spiralling in, 2 – merger, and 3 – ‘ringdown’; when the gravitational wave emission ends.

Compact binary systems

Compact objects are stars that concentrate their mass in an unusually small volume. The most compact are black holes: one with the mass of the Sun would have a diameter of just 3 km. Neutron stars are another type of compact object: gravity shrinks these so much that protons and electrons merge, forming neutrons.

When two compact objects orbit around one another, general relativity predicts that the system slowly loses energy through the emission of gravitational waves. Consequently, their motion accelerates and the stars get closer. Although this spiralling-in

phase can last hundreds of millions of years, there is a strong peak in the gravitational wave emission in the final moments before the two compact objects merge. Gravitational waves from such an event were first successfully detected in 2015.

Pulsars

Pulsars are spinning, magnetised neutron stars. Like cosmic lighthouses, they emit a beam of electromagnetic waves at a frequency twice that of the pulsar’s spin, which can be detected by radio telescopes if Earth is within its sweep. In theory, pulsars should also emit gravitational waves continuously,



but the strength of these waves would depend on the star's shape and how spherical it is – because objects that are perfectly symmetrical about their axis (such as spheres) are predicted not to radiate gravitational waves at all. Like other stars, pulsars are likely to be almost perfect spheres, and the fact that no gravitational waves have yet been detected from any pulsar suggests that any irregularities on the surface of these stars must be very limited in size.

Detecting gravitational waves

Detecting gravitational waves is an extreme pursuit: it means finding the tiniest vibration signalling that a gravitational wave has passed, completely buried within 'noise' – the vibrations from all other sources. On Earth, the worldwide network of interferometer-type detectors currently includes four instruments: two LIGO detectors in the USA, Virgo in Italy and GEO-600 in Germany. A fifth detector (KAGRA, in Japan) will come online by the end of this decade, and there are plans to build a third LIGO detector in India during the following decade.



The LIGO gravitational wave detector at Livingston, Louisiana, USA

Image courtesy of Caltech/MIT/LIGO Lab

No single detector alone can claim to have detected a gravitational wave: it must be picked up by at least two detectors, otherwise the rate of false alarms – fake detections due to noise – would simply be too high. For this reason, all the data recorded within the network is analysed jointly to look for signals that coincide in time and appear similar in each instrument.

“No single detector alone can claim to have detected a gravitational wave.”



The VLA (very large array) radio telescopes in Socorro, New Mexico, USA

Image courtesy of NRAO/AUI and NRAO

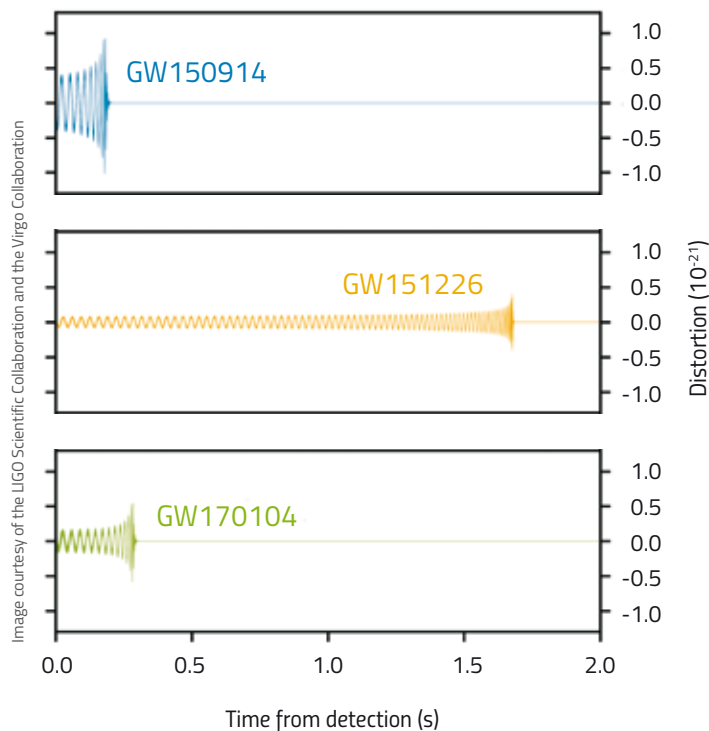


Figure 2: The first three gravitational waves detections on (from top) 14 September 2015, 26 December 2015 and 4 January 2017, all produced by merging black holes. As these traces show, each signal builds up gradually and decays rapidly once the merger has happened. The horizontal axis shows the time from when the signal was first seen in the detector, while the three vertical axes show the tiny fractional distortions registered.

The detections of gravitational waves in 2015 (see Kwon, 2017) and in 2017^{w2}, generated by the merging of two black holes (see figure 2), have opened a new window onto the Universe – and a new era in astronomy. Gravitational wave signals now complement the probes scientists are already using to observe the cosmos, including the telescopes that scan the skies using different parts of the electromagnetic spectrum. Information is exchanged both ways: when a potential gravitational wave signal is detected, an alert is sent to telescopes that can quickly observe the region thought to contain the source of the signal – if it is real. And telescopes can ask gravitational wave detectors to look for the counterpart of an event they have detected.

So detecting electromagnetic waves, particles and gravitational waves from the same source is now a realistic possibility. And the more data we have from a source, the deeper our understanding of it can be.

References

- Arnaud N (2017) Good vibrations: how to catch a gravitational wave. *Science in School* **40**: 26–30. www.scienceinschool.org/content/good-vibrations-how-catch-gravitational-wave
- Kwon D (2017) Turning on the cosmic microphone. *Science in School* **39**: 8–11. www.scienceinschool.org/content/turning-cosmic-microphone

Web references

- w1 To find out more about the LISA project, see: www.elisascience.org
- w2 To learn more about the third gravitational wave detection, read the summary on the LIGO website: www.ligo.org/science/Publication-GW170104/

Resources

- Find out more about the recent third gravitational wave detection: *Symmetry*, a magazine produced by Fermilab/SLAC, has published several articles on gravitational waves. Search at www.symmetrymagazine.org, or read: Jepsen K (2017) At LIGO, three's a trend. *Symmetry* magazine, 6 Jan. www.symmetrymagazine.org/article/at-ligo-threes-a-trend

Read about how astronomers use different electromagnetic waves to study the cosmos in the 'More than meets the eye' series in *Science in School*. For example: Mignone C, Barnes R (2017) More than meets the eye: the cold and the distant Universe. *Science in School* **40**: 17–22. www.scienceinschool.org/content/more-meets-eye-cold-and-distant-universe

Nicolas Arnaud is a staff physicist at the French National Centre for Scientific Research (*Centre National de la Recherche Scientifique*, CNRS) in France. After completing a PhD on the Virgo experiment during its construction phase, he worked in particle physics for a decade before joining Virgo again in 2014. Since September 2016, he has worked at the European Gravitational Observatory in Italy, on the site of the Virgo detector. He has been involved in various outreach and education activities since 2003 and is coordinating some of these activities at the national level.





*A great white shark,
Carcharodon carcharias*

Design inspiration: the secrets of shark skin

Shark skin is adapted for energy-efficient swimming in remarkable ways, some of which are now being copied by designers and engineers.

By Claas Wegner, Rico Dumcke, Nora Tönnemann

Sharks have an image problem: throughout the world, they are portrayed as bloodthirsty monsters – most famously in the movie 'Jaws'. Fear of sharks is common, especially in coastal areas where ideal surfing and swimming conditions occur alongside resident sharks. In such situations, the white undersides of surfboards and constantly moving limbs

can easily provoke these animals – with potentially tragic consequences.

In fact, shark attacks are relatively rare, and many species of shark are now themselves in need of protection from human activities, especially fishing. Far from being just movie monsters, sharks form an important and diverse group of

cartilaginous fish, comprising some 360 species within 30 families in eight taxonomic orders. Research on sharks has revealed just how well adapted they are: in particular, their skin has remarkable features that helps sharks to swim in an especially energy-efficient manner. These features have been taken up in various areas of technology, from swimsuits to aeroplanes.

Streamlined shape

So how are sharks adapted to their lifestyle? The most obvious feature (which they share with other fish) is their streamlined body, which allows them to swim very fast with minimal energy. In the supplementary worksheet^{w1}, we provide instructions for a simple experiment to explore how shape affects the force needed to move through water. In the experiment, which is suitable for secondary schools, the students make shapes, including cubes, cuboids, spheres and cylinders – plus a shark shape – out of identical masses of modelling clay and carry out a speed trial, comparing how long it takes each clay shape to fall to the bottom of a tall, water-filled cylinder.

Image courtesy of Carolin Zehne

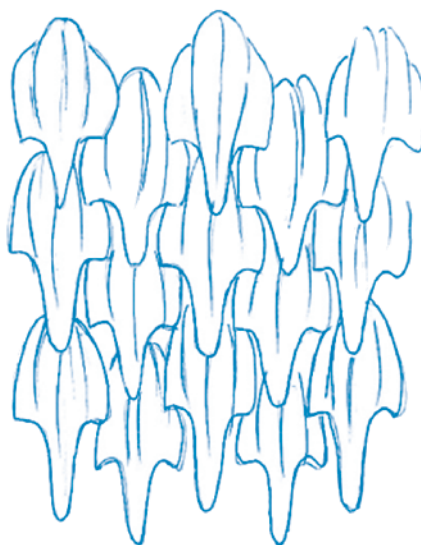


Diagram of the placoid scales of a cat shark, showing their tooth-like shape

Scales: going with the flow

Of course, an animal's locomotion through water is influenced not only by its shape, but also by how the water flows over its surface – just as competitive swimmers like their skin and swimwear to be as smooth as possible. If you were to stroke shark skin, you would notice that it feels smooth in one direction only; in the opposite direction, it feels very rough – as if you were to run your fingers along a pine cone from the tip downwards, rather than the base upwards. This difference in texture is because most shark species have fine, tooth-shaped scales covering their surface. These 'placoid' scales provide protection against parasites and injuries. In addition, researchers have found connections between the exact shape of these scales and the lifestyle of different shark species.

For example, sharks living near reefs (such as gulper sharks, Centrophoridae) have smooth scales, as these best protect them against mechanical abrasion by rocks. This is not the case for fast-swimming hunting sharks, such as the great white shark (*Carcharodon carcharias*), silky shark (*Carcharhinus falciformis*) and hammerhead sharks (Sphyrnidae). The scales of these species have a striking additional feature: fine, raised ridges or 'riblets' along the length of the scale. These riblets are aligned to form tiny ridges that run longitudinally along the shark's body. Although the riblets are only a few micrometres

“If you were to stroke shark skin, you would notice that it feels smooth in one direction only.”



Magnified images of the scales of different shark species, showing their varying shape and riblet form: Top, blacktip reef shark; middle, hammerhead shark; bottom, cat shark



Image courtesy of Science Photo Library / Kinsman, Ted



Image courtesy of Science Photo Library / Kinsman, Ted



Image courtesy of Rico Dumcke

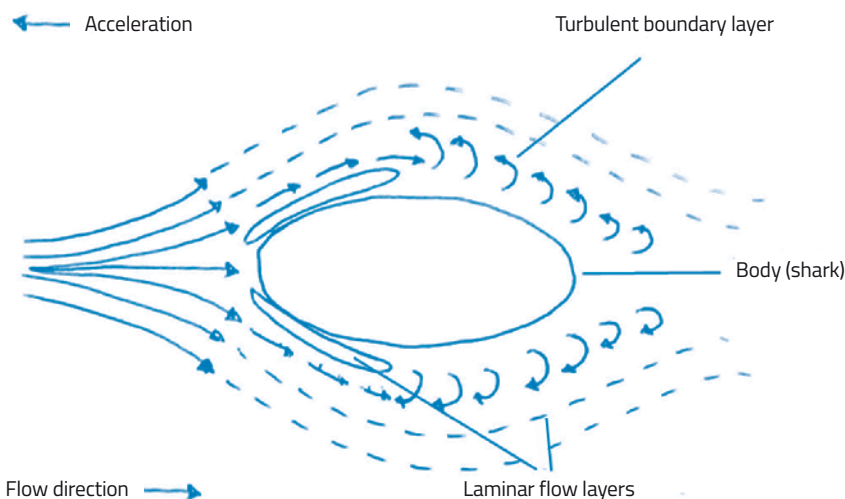
high, experiments have shown that they reduce drag as the shark swims, allowing it to swim faster using the same amount of energy. In contrast, sharks that swim slowly – for example, cat sharks (Scyliorhinidae) – have fewer riblets on their long, pointy scales.

Fluid flow: a closer look

So how do shark scales and riblets work? To find out, we need to look more closely at the laws of fluid dynamics.

There are two different forms of dynamic flows: laminar and turbulent. In laminar flow, the fluid moves in one direction only; the particles of the fluid may move at different speeds in different layers, but the layers do not mix. In turbulent flow, however, there are fluctuating flows against or across the main flow direction, which cause swirls in the layers. Here, fluid particles are constantly changing their position and speed, which consumes energy.

When a fish (or a ship) moves in water – or an aeroplane flies in air – the moving body is surrounded by a fluid medium. Due to friction, fluid particles that are in contact with the surface of the body move at zero speed relative to that body, while further away, the fluid flows smoothly around the body. In between



Turbulent and laminar flow around a body moving through water



- ✓ Biology
- ✓ Physics
- ✓ General science
- ✓ Ages 14–19

REVIEW

This article makes links between two separate disciplines: hydrodynamics (physics) and biology. The morphological characteristics of sharks are described in relation to fluid dynamics, which allows readers to understand how these different phenomena are connected.

The article also features examples from engineering, where the development of new structures is inspired by biological adaptations.

Bartolome Piza Mir,
science and mathematics
teacher, Spain

Image courtesy of Carolin Zehne



Surfers: the constant movement can attract the attention of sharks.

“The optimal spacing of the riblets depends on the velocity of movement, so in sharks it varies between species.”

is the turbulent boundary layer, where the resistance to the movement occurs.

Linear ridges like the shark's riblets reduce this resistance by changing the flow in the boundary layer. This is because, deep within the valleys between the riblets, the flow velocity is low, so there is less friction. However, high-velocity vortices form at the tip of these riblets; but because the surface area of these tips is low compared to the surface of the whole animal, the total friction is reduced (Dean & Bhusan,

2010). The optimal spacing of the riblets depends the velocity of movement, so in sharks it varies between species.

Biomimetic opportunities

Such discoveries about shark skin have attracted the interest of engineers and technologists as well as biologists – an example of potential 'biomimetic' applications, where biological features have found a use in technical applications.

Often, biomimetics is a top-down process. For example, to solve an environmental problem, we can search for an analogy in nature to help find a solution – such as the development of pyrethroid insecticides, which were inspired by the naturally occurring plant-based insecticide pyrethrum. On the other hand, in a bottom up-process, biological systems are analysed to identify procedures or constructions that may have some useful technological application. The discovery of shark scale riblets is such a case, and these are now

being used as an inspiration for other surfaces that move through fluids, as the following examples illustrate.

Riblet foils on aeroplanes

As far back as 1989, the aircraft manufacturer Airbus carried out a riblet experiment. They covered 70–80% of an Airbus A380 with metallic riblet foil, with the riblets in the form of sharply pointed triangles. Tests showed that the foil reduced friction by up to 8%, equivalent to a fuel saving of 1–2% under real-world conditions, which would allow a long-distance A380 flight to carry an additional 4 tonnes of payload. More recently, a polymer version has been developed, whereby a coating is applied to a surface and the riblet microstructure is impressed onto it, then hardened. This version has the advantage of being easier to apply to curved surfaces.

Keeping ship hulls clean

Ship hulls lying below water acquire layers of biological growth from

barnacles, algae and other materials. This accretion causes increased drag and thus additional fuel costs for shipping. Research has shown that creating an uneven surface like the riblet scales on a shark's skin is a huge help, as it both reduces the amount of growth over a year by some 60% and makes cleaning off the growth easier (while avoiding the environmentally damaging effects of some antifouling agents). Similarly to aircraft, riblet surfaces on ships can also reduce drag in water by up to 10% (Fu et al., 2017).

Swimming like a shark?

Finally, and most controversially, some Olympic swimmers have chosen to wear full-body swimsuits made from a riblet-effect material – and have then won gold medals. Although the extent to which the riblet effect contributed to these triumphs is still a controversial issue, full-body swimsuits were banned from competition in 2010. So, while the riblet scales have given sharks an evolutionary advantage, applying this advantage to the world of competitive swimming is a more questionable issue.

Acknowledgment

The editors would like to thank Dr Katharina Sonnen for her advice on the article.

References

- Dean B, Bhusan B (2010) Shark-skin surfaces for fluid-drag reduction in turbulent flow: a review. *Philosophical Transactions of the Royal Society A* **368**: 4775–4806. doi: 10.1098/rsta.2010.0201
- Fu YF, Yuan CQ, Bai XQ (2017) Marine drag reduction of shark skin inspired riblet surfaces. *Biosurface and Biotribology* **3(1)**: 11–34. doi: 10.1016/j.bsbt.2017.02.001

Web reference

- w1 Download the supporting classroom activity from the *Science in School* website. See: www.scienceinschool.org/2017/issue41/sharks

Resources

- To find out more about how fast sharks swim and more, see: www.elasmo-research.org/education/topics/p_shark_speed.htm
- Information on how Airbus Group are developing riblet technology is available here: www.technology-licensing.com/etl/int/en/What-we-offer/Technologies-for-licensing/Green-Technologies/Metallic-riblet-surfaces.html or use the direct link: <https://tinyurl.com/yaz9zkum>

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Hammerhead shark – a fast-swimming species

Image courtesy of Christa Rohrbach / Flickr



Evolution in action: the 67 000-generation experiment

A unique experiment tracks microbes changing over thousands of generations – so we can watch evolution on fast-forward.

The striking black and yellow colouration gives fire salamanders advantages in natural selection, providing camouflage and acting as a warning to would-be predators.



- ✓ Evolution
- ✓ Genetics
- ✓ Population genetics
- ✓ Nature of science
- ✓ Ages 14–19

REVIEW

Teaching evolution is of vital importance in enabling students to become biologically literate citizens. Teachers are sometimes unable to convince their students of this important biological idea, so other interpretations (e.g. creationism) may find their way into the students' thinking. This article can help teachers by providing experimental new results that support the theoretical concepts of evolution.

The article can be used in any lessons relating to the study of evolution. Comprehension questions that students could be asked to answer include:

- How do organisms acquire diversity?
- Describe how genetic diversity is affected by natural selection.
- What does 'fittest' mean when used to describe organisms?
- What does this experiment tell us about the micro-evolution of organisms?

Panagiotis K Stasinakis, biology teacher,
4th High School of Zografou, Greece

Image courtesy of Marcin Bajer / Flickr

By Jarek Bryk

As an evolutionary biologist, I like to think that studying evolution is akin to studying the stars. No astronomer lives long enough to observe a star being born, getting old and dying. The Sun, for example, has a life cycle of about 10 billion (10^{10}) years – a timescale out of all proportion to a human life. But because the Universe is full of stars, with millions of them in the Milky Way alone, astronomers can observe many stars at different stages of their life cycle. From these observations, they can gather enough data to work out the different stages of a star's life and map their whole evolution.

Evolutionary biologists live no longer than astronomers, so no-one has seen a single vertebrate species diverging and evolving into two or more different species. But like astronomers, we can exploit the fact that there are millions of species on Earth that split from others at different points in time, and we can access the records of this history preserved in rocks and in the genetic material of organisms, either dead or alive.

In this context, evolutionary geneticists who study micro-organisms have an advantage over biologists concerned with the evolution of more complex species such as vertebrates: the

Image courtesy of ESO / B. Tafreshi (twanight.org)



Night sky showing (in red) the Carina Nebula, studied by astronomers to understand the birth and death of stars.

Image courtesy of Paul Williams / Flickr



Ammonite fossil on a beach in Dorset, UK. Known as the Jurassic coast, this location is rich in fossils.

microbes reproduce and mutate so rapidly that they put evolution on fast-forward. In this article, we look in detail at an extraordinary experiment that has tracked the evolution of the bacterium *Escherichia coli* over an amazing 67 000 generations. Translated into human generations, this number is equivalent to around one million years – which would take us back to well before the beginning of our own species, *Homo sapiens*. Using *E. coli*, which replicates itself six or seven times each day, it has all happened in less than 30 years.

But how can tracking populations of micro-organisms tell us anything about the evolution of other species, or even of humans themselves? First, let's have a look at what we mean by evolution.

“Microbes reproduce and mutate so rapidly that they put evolution on fast-forward.”

What is evolution?

Evolution is any change in the frequency of genetic variants (alleles) within a group of organisms of the same species (population) from one generation to the next. There are several mechanisms that can cause evolution, including migration (when a group of new individuals join or leave an existing

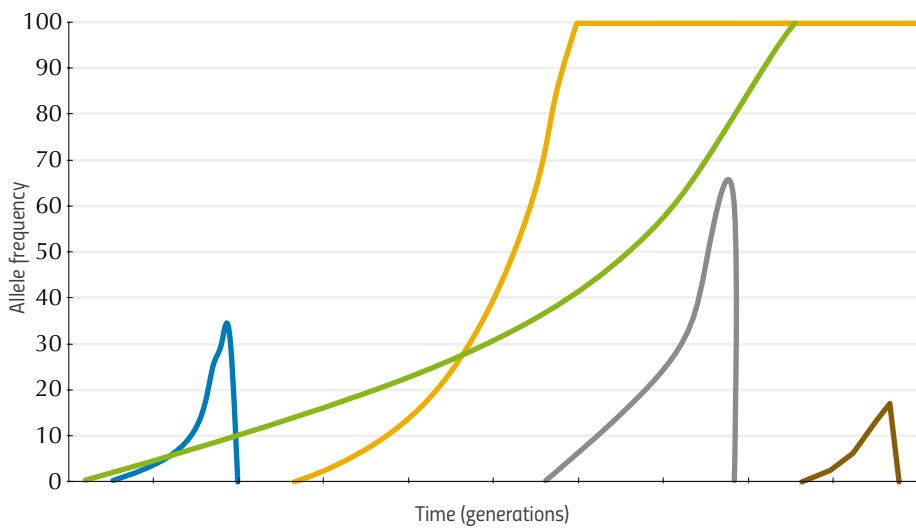
population) and simple chance (when individuals have unequal opportunities to reproduce). The best-known mechanism, which is often mistaken for evolution itself, is positive natural selection: the mechanism by which individuals with some combinations of alleles in a species within a given environment produce more offspring than individuals with other combinations, leading to adaptations in that species.

Many changes in allele frequency do not lead to the emergence of a new species – but when a split occurs, this is always the consequence of many different genetic variations accumulating in separate populations. Studying such fundamental mechanisms of evolution – how genetic changes arise and then spread through or disappear from a population, and how they contribute to an organism's 'fitness' (a measure of its reproductive success) – tells us about how evolution happens. And studying the mechanisms of evolution is easier and faster when it's done with micro-organisms.

LTEE: a very long-term experiment

The experiment that aims to watch bacterial evolution in action is known as the *E. coli* long-term evolution experiment, or LTEE. In the experiment, which began on 24 February 1988, populations of *E. coli* are tracked over time to find out what changes take place in their genomes, and what impact these changes have on the organisms' characteristics.

At the start of the experiment, Richard Lenski at Michigan State University, USA, set up 12 flasks with a bacterial medium containing the absolute minimum nutrients needed by bacteria to survive, then inoculated all 12 flasks with the same culture of *E. coli*, and left them incubating at 37 °C. The next day, he took out a small volume of the culture in each flask, diluted it with a fresh portion of the medium, and again left it to incubate overnight, discarding the previous day's culture. This same process has been repeated every day



Graph showing a fictional example of the fate of five different alleles (coloured lines) in a population over time. The alleles appear at different times and rise in frequency at different rates. They then either disappear (blue, grey and brown lines) or spread to the entire population (yellow and green lines).

since then – over 10 000 days so far. So how do the LTEE researchers find out whether the *E. coli* are evolving – and if so, how? Every 75 days (about 500 generations), a sample of the culture in each flask is frozen in a way that lets it be recovered, regrown on a Petri dish and analysed when needed. For each analysis, the researchers look at the DNA in the genomes of the different

E. coli strains to map the genetic changes that occurred since the previous frozen generation in each flask. Crucially, they also compare how well strains from different flasks and time periods grow when competing with each other, because their growth rate is a good measure of evolutionary fitness: bacteria that grow and multiply faster are, in evolutionary terms, fitter.

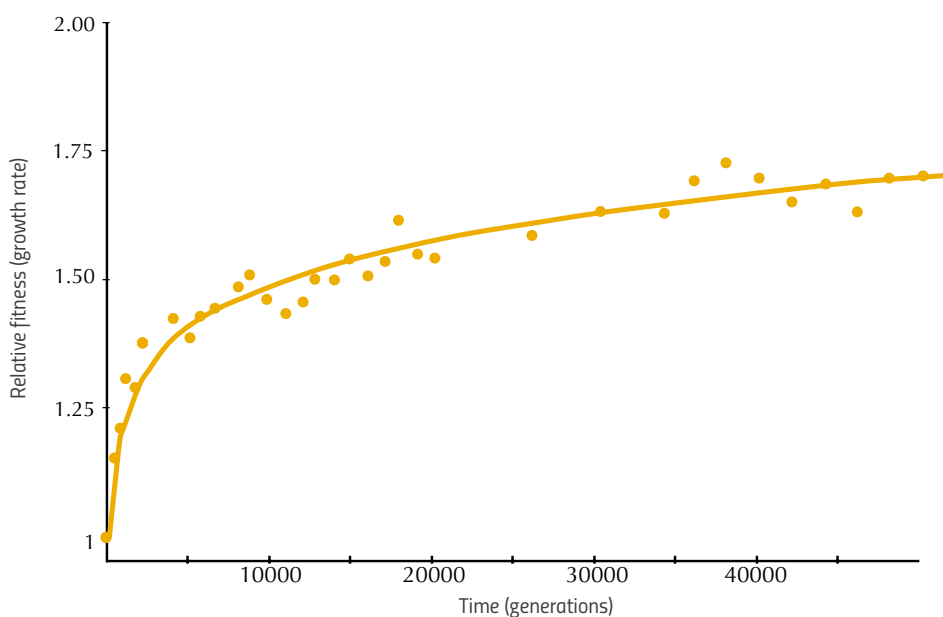


Figure 1: Graph showing the change in relative fitness (growth rate) of the *E. coli* populations over time (adapted from Wiser et al., 2013)



Image courtesy of Zachary Blount, Michigan State University

Some of the thousands of Petri dishes containing cultures removed from the flasks for analysis. In front of the flasks is Zachary Blount, graduate student of Richard Lenski.

From these analyses, Richard Lenski and his colleagues were able to establish the relationship between the mutations occurring in the *E. coli* genome and their effect on fitness – that is, they showed how the bacterium was evolving. Some of these findings are illustrated in figure 1. Here, the vertical axis shows the average growth rate of bacterial populations from six of the flasks, relative to the fitness of bacteria at the beginning of the experiment (i.e. how much better or worse the later cultures grow compared to the first), and the horizontal axis shows the generation number. We can see that in the earlier generations, the growth rate increases rapidly, indicating that the early mutations had a large effect. Later changes in DNA have a smaller influence, but the bacteria continue to adapt. There is no single ideal DNA sequence that provides perfect fitness in this environment, but rather a fitness-increasing path that the bacteria continue to climb.

Another observation was that two unusual mutant strains emerged. One of them, which appeared independently in three populations between generations 2500 and 8500, was named the ‘hypermutator’ strain, because its DNA changed much faster

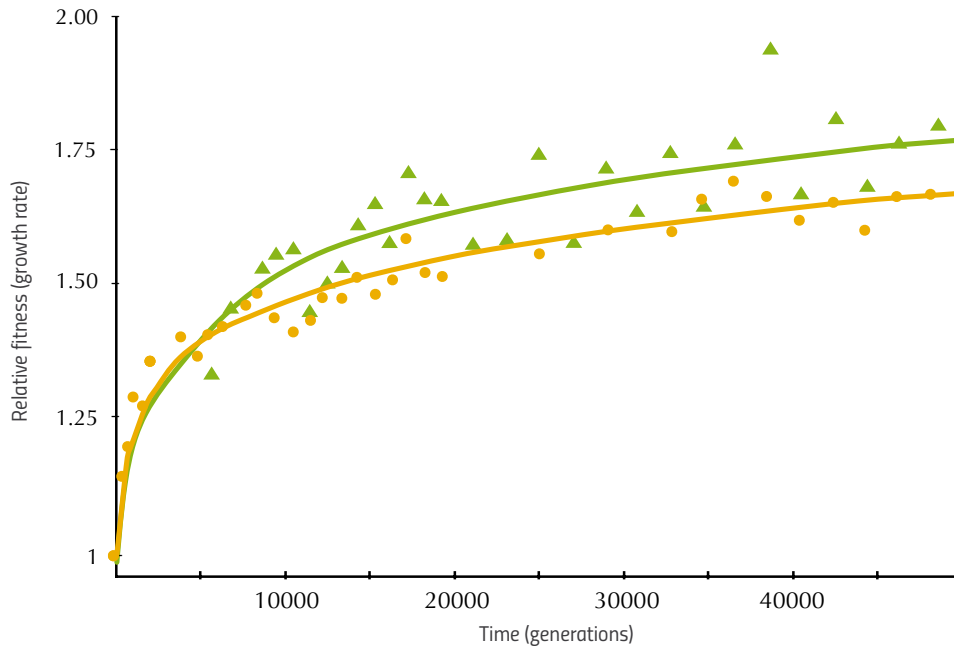


Figure 2: Graph showing the emergence of the 'hypermutator' strain (green) and its higher relative fitness in a given generation to the normal mutation rate strains (yellow) (adapted from Wiser et al., 2013)

than the DNA in other strains. The hypermutator strain achieved higher fitness sooner than other strains, because more mutations – more genetic variants of the genome – meant that useful variants providing higher fitness were more likely to occur.

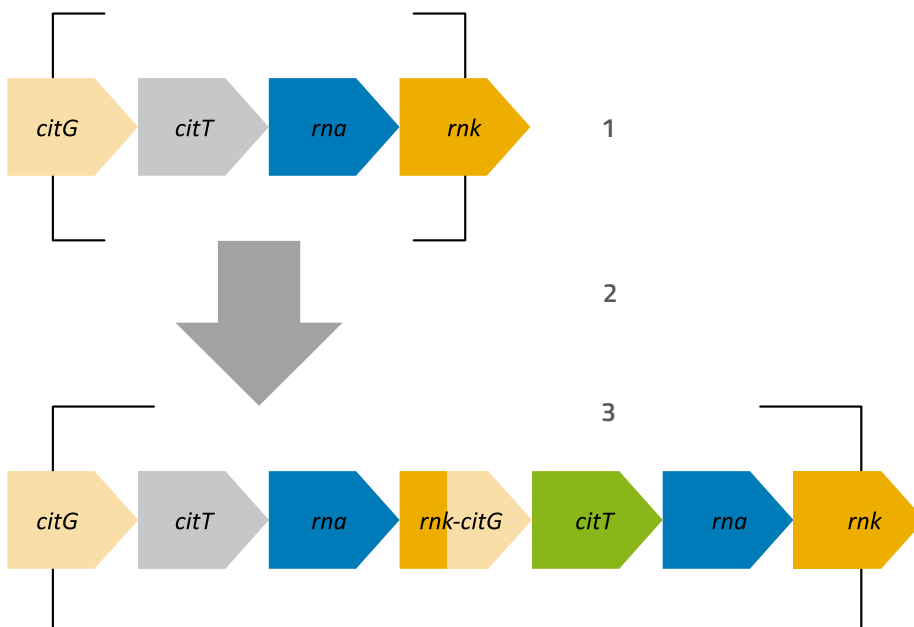
The second mutant that Lenski and his team discovered was even more impressive (Blount et al., 2012). Around generation 31 000, one strain started to grow much, much better than anything

before it. Careful analysis of this mutant strain showed that it could use an alternative substance, citrate, as a key nutrient, in place of the small amount of glucose in the medium. The progeny of this mutant quickly took over the flask, and the mutation that enabled the bacteria to use citrate (see figure 3) became dominant in the population – a clear example of an advantageous mutation appearing and spreading throughout a population: positive natural selection in action.

Learning from mutants

The citrate-eating mutant is a case in which it was possible to see evolution happening with the naked eye: a clear medium becoming cloudy with billions of cells literally swimming in a new source of food and growing explosively in number within hours. Although the initial mutation conferred only a small advantage over the previous generation of bacteria, it was enough to ensure the reproductive

Figure 3: How a mutation in the *E. coli* genome led to the ability to use citrate continuously (adapted from Blount et al., 2012).



Stage 1: Original arrangement of the genome fragment, where citrate can only be used when no oxygen is present. The *citT* gene encodes a protein that transports citrate into the cell. When oxygen is present, this gene is inactive and the protein is not produced

Stage 2: The genome fragment is duplicated.

Stage 3: After duplication, parts of the *rnk* and *citG* genes fuse. The activity of the *rnk* gene is not dependent on oxygen, and the activity of the *rnk-citG* fusion disrupts the control of the adjacent *citT* gene (green), activating it whether or not oxygen is present. The original copy of *citT* (grey) remains inactive in the presence of oxygen.



Flasks containing the cultures after the citrate mutant evolved. The middle flask at the front contains the citrate mutant; the contents have become cloudy due to the presence of so many bacteria.

success of the mutants. Soon, the entire population was able to use citrate as a food source. This is just one example of how the short generation time of micro-organisms, coupled with our new ability to sequence genomes very rapidly, allows us to see the effect of genetic variants playing out almost in real time. Studying these hallmarks of evolution in micro-organisms also enables scientists to comprehend evolutionary processes that take place in other organisms over much longer timescales – including the emergence of new species.

References

- Blount ZD et al. (2012) Genomic analysis of a key innovation in an experimental *Escherichia coli* population. *Nature* **489**: 513-518. doi: 10.1038/nature11514
- Download the article free of charge on the *Science in School* website (www.scienceinschool.org/2017/41/evolution), or subscribe to *Nature* today: www.nature.com/subscribe
- Wiser MJ, Ribeck N, Lenski RE (2013) Long-term dynamics of adaptation in asexual populations. *Science* **342**: 1364-1367. doi: 10.1126/science.1243357

Resources

- Read an excellent discussion on how to define evolution: www.sandwalk.blogspot.co.uk/2012/10/what-is-evolution.html
- For Richard Lenski's blog entries about LTEE and related matters, see: www.telliamedrevisited.wordpress.com/2017/03/13/some-wrinkles-in-time/
- Find out about evolution at the molecular level: Byrk J (2010) Natural selection at the molecular level. *Science in School* **14**: 58-62. www.scienceinschool.org/2010/issue14/evolution

Byrk J (2010) Human evolution: testing the molecular basis. *Science in School* **17**: 12-16. www.scienceinschool.org/2010/issue17/evolution

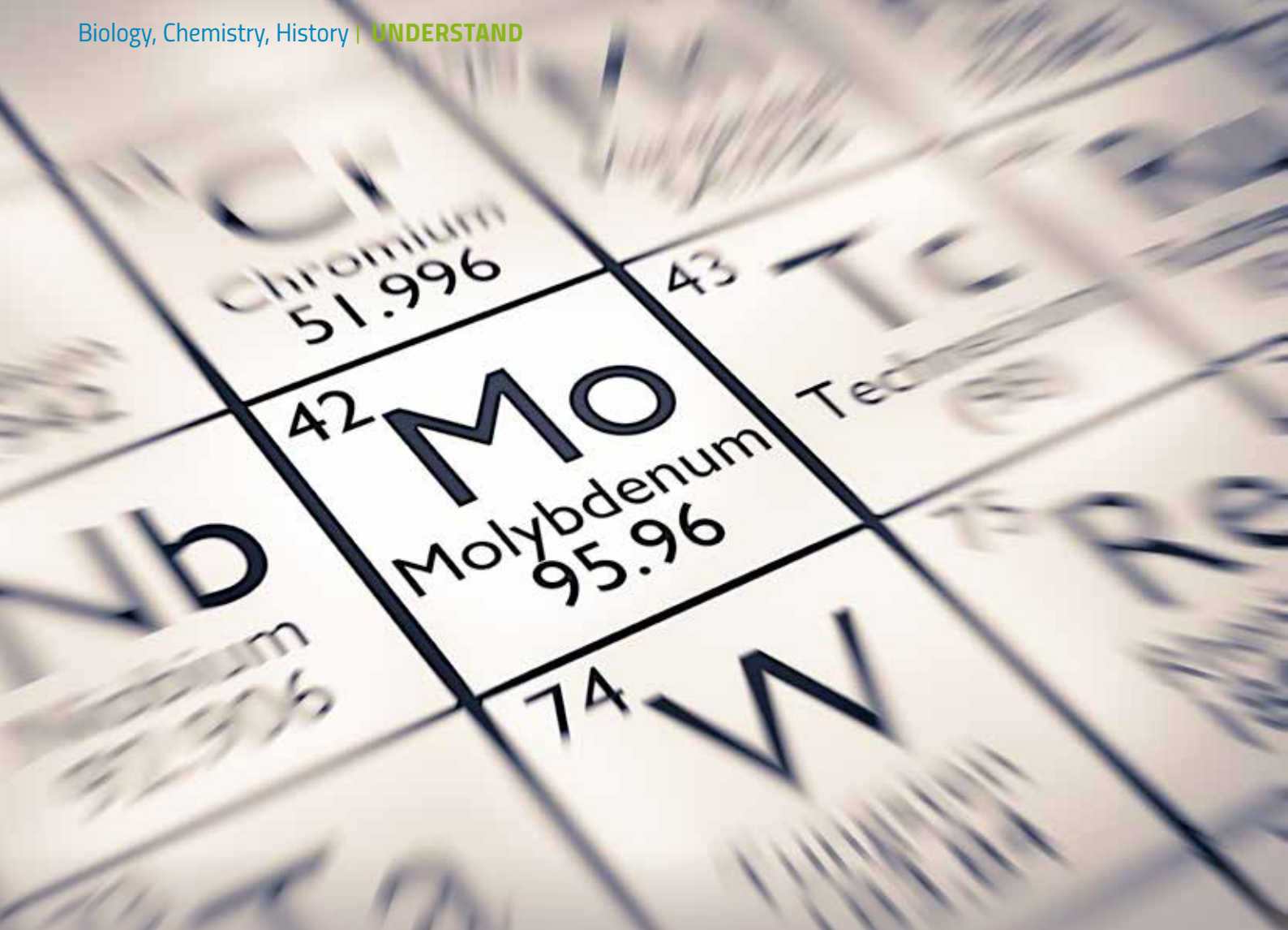
For *Science in School* articles on the anti-evolution idea, creationism, see:

Leigh V (2008) Interview with Steve Jones: the threat of creationism. *Science in School* **9**: 9-17. www.scienceinschool.org/2008/issue9/stevejones

Pathmanathan S, Rau M (2008) Teaching in Sweden: tackling creationism, making waves. *Science in School* **10**: 88-93. www.scienceinschool.org/2008/issue10/perkornhall

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Molybdenum in the spotlight

From samurai swords to healthy tomato plants, this little-known element has wider uses than you might expect.

The element molybdenum, symbol Mo, in its periodic table position

Image courtesy of Antoine2K / Shutterstock.com

By Anastasiia Batsmanova, Mikhail Liabin, Yelizaveta Stepanova and Susan Watt

Only around 90 chemical elements occur in nature. Some of these are very familiar – from lustrous precious metals such as gold and platinum, to the oxygen in the air we breathe and the carbon that forms the backbone of the molecules of life. Many other elements are much less familiar – but, as members of this select band of 90, perhaps even the more obscure elements deserve to be slightly better known.

In this article, we push one of these low-celebrity elements – molybdenum – into the spotlight and reveal its unique history and character.

What is molybdenum?

To look at, molybdenum is unremarkable: a hard, silvery-grey metal, with a density some 30% more than iron. In nature, it occurs only as a compound – mostly in the form of the mineral molybdenite, MoS_2 . And although molybdenum has been known since ancient times, the story of its identification began with confusion.

The word ‘molybdenum’ comes from the ancient Greek word for lead, *molybdos*. Like lead and graphite, molybdenite can be used to make a mark on a surface, so for centuries it

was thought to be just another lead-containing mineral. In the late 18th century, during the early decades of modern chemistry, some people began to suspect that molybdenite was in fact a different substance from lead or graphite. In 1778, the great Swedish chemist, Carl Wilhelm Scheele – who also played a major role in the discovery of oxygen and several other chemical elements – proved chemically that molybdenite was in fact a sulfur compound of a new, unidentified element. Another Swedish chemist, Peter Jacob Hjelm, then isolated the metal in 1781, but it was not properly purified until several decades later.

On Earth, molybdenum is not abundant: it ranks 53rd among elements in Earth’s crust. Pure, elemental molybdenum has never been found on Earth (only as a compound with other elements) – but the Russian Luna 24 mission to the Moon in 1976 brought back a tiny piece of pure molybdenum. Even in space, molybdenum is rare, as – unlike lighter metallic elements – it is not made in normal nuclear fusion processes in stars, but is created in supernova explosions.

Special characteristics

Molybdenum’s most remarkable physical characteristics are its very high melting point, over 1000 °C higher than that of iron, and its very low expansion when heated. This means molybdenum is a good material to use where stability at high temperatures is needed, such as in furnaces. A common use until recently was in glowing filament light bulbs, where pure molybdenum wire was used to support the hot filament. Chemically, molybdenum is closely related chemically to tungsten, which is situated directly below it in the periodic table, and it shares with tungsten the ability to form very hard alloys with iron and other elements. Molybdenum is a transition metal, and so – like other transition elements – it can form compounds with varying valency (the number of electrons used in bonding). This is because the atoms in transition metals have spaces not



- ✓ Chemistry
- ✓ Biology
- ✓ Ages 14–19

REVIEW

This article could be used to deepen students’ knowledge about molybdenum, one of the less well known elements that occur in nature. It can also be a starting point for discussing the essential role of such little-known elements in life, and to raise awareness of the importance of research in the development of technology.

Possible comprehension questions include:

- Can you name two scientists involved in the discovery of molybdenum? Explain their role in the discovery of this element.
- Why is molybdenum a good material to use where stability at high temperatures is needed?
- Why are molybdenum enzymes essential to plants?
- Why was molybdenum used in samurai swords?
- Can you mention three everyday products that contain molybdenum?

Mireia Güell Serra, chemistry teacher, INS Cassà de la Selva, Spain

Public domain image / Wikimedia Commons



Print of Japanese warriors and their swords by Utagawa Kuniyoshi (1798–1861). Molybdenum was used in the alloy for a 14th-century samurai sword, but this technique was later lost.



BACKGROUND

Molybdenum facts

- Element name: molybdenum
- Atomic number: 42
- Relative atomic mass: 95.96
- Density: 10.22 g/cm³
- Melting point: 2623 °C
- Coefficient of thermal expansion: 4.8 x 10⁻⁶ / K at 25 °C
- Valency: oxidation states from -II to VI



Many vegetables, especially beans, contain molybdenum, but the amount depends on the soil they grew in as well as the type of vegetable.

only in their outermost electron shell but also in a lower shell, because of the shells' overlapping energy levels. This rather fluid arrangement is the basis for molybdenum's role in living organisms as an electron carrier, because it can loan and accept a variable number of electrons at the same time.



Image courtesy of American Society of Plant Biologists, reprinted with permission

Tomato plants with molybdenum deficiency. In A, the leaf on the left is mottled due to lack of molybdenum; in B, the leaves at centre and right have advanced molybdenum deficiency. Normal leaves are shown on the right in A and left in B. (From Arnon & Stout, 1939)

Vital for life

Molybdenum is vital for life, in both plants and animals. It is the only essential trace element within the second row of the transition elements in the periodic table, which runs from yttrium (atomic number 39) to cadmium (atomic number 48). Molybdenum-containing enzymes are found in both bacteria and archaea, two of the most ancient forms of living organisms.

Based on this finding, some scientists speculate that molybdenum may have been present in the earliest life forms on Earth – and also in the 'last universal common ancestor' of all living things.

Whatever the case, it's certain that molybdenum-containing enzymes are essential to plants. Some plants can obtain the nitrogen they need through a symbiotic relationship with nitrogen-fixing bacteria in their roots. These bacteria use nitrogenase enzymes containing molybdenum to capture atmospheric nitrogen and turn it into useful nitrogen compounds (Hernandez, 2009), including amino acids and proteins. Plants can also use nitrogen compounds (such as nitrates) in the soil with the help of another molybdenum enzyme, nitrate reductase. A study

“Some scientists speculate that molybdenum may have been present in the earliest life forms on Earth.”

carried out in 1939 with tomato plants first established molybdenum as an essential nutrient in plants (Arnon & Stout, 1939).

Many animals require molybdenum too: the average human needs to take in around 45 micrograms of molybdenum daily, which we normally obtain from vegetables (1 kg of dehydrated vegetables contains around 1 milligram of molybdenum), as well as from milk and nuts. The metal is a component of several metabolic enzymes, including sulfite oxidase. This enzyme breaks down the sulfite formed from amino acids and thus prevents sulfite accumulating in the body, where it can cause fatal damage. Another important molybdenum enzyme is xanthine

Image courtesy of Nicole Kinsman / IMOA



The helix bridge in Singapore, constructed using an alloy containing 2% molybdenum

Image courtesy of Nicole Kinsman / IMOA



The One World Trade Center building in New York, which opened in 2014. An alloy containing 2% molybdenum was used in its construction.

oxidase, which breaks down xanthine (found in meat and other foods) to uric acid; this is then removed from the body by the kidneys. For this reason, xanthine oxidase inhibitors are used to treat gout – a disease in which excess uric acid builds up in the joints and muscle tendons, causing pain.

Technology and industry

A remarkably early technological use of molybdenum dates from 14th-century Japan: a samurai sword from this era has

been found to contain molybdenum, which would have helped to enhance the legendary strength and sharpness of such blades.

In the West, molybdenum's first industrial use came in the late 19th century as a substitute for tungsten in steel-making. By the time of World War I, tungsten supplies were so depleted that molybdenum started being mined on a large scale, particularly in the USA. The main source was the mine at Climax, Colorado, USA. Starting

in 1915, for many years this mine supplied three-quarters of the world's molybdenum.

Molybdenum was used in Germany during World War I to make steel for military hardware – gun barrels, armour plating, shells and submarine parts. Adding a small amount (1–2%) of molybdenum dramatically improved the steel's strength: shells that had easily penetrated 75 mm armour plating became powerless against a 25 mm molybdenum steel plate. This 'German

Image courtesy of Gord McKenna / Flickr



The molybdenum mine in Climax, Colorado, USA



Illustration showing the Cassini spacecraft crossing the rings of Saturn

steel secret' was followed by the development of molybdenum steel in other countries.

Molybdenum today

Today, the main use for molybdenum is still in alloys, particularly steel. One much-used alloy (316L stainless steel) contains 2–3% molybdenum and is tough, corrosion resistant and hypoallergenic, so it is used for a huge range of products, from smartphone cases to body-piercing jewellery, as well as in building construction.

Molybdenum compounds are also used in high-tech electronics. Here, they help to provide the touch-screen technology increasingly used in smartphones and tablets, as well as being used in more conventional liquid-crystal displays (LCDs) and solar panels.

A sample of molybdenite ore from the Climax mine in Colorado, USA



Image courtesy of James St. John / Flickr

Molybdenum is also a component of many 'permalloy' materials used in electronic devices, with uses ranging from power supplies and transformers to microelectronic components. Space agencies NASA and ESA have used molybdenum (MPP) materials in missions to Jupiter, Saturn and Mars. The Cassini-Huygens mission used these materials on its on-board mass spectrometer, which sent back data on the atmosphere of Saturn and its moons. So molybdenum may one day help us to detect life on another planet – as well as sustaining life on our own.

Acknowledgment

The authors would like to thank Dr Ulrike Kappler for her advice on the article.

References

- Arnon DI, Stout PR (1939) Molybdenum as an essential element for higher plants. *Plant Physiology* **14**(3): 599-602. doi: 10.1104/pp.14.3.599
- Hernandez JA, George SJ, Rubio LM (2009) Molybdenum trafficking for nitrogen fixation. *Biochemistry* **48**(41): 9711-9721. doi: 10.1021/bi901217p

Resources

- For a comprehensive account of molybdenum at an introductory level, see:
- Lepora N (2007) *The Elements: Molybdenum*. New York, USA; Marshall Cavendish. ISBN: 0761422013

Find out more about the chemical element molybdenum and its place in the periodic table: www.webelements.com/molybdenum/

The website of the International Molybdenum Association has plenty of useful resources on this element, its role in biology and its applications. See: www.imoa.info/index.php

For information on the uses of molybdenum in products and industry, see the website of HC Starck: www.hcstarck.com/en/products/technology_metals/molybdenum.html

Find out more about how heavy elements are made in stars:

Rebusco P, Boffin H, Pierce-Price D (2007) Fusion in the Universe: where your jewellery comes from. *Science in School* **4**: 52-56. www.scienceinschool.org/2007/issue5/fusion

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Supporting African science: the role of fruit flies

Not only is the fruit fly a valuable model organism, but it is also helping to put Africa on the scientific world map.

Image courtesy of Isabel Palacios



Isabel Palacios one of the founders of the DrosAfrica project

By Edward Dadswell

Isabel Palacios studies fruit flies. Not because she has any particular interest in flies themselves, but because they help her to answer fundamental questions about animal development. Most animals start life as a single, roughly spherical cell. Somehow the symmetry of that cell is lost and the animal ends up with a distinct head

and tail. The curious thing is that even in that first cell – even before it's fertilised – microscopic cellular machinery is working to create subtle asymmetries that prepare the cell for development. Isabel, a researcher at the University of Cambridge, UK, wants to understand how this happens.



The fruit fly Drosophila

But that's not the only ambition she has for her flies. As a founder of the DrosAfrica project, she believes the fruit fly, *Drosophila*, can play an important role in developing the research infrastructure of an entire continent, helping African scientists undertake high-impact projects and form collaborations around the world. The aim of the project is to teach scientists how to use the fly as a model system for studying human disease, ultimately creating an interconnected community of *Drosophila* researchers in Africa. This involves organising local workshops to train scientists and providing basic equipment such as microscopes and antibodies.

A model for research

"People who don't know about the fly ask: 'How could it help with African research?'" says Isabel. "But actually there are a lot of questions you can answer." *Drosophila* has long been used in genetic studies and allows researchers to gain insight into many types of human disease, including cancer, diabetes and neurodegenerative disorders such as Alzheimer's or Parkinson's. Flies can also be used in the study of host-pathogen interactions, including infection by viruses or *Plasmodium* – the organism that causes malaria. They have a broad range of uses in basic biomedical research. The other thing about fruit flies – as some of us have had the misfortune

to discover outside the laboratory – is that they reproduce rapidly, without human assistance. This means you can produce adequate numbers at low cost. Also, very little specialist equipment is required to look after them. There are many companies and university departments offering gene-editing services for *Drosophila*, so it's easy, fast and inexpensive to obtain flies with the genes you want to study. Isabel points out that the community is very open and willing to share, so if there's a particular type of fly that you'd like to research, there will often be someone in another part of the world who can send it to you, and the cost of shipping is very low. All these things make *Drosophila* an ideal organism to work with on a limited budget.

International science

Isabel compares the situation in Africa to that of Spain 40 years ago, when the country underwent a period of rapid development. It was then that Antonio García-Bellido, a developmental biologist, began training a few *Drosophila* researchers who went on to train others, creating a large community of fly researchers in Spain. Some of them went abroad to start their own research groups. "Suddenly you could do competitive science using the fly, because it's very inexpensive and the techniques are very easy to learn," says Isabel. "In terms of research, it helped put Spain in the international picture."



- ✓ Biology
- ✓ Cell biology
- ✓ Ages 16–19

REVIEW

This article links biology and the social aspects of research with the life history of a research project, creating a compelling story about international research. It could be used for a lesson on cell biology or model organisms, to highlight the applications of basic research to other subjects such as medicine and pharmacology. It also illustrates the importance of research in the developing world and the collaborative nature of science.

Marina Minoli, biology teacher, Italy

It was against this backdrop that Isabel grew up. At the time, Madrid had the only university in Spain that offered any courses in molecular biology, so she enrolled instead in a general biology degree at the University of La Laguna

Isabel Palacios (centre) with participants of the 2013 DrosAfrica workshop at Kampala International University in Uganda



Image courtesy of Isabel Palacios

Image courtesy of Isabel Palacios



Staff members from Kampala International University with participants and faculty of the 2013 DrosAfrica workshop in Uganda

in Tenerife. “But”, she says, “any time they touched on a more cell biological aspect, that was what really interested me.” After the first year, she decided to make the move to Madrid. “Financially, it was quite a stretch for my parents”, she explains. “But once I was there, I loved it. I knew that this was what I wanted to do.”

She went on to study for a PhD at the European Molecular Biology Laboratory (EMBL) in Heidelberg, Germany. “I applied thinking there’s no way they’ll invite me there, but they did, and then there’s no way they’ll offer me a place, but they did. I’d already started a PhD in Madrid, but my supervisor, Juan Ortín, said, ‘Take this chance, it’s a really good one’, so that’s where I went,” she says, laughing. “Suddenly I was at one of the best molecular biology institutes in Europe! I couldn’t believe my luck and I’ve been lucky ever since.”

Building relationships

Isabel explains that the idea for DrosAfrica came from a chance meeting between one of her colleagues, Lucia Prieto Godino, and Sadiq Yusuf, a professor from Kampala International University (KIU) in Uganda. Godino and Yusuf decided to organise a workshop at KIU that would teach Yusuf and his students the skills needed to work with *Drosophila*. Isabel was invited to lead

some of the sessions at the workshop. “It was clear that these scientists had a great desire for knowledge and wanted to do good research,” she says, “but they didn’t have the money or the facilities.” Isabel and her colleagues realised that *Drosophila* could help the researchers – and others in Africa – achieve their goals.

Since then, they’ve organised several workshops in Uganda and Kenya, and more are planned for Nigeria, South Africa and Egypt. Three years into the project, they’re seeing attendees from the workshops setting up fly laboratories at their own institutions. They’ve had master’s students successfully defend their theses on *Drosophila*, and there are PhD students who will soon be doing the same. A network of scientists from several African countries is also developing. They’ve started organising workshops, and Isabel hopes they’ll soon be running laboratories and applying for grants independently.

Another idea Isabel is considering is the establishment of an institute for basic biomedical research in Uganda, so instead of arranging workshops in several countries, scientists could come to a central hub where they would develop the skills needed to work with inexpensive model systems like *Drosophila*. Over time, their research could expand to other model systems and a broader range of cell biology

techniques. “But it has to be from the inside,” she says, “with scientists talking to their governments and trying to get that kind of research institute going. Maybe one day there could be an organisation of several African countries working together, similar to EMBL in Europe.”

When I ask Isabel about some of the difficulties she’s faced with the DrosAfrica project, she answers without hesitation. “The challenges are always time and funds. For most of us, this is not our main job and we also need to focus on the other aspects of being a scientist – publishing papers and getting grants”, she explains. “But with DrosAfrica, what you put in and what you get out are a lot more balanced than it usually is in science. I find it the most satisfying project I have.”

Resources

To learn more about model organisms, including *Drosophila*, see:

Torti F (2017) Life models. *Science in School* **39**: 21–24. www.scienceinschool.org/2017/issue39/models

For examples of research using *Drosophila* as a model, see:

Békési A, Vértessy BG (2011) Uracil in DNA: error or signal? *Science in School* **18**: 27–31. www.scienceinschool.org/2011/issue18/uracil

EIROforum (2012) Bigger, faster, hotter. *Science in School* **24**: 27–31. www.scienceinschool.org/2012/issue24/eiroforum#embl

Edward Dadswell has a degree in physics from Imperial College London and a master’s degree in creative writing from the University of East Anglia, UK. His previous jobs have involved gutting fish, selling books, managing clinical trials in cancer research, and teaching English in Russia. Now a science writer at the European Molecular Biology Laboratory, he thinks he’s finally figured out what he wants to be when he grows up.



How do birds fly?

A hands-on demonstration

Image courtesy of Andrew Burgess / shutterstock.com



Dissect a chicken from the supermarket to discover the unusual pulley system that enables birds to fly.

By Edmond Hui, Faye Blackshaw, Alma Talbot

Many biologists are able to look at an animal, living or dead, and learn how it works. In previous decades, this ability was acquired in whole dissections of rats, frogs and earthworms.

These days, students have legitimate concerns about whether it's right to kill animals solely to take them apart and study them. Fewer dissections are performed in schools, and they rarely involve whole animals – instead, individual organs such as the heart are used. At the same time, meat is increasingly sold pre-prepared and packaged to minimise handling or processing in the kitchen. Many children don't grow up watching their parents handling meat or preparing whole chickens, rabbits or other animals in the kitchen. Consequently, today's students approach dissection with less

experience and a more profound feeling of squeamishness than ever before.

Nonetheless, the land vertebrate most commonly sold for food in a nearly complete state is probably the chicken, and it is therefore the livestock most familiar to students. Even without its internal organs, the chicken provides an excellent introduction to dissection.

The flight muscles of birds

The flight of birds has always fascinated humans. Our arms have the same sets of bones and we share many of the same muscles as birds, yet we can only flap our arms and imagine



REVIEW

- ✓ Biology
- ✓ Anatomy
- ✓ Animal physiology

This article about the anatomy and physiology of bird wings and how they function is a wonderful opportunity to lighten up early science teaching. Young students are keen to explore and come to their own conclusions; a chicken dissection is perfect.

The hands-on approach, in contrast to learning from anatomical drawings presented in textbooks, will boost students' learning and memory. Comparing bird anatomy to our own anatomy may lead to some fun, and also to speculation about why humans cannot fly. Students of all ages could create labelled sketches of the bird's anatomy – similar to da Vinci's, but now including the shoulder! Older students could dig deeper into the physiology of wing movements using anatomical charts of different birds – especially flightless birds.

If the dissection is done in a food technology room rather than a science laboratory, you can cook and eat the chicken afterwards. This highlights the knowledge

- ✓ Physics
- ✓ Evolution
- ✓ Ages 11–19

to be gained by paying attention to everyday habits – meat-eating students might eat chicken breasts on a fairly regular basis, but it's unlikely that they will ever have stopped to consider the function of the muscles they are eating. Be prepared for the question 'how was this chicken killed?', which may arise particularly from non-meat-eating students, and always perform a professional dissection to show respect for the animal.

There is also plenty of room for discussion about:

- Differences in wing anatomy of various birds
- Flying patterns in different birds and how they affect anatomy
- Muscle weight and how this reflects function
- Differences in dark and white meat.

Friedlinde Krotscheck, secondary-school biology teacher (retired), Austria

ourselves flying. Leonardo da Vinci, for example, was fascinated by the possibility of human mechanical flight and had a lifelong passion for studying the flight of birds and the mechanical workings of the human body. He produced countless annotated sketches of the shoulders and arms of humans and how they attach to the torso. Yet when he studied the structure of a bird wing, he drew it only as far as the shoulder joint. By not investigating the connections of the wing to the muscles that make it flap, he seems to have stopped just when things got interesting.

The primary purpose of this activity is to show the two main muscles of the wing-flapping mechanism and demonstrate how they work. It is perhaps surprising that although the structure of chicken wings and the muscles that make them flap are familiar to almost anyone who is not a vegetarian, people rarely make the connection between the two because the wings and the breast are often eaten separately. The secondary purpose of this activity is to familiarise students with the process and scientific

“Our arms have the same sets of bones and we share many of the same muscles as birds.”

value of dissections in general – that dissections are key to understanding how living things function.

The activity could be used in a biology lesson on bird flight or animal locomotion or related to a physics lesson on forces. It could also support a lesson on evolution – the reason birds' wings are so similar in structure to our arms – or on model organisms, including how chickens can be used to investigate human limb development^{w1}.

Depending on the age or ability of the students, teachers can either perform the dissection or encourage the students to do it themselves.

Materials

- A plucked chicken (see below)
- A sharp knife or scalpel
- A bamboo or metal kebab skewer
- Gloves

The more complete the chicken, the more interesting the demonstration. In some European countries, plucked chickens are readily available from supermarkets with the head, neck, feet and internal organs (giblets) intact. Teachers can extend this demonstration to other organ systems as desired. Alternatively, a wrapped supermarket chicken as sold in the UK without feet, neck or giblets is perfectly adequate for the demonstration as described here. Teachers may choose to buy organic or free-range chickens.

Safety note: This demonstration carries risks associated with the bacteria found

Image courtesy of L Shyamal / Wikimedia Commons

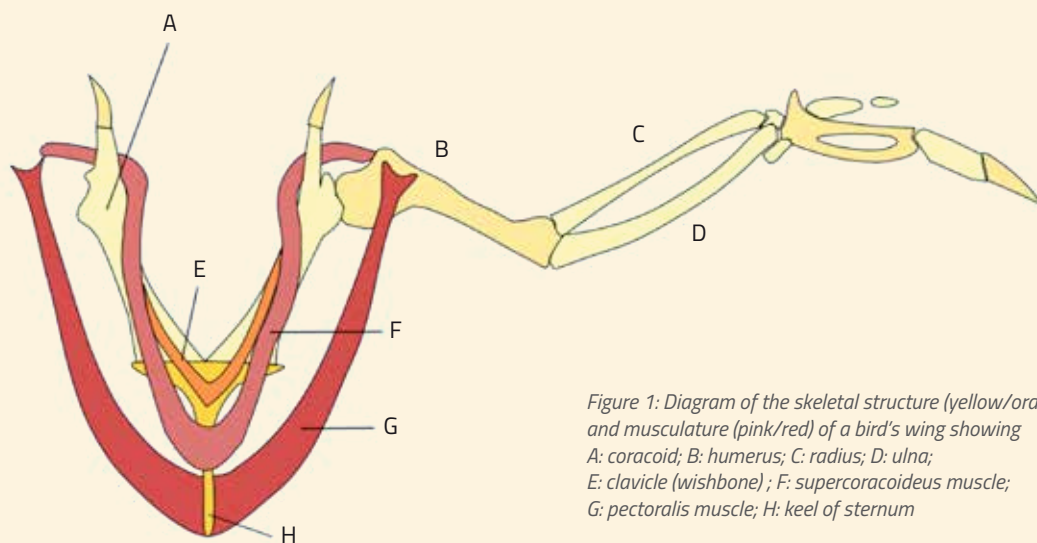


Figure 1: Diagram of the skeletal structure (yellow/orange) and musculature (pink/red) of a bird's wing showing A: coracoid; B: humerus; C: radius; D: ulna; E: clavicle (wishbone); F: supracoracoideus muscle; G: pectoralis muscle; H: keel of sternum

on raw poultry such as salmonella and listeria, as well as with sharp knives or scalpels. Teachers should follow their local health and safety rules. Gloves should be worn to reduce the risk of contamination but are not a substitute for thorough washing of hands afterwards. See also the general safety note on the *Science in School* website and at the end of this print issue.

Method

1. Before you start the dissection, identify the homologies (similarities based on descent from a common ancestor) between the chicken's wings and the human arm.

Students will see the similarities between the features in humans – the single bone (humerus) in the

upper arm, the elbow, the two bones (radius and ulna) in the forearm, the multi-boned wrist, and the hand with the thumb – and their counterparts in the chicken wing (figure 1).

2. Extend the wing by inserting a skewer (figure 2). This keeps the arrangement of the wing bones approximately as they would be in flight. We also attached a feather to the skewer to show the wingspan of the chicken.

Explain to the students that in humans, the muscles moving the arms in a 'downstroke' motion are the pectoralis (or chest) muscles, while the 'upstroke' muscles are on the back. In a bird, both sets of muscles are in the chest. The muscles are easily identified, even

in supermarket chicken breast fillets – the downstroke muscle is the larger pectoralis muscle on the outside, while the upstroke muscle is the supracoracoideus on the inside (figure 3). This smaller muscle is often sold as a 'mini fillet' in the UK or 'aiguillete' in France (figure 4). The antagonistic action of these two muscles on the wing (one muscle opposes the action of the other) will be demonstrated later.

3. Remove the skin from the breast of the chicken (figure 5). Identify the left pectoralis muscle (this is easier if the demonstrator is right-handed). Note that it is attached not only to the keel of the sternum, but also dorsally to part of the rib structure and anteriorly to the clavicle (or 'wishbone') (figure 1).

Images courtesy of Edmond Hui



Figure 2: The wing is extended using a bamboo skewer.

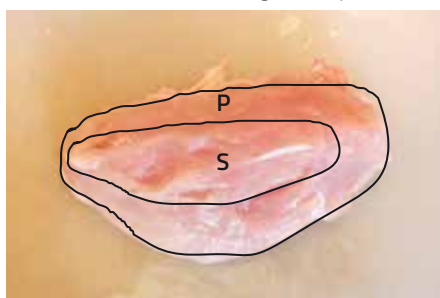


Figure 3: A chicken breast consists of the larger pectoralis muscle (P) and smaller supracoracoideus muscle (S).

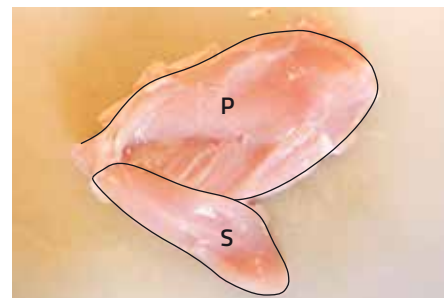


Figure 4: The smaller supracoracoideus muscle (S), attached to the pectoralis muscle (P).

Figure 5: The skin is removed from the left pectoralis muscle (P).

4. Using the knife, carefully separate the pectoralis muscle from the sternum, ribs and clavicle, taking particular care near the anterior end (figure 6). Leave the muscle attached to the humerus. Note that pulling on the pectoralis moves the wing in a downstroke.
5. Flip the pectoralis over (figure 7) and separate the supracoracoideus from the sternum (figure 8), noting that it terminates in a tendon that disappears anteriorly under the coracoid bone (figure 9). Explain that this tendon is inserted dorsally into the humerus, having passed around a 'pulley' or curved channel in the coracoid bone.
6. Hold the pectoralis muscle in the left hand and the supracoracoideus muscle in the right (figure 10). Use the heel of the right hand to pin the chicken to the table. Pull the pectoralis in a ventral direction and note that the wing performs a downstroke. Pull the supracoracoideus ventrally and note that the wing performs an upstroke (figure 11). With a little practice, the two muscles can be pulled alternately and rhythmically to produce a continuous flapping motion in the wing. A video showing the wing-flapping mechanism is available on the *Science in School* website^{v2}.

The students should be given an opportunity to try this – by pulling on the pectoralis and supracoracoideus muscles, they will appreciate the amount of force that is needed to flap the wings during flight. It's also remarkable to see that the muscles that move the wing upwards and downwards are both located below the wing. This is counter-intuitive because our human 'upstroke' muscles are on our back, not our chest.

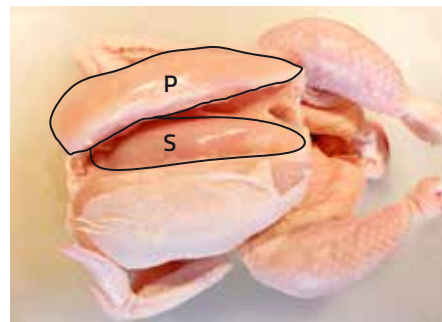
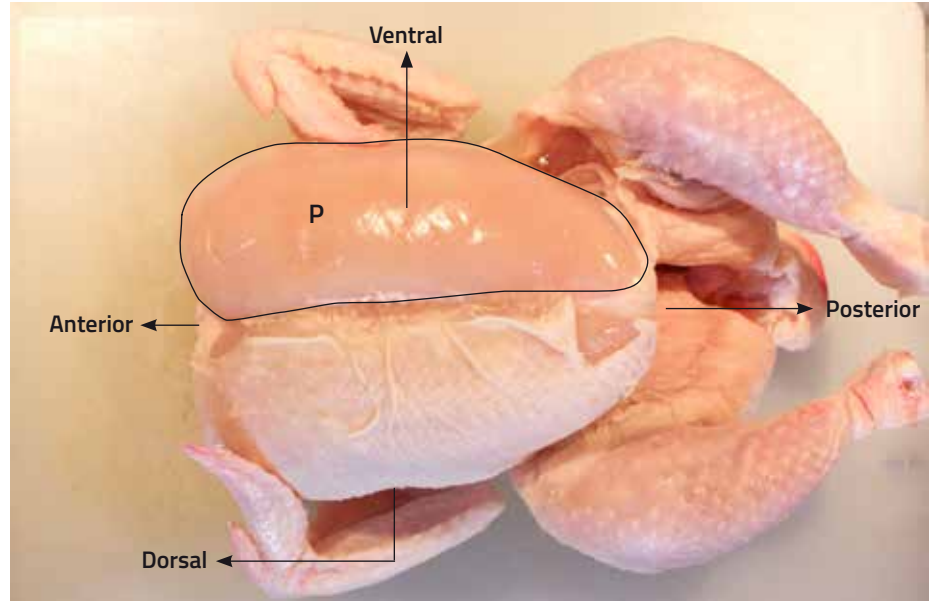


Figure 6: The pectoralis muscle (P) is separated from the sternum and moved laterally to reveal the supracoracoideus muscle (S) underneath.

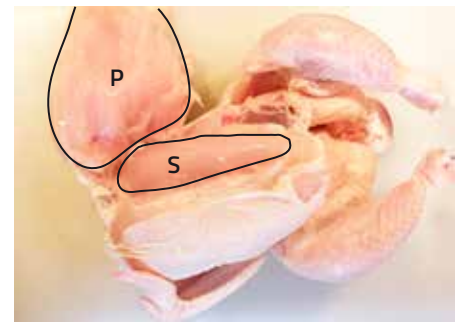


Figure 7: The pectoralis muscle (P) is flipped over to expose the supracoracoideus muscle (S).

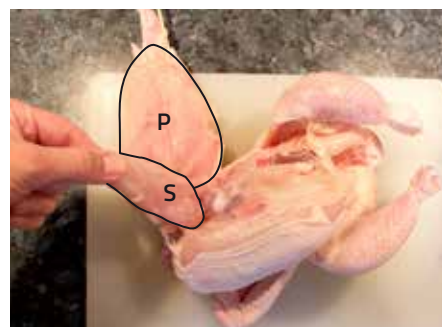


Figure 8: The pectoralis muscle (P) and the supracoracoideus muscle (S), which is separated from the sternum

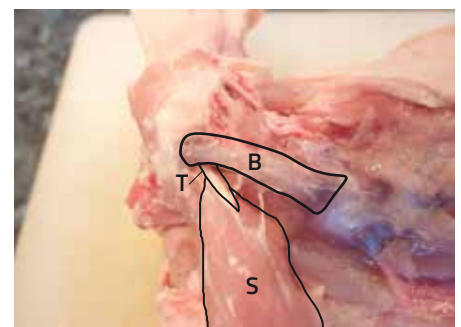


Figure 9: The supracoracoideus tendon (T) disappearing under the coracoid bone (B). S: supracoracoideus muscle



Figure 10: The wing ready to be pulled in a downstroke



Figure 11: Pulling the pectoralis muscle in a ventral direction creates a downstroke.

Images courtesy of Edmond Hui, Faye Blackshaw, Alma Tailbot

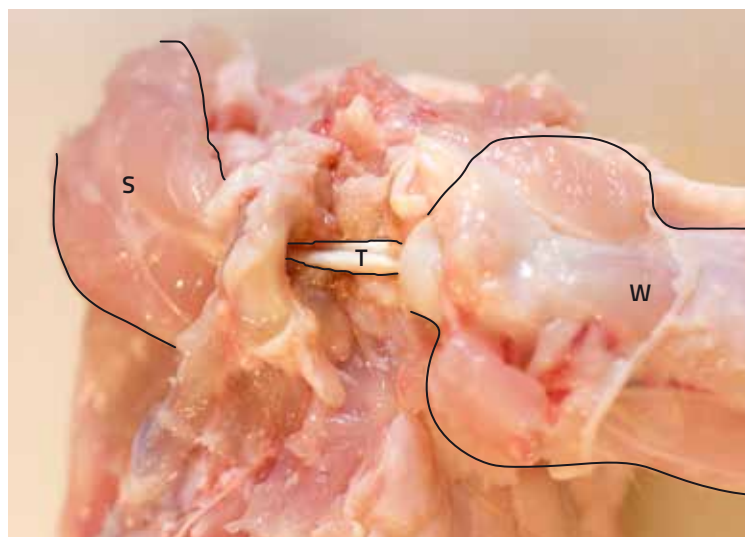


Image courtesy of Edmond Hui

Figure 12: The shoulder joint is disarticulated and the wing (W) is in the full upstroke position. The supracoracoideus tendon (T) is clearly visible and is now the only connection between the wing and the body. The channel of the 'pulley' can be seen above and to the left of the tendon. S: supracoracoideus muscle

Extension activities

The dissection can be extended to any other parts of the chicken, depending on the completeness of the bird. For example:

- Remove the pectoralis muscle completely and trace the path of the supracoracoideus tendon around the shoulder joint, pointing out the 'pulley' or channel in which the tendon runs (figure 12).
- Remove the pectoralis and supracoracoideus muscles and weigh them

individually. The ratio of their masses, which is about 5:1 for most birds (Biewener, 2011), gives an estimate of the relative forces required to move the wing downwards and upwards. The pectoralis of one of our specimens weighed 200 g, and the supracoracoideus 45 g, giving a ratio of 4.44:1.

We would expect the ratio to reflect the flight habits of the respective species, with atypical birds that generate considerable lift on the upstroke – such

as hummingbirds – having smaller ratios; and faster flying migratory birds that use aerodynamic forces to aid the upstroke – such as waterfowl – to have higher ratios.

Point out that there is a continuous seal around the supracoracoideus – it is in a cavity enclosed entirely by the pectoralis and sternum. Usually, antagonistic muscles are located on opposite sides of the joint that they act upon. The arrangement of both muscles being on the same side in birds, with one muscle wrapped around and fully enclosing its antagonist, is unusual. It would be interesting to discover whether this morphology exists elsewhere in the animal kingdom.

- If the chicken has intact legs, the same style of investigation can be used to demonstrate the muscles and tendons of the leg, which can flex and extend the foot and the claws (figure 13). Note the remarkably smooth and slippery nature of the cartilage of the joints, and point out the importance of reducing friction in these articulations.

Conclusion

This demonstration is an opportunity to achieve three objectives with one bird.

1. Using a familiar supermarket chicken alleviates some of the logistical, cultural and psychological pressures that lead to a reduction in school dissections while still yielding real anatomical information.
2. By simply pulling on the chicken's breast muscles, students see the action of antagonistic muscles to flex and extend vertebrate limbs, which is part of many standard biology curricula.
3. Attempting to answer questions such as 'how does a chicken flap its wings?' or 'what is the role of a chicken's breast?' allows students to experience perhaps the most difficult part of science to teach – the act of discovery. They will almost certainly be surprised to discover not



Image courtesy of Edmond Hui

Figure 13: Investigating the muscles of the legs



only that the chicken breast they eat is responsible for the bird's flapping strokes, but also that they can demonstrate this themselves.

References

Biewener A (2011) Muscle function in avian flight: achieving power and control. *Philosophical Transactions of the Royal Society B* **366**: 1496-1506. doi: 10.1098/rstb.2010.0353

Hui E, Taplin A (2013) From the bottom of our hearts: a hands-on demonstration of the mammalian heartbeat. *Science in School* **27**: 20-25. www.scienceinschool.org/2013/issue27/hearts

Web references

w1 Megan Davey explains in a video how she investigates the development of the human hand using chickens as a genetic model. See: <https://tedinnovations.ted.com/2016/06/08/why-do-we-have-five-fingers-a-gene-called-sonic-hedgehog>

w2 Watch a video showing how to simulate the wing-flapping mechanism by alternately pulling on the right pectoralis and supracoracoideus muscles. See: www.scienceinschool.org/2017/issue41/chicken

Resources

A video of the flight muscles of snow geese could be used to support the activity, particularly if a dissection at school is not feasible. See: www.youtube.com/watch?v=aFdvkOpOmwo

Edmond Hui is a marine biologist by training and the network manager at Teddington School, UK. His previous article for *Science in School* describing a new demonstration of the mammalian heartbeat (Hui & Taplin, 2013) was made into an animated lesson at TED.com. Faye Blackshaw and Alma Talbot are enthusiastic 13-year-olds and are both members of the Teddington School STEM club.



Image courtesy of FiledIMAGE / Shutterstock.com



To the Moon and back: reflecting a radio signal to calculate the distance

Using a simple calculation, measure the distance between Earth and the Moon with the help of a local amateur radio station.

By Richard Middelkoop

Inspired by an earlier article in *Science in School* that used photography to measure the distance to the Moon (Cenadelli et al., 2016), we set up an experiment with groups of scouts around the globe to do the same with radio signals. With help from a qualified radio user, the groups sent radio signals from their transmitter stations to the Moon. The signals bounce off the surface of the Moon and back to Earth, where they are detected by a receiver. This radio transmission technique, which is known as 'moon bounce' or 'Earth-Moon-Earth' communication, was used extensively for military communication in the days before satellites.



Since radio waves are a type of electromagnetic radiation, they travel at the speed of light. Due to the travel time between Earth and the Moon, the reflected radio signal is delayed typically by a few seconds. Using this time delay, the groups calculated the distance that the radio wave travelled and successfully measured the distance to the Moon.

Measuring the distance from Earth to the Moon

In this article, we describe how to conduct the activity at your school, beginning with contacting a radio amateur (a person licensed by the relevant authorities to transmit high-power radio signals) for help. We then explain how to transmit and measure the radio signal, and carry out the final calculation. The experiment, which must be carried out when the Moon is above the horizon^{w1}, is suitable for students aged 11 and above and will take around 1.5–2 hours, including set-up time.

For the teacher

The use of an amateur radio station is essential to send the radio signal to the Moon, so you will need to ask your local or national radio amateur club^{w2} (most countries have one) for their assistance. People with an interest in radio transmission can take an examination to obtain a licence that allows them to transmit radio signals at amateur radio frequencies.

The radio amateur can send and receive the signal at their amateur radio station, or the necessary equipment can be set up at your school.

This requires:

- An antenna capable of being pointed at the Moon to convert the signal into radio waves, and vice versa (figure 1)
- A radio transmitter/receiver (figure 2) to transmit the radio waves and receive the bounced waves from the Moon
- A dual-channel oscilloscope (figure 3) to show the time delay between transmitting and receiving the radio waves (figure 4)



REVIEW

- ✓ Physics
- ✓ Electromagnetic waves
- ✓ Radio communication
- ✓ Planetary and moons' orbits
- ✓ Ages 14–19

This activity can provide students with a unique opportunity to take a peek into the world of the experts, observe them while working and understand the science behind the instruments used. It is a fantastic way to put some of the theory learned about radio waves into practice, by calculating the distance of the Moon from different locations, and to investigate the Moon's orbital pattern. It would also be a great opportunity to collaborate with another school on the other side of the globe and share results and experiences.

Catherine Cutajar, physics teacher, St. Martin's College Sixth Form, Malta

Your radio amateur will be able to provide the equipment, if necessary with the help of a local amateur radio club. If the radio amateur sends the signals from the amateur radio station, the returning signals can be streamed via the internet to be viewed at your school (see 'A louder alternative' section).

For the radio amateur

1. Set up the transmitter/receiver and connect it to the antenna.

Image courtesy of Yiyi_2b / Flickr



Figure 1: Yagi radio antenna

Image courtesy of Dave Clausen / Wikimedia Commons



Figure 2: Radio transmitter/receiver

Image courtesy of Elborgo / Wikimedia Commons



Figure 3: Dual-channel oscilloscope to measure the time delays

Image courtesy of Nicola Graf

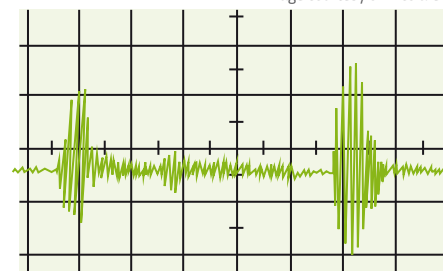


Figure 4: The oscilloscope will show a radio signal pattern, similar to the signal shown, as it is transmitted and received.

The antenna and radio transmitter should be within line of sight of the Moon, and the receiver should not be disturbed by interference signals, such as large electric installations nearby. You can find out where exactly the Moon is positioned in the sky, as seen from your location at the time of the experiment, by looking on the Sky Live website^{w3}.

2. Select an appropriate frequency in a VHF or UHF amateur radio band.
3. Point the antenna towards the Moon.
4. Connect the oscilloscope to the sound input of the transmitter so that it shows the signal being transmitted.
5. Connect the output of the transmitter/receiver to the second channel of the oscilloscope.
6. Transmit a signal in Morse code or as a series of pulses that easily show on the oscilloscope.
7. On the receiver, listen for the reflection of your signal and watch it on the oscilloscope.
8. Set the transmitter/receiver in the 'break-in mode' to quickly switch between transmitting and receiving.

9. Adjust the antenna direction if needed.
10. Align the two signals seen on the oscilloscope and read the time delay between them from the screen.

For the students

Using the time delay, calculate the distance d to the Moon using the following equation:

$$d = \frac{(c \times t)}{2}$$

where:

d = distance of Earth to Moon in metres

c = the speed of light, 3×10^8 metres per second

t = time delay in seconds

The radio signal covers the same distance twice (Earth to the Moon, and back), hence the need to divide by 2.

For example, with a delay time of 2.56 seconds:

$$d = \frac{[(3 \times 10^8) \times 2.56]}{2}$$

$$d = 348\,000\,000 \text{ m}$$

Extension options

- The radio amateur could send and receive multiple signals so that students obtain several time-delay measurements to find the mean and standard deviation and thus achieve a more accurate result.
- Digitally record the transmitted and received signals using a simple audio recorder, such as on a smartphone, to analyse the signals at a later stage. This enables other students to carry out the activity without the radio amateur present.

Questions

Why does the distance to the Moon vary slightly depending on the observation point on Earth?

Due to the curvature of Earth, the simple formula introduces a small error: the distance to the Moon is slightly different depending on where the observation point is on Earth – close to the equator or closer to one of the poles (see figure 5). This error is very small compared to the huge distance from Earth to the Moon, so it is ignored for this experiment.

Image courtesy of WOSM



Scouts from the USA taking part in the activity

Image courtesy of Nicola Graf

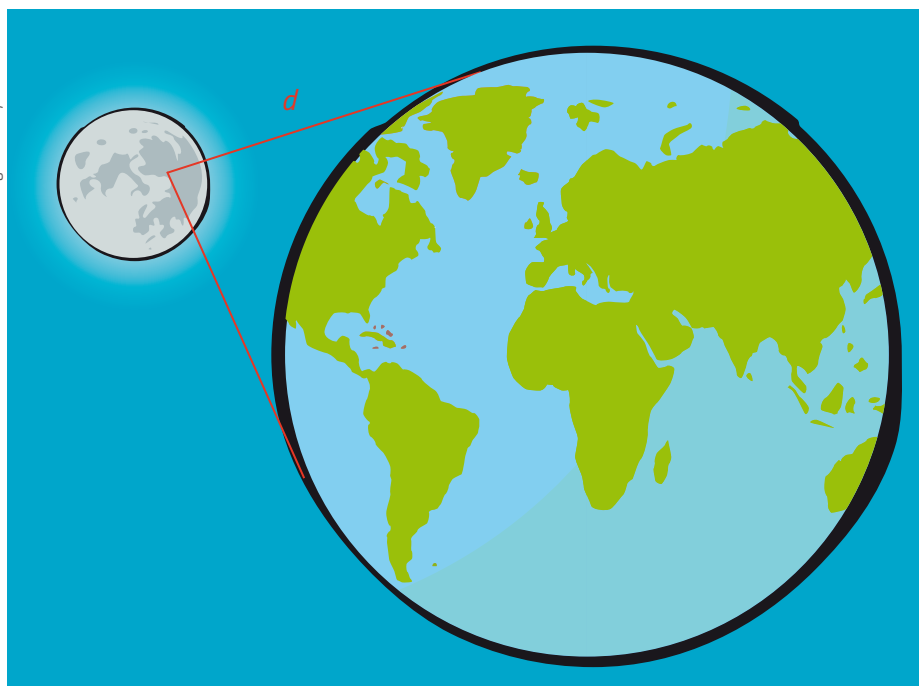


Figure 5: Depending on the Earth observation point, the distance d from Earth to the Moon varies (image not to scale).

The experiment to measure the distance to the Moon and back was carried out by several scout groups during their annual event, called Jamboree-On-The-Air^{w4} (JOTA) in October. The groups were scattered all over the globe, so the aspect angle between their observation points and the Moon were all different.

Why would the result vary if you repeated the experiment two weeks later?

The distance from Earth to the Moon is not completely fixed. The Moon's orbit around Earth is not a perfect circle, so the distance varies slightly (figure 6). The experiment was carried out in the same weekend so the distance variation had little to no influence.

What other sources of small errors are there in your experiment?

- Delays in streaming the signals over the internet introduces a small error in the calculated distance. This extra delay is typically an order of magnitude smaller than the delay caused by the signal travel time between Earth and the Moon and is therefore ignored in this experiment.
- The accuracy of the oscilloscope, which depends on the time base (the number of seconds per screen division), can also introduce errors. Typically, the reading can be accurate up to one-tenth of the time base setting. The lower the time base is set, the higher the sweep frequency and the more accurate the result.

Image courtesy of Darekk2 / Wikimedia Commons

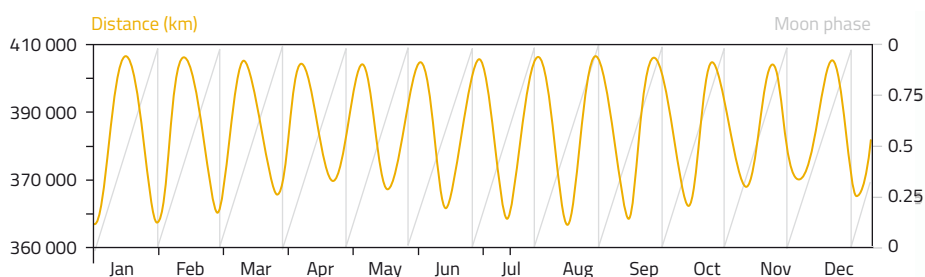


Figure 6: Distance of the Moon and the Moon phases in 2014.

- A weak signal (one that is only just visible above background noise) is more difficult to read on the oscilloscope screen. Identifying the time delay is open to errors, and variations of up to several hundreds of milliseconds can easily occur. Taking multiple measurements and using the average can reduce the error margin.
- Objects that partially block the path of the radio wave can cause the signal to scatter. This is more likely to occur in urban areas than in open fields and can result in multiple echoes that are visible on the oscilloscope, which in some cases can be stronger than the directly reflected signal from the Moon. As a result, students may mistakenly use the wrong echo to read the time delay.

A louder alternative

If the signal is not strong enough to carry out the activity using the method described for the radio amateur, or you wish to stream the radio signals via the internet, you can use this alternative method instead.

To determine whether the signal will be strong enough, the radio amateur should check the equipment sensitivity and find out exactly where the Moon is positioned in the sky prior to the activity. If they can't hear the reflected signal, or if the visual signal is lost amongst background noise on the oscilloscope, they can use a large astronomy radio telescope at the Dwingeloo Radio Observatory in the Netherlands as the receiver (figure 7). The radio telescope has been refurbished and is operated by a group of radio amateurs. It receives the radio signal and converts it into a visible signal, which is streamed online and is available for anyone to view^{w5}.

For the radio amateur

1. In preparation, use the C A Muller Radio Astronomie Station (CAMRAS) website^{w6} to check for planned activities at the Dwingeloo Radio Observatory. If the telescope is unavailable,

Image courtesy of Uberprutser / Wikimedia Commons



Figure 7: The amateur telescope at the Dwingeloo Radio Observatory in the Netherlands

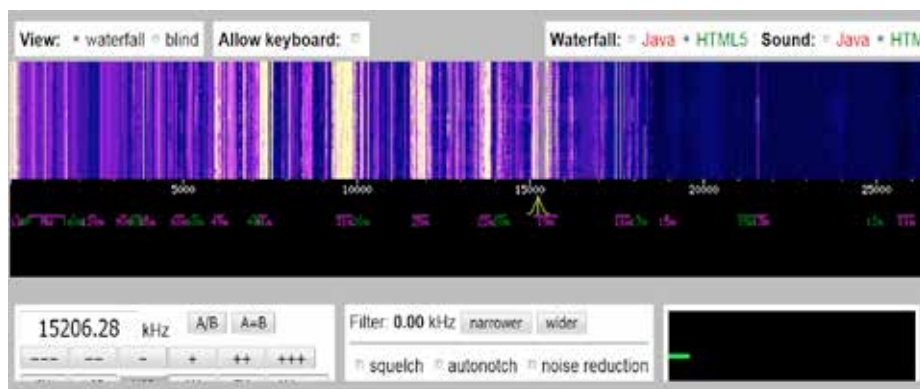


Figure 8: Set the correct frequency on the CAMRAS WebSDR stream to make the radio signals visible (data source: <http://websdr.camras.nl:8901>)

- you can find an alternative receiver listed on the WebSDR website^{w7}. Anyone – not just radio amateurs – can use the website at any time. Check that the Moon will be visible from the observatory at the time of your planned experiment^{w3}. Follow steps 1–4 of the original procedure.
- On the CAMRAS webpage showing the WebSDR stream^{w5}, shift the yellow slider to the same frequency that will be used to transmit your signal to the Moon (see figure 8).
- Transmit a signal in Morse code or as a series of pulses that easily show on an oscilloscope connected to your computer.
- On the computer, listen for the audio signal of the reflected radio wave and watch it on the oscilloscope. Students could also view the signals on separate computers.

- Align the two signals seen on the oscilloscope and read the time delay between them from the screen.

Reference

Canadelli D et al (2016) Geometry can take you to the Moon. *Science in School* **35**: 41–46. www.scienceinschool.org/content/geometry-can-take-you-moon

Web references

- To find out the positions and times that the Moon rises and sets, visit the Heavens Above website. See: www.heavens-above.com
- Find your radio amateur using the International Amateur Radio Union website. See: www.iaru.org/member-societies
- Find out exactly where the Moon is in the sky from your location at the time of your experiment using the Sky Live website. See: <http://theskylive.com/planetarium?obj=moon>
- Jamboree-On-The-Air (JOTA) is an international event of the World Organization of the Scout Movement^{w8}

(WOSM), encouraging scouts around the world to communicate with one another using amateur radio and the internet. See: <http://jotajoti.info>

- Visit the CAMRAS WebSDR stream to hear radio signals received by the Dwingeloo Radio Observatory amateur telescope in The Netherlands. See: <http://websdr.camras.nl:8901/>
- Find out whether the Dwingeloo Radio Observatory telescope will be available at the time of your experiment by visiting the CAMRAS website. See: www.camras.nl/agenda/
- To see a list of available radio receivers and to stream signals via the internet, visit the WebSDR website. See: www.websdr.org
- The World Organization of the Scout Movement (WOSM) is an independent, non-political, non-governmental organisation that is made up of 164 National Scout Organisations (NSOs) from 224 countries and territories around the world. With over 40 million members, WOSM is one of the largest youth movements in the world. See: www.scout.org

Resources

For a physics experiment showing wireless electromagnetism, see:

Iskra A, Quaglini MT, Rossi G (2006) Introducing radio transmission with a simple experiment. *Science in School* **3**: 39–42. www.scienceinschool.org/2006/issue3/radio

For an activity explaining how to make terrestrial measurements using the parallax method, see:

Pössel M (2017) Parallax: reaching the stars with geometry. *Science in School* **39**: 40–44. www.scienceinschool.org/content/parallax-reaching-stars-geometry

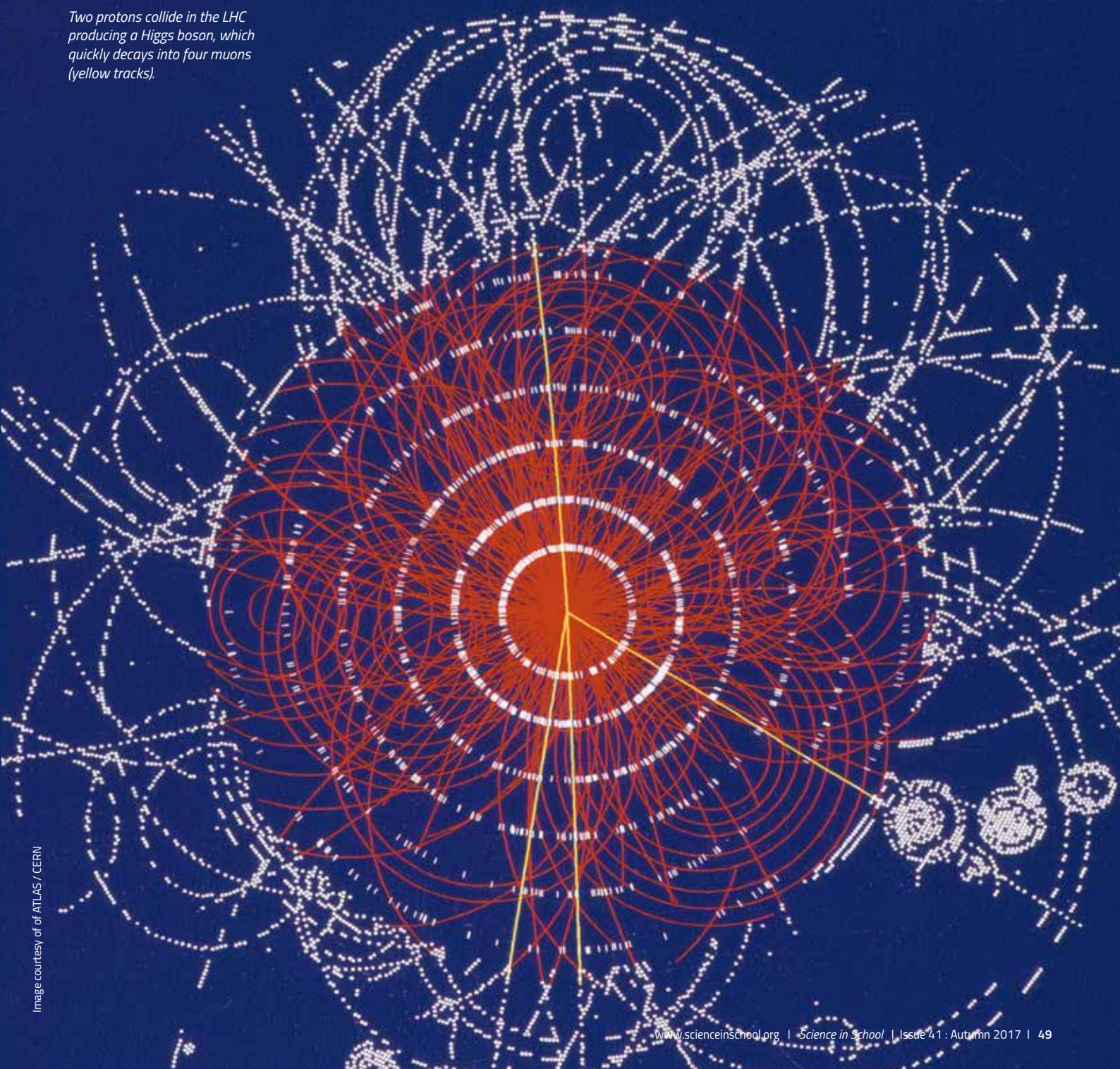
Richard Middelkoop has a bachelor's degree in electrical engineering and a master's degree in telecommunications from the Eindhoven University of Technology in The Netherlands. He volunteers at the World Organization of the Scout Movement^{w8} (WOSM) to lead a team that organises an annual get-together^{w4} for 1 million young people around the globe, by means of radio and internet connections.



A particle accelerator in your salad bowl

Create a particle accelerator using a Van de Graaff generator, a ping-pong ball and a salad bowl to understand how it is used to study matter at the smallest scale.

Two protons collide in the LHC producing a Higgs boson, which quickly decays into four muons (yellow tracks).



By Ricardo Torres

Scientists are always on the hunt to find the smallest building blocks in the Universe. The atom, once believed to be indivisible, was the smallest fundamental particle until it was split to reveal electrons, protons and neutrons. More powerful particle accelerators revealed that protons and neutrons could be divided even further: each contains three quarks. The latest of these discoveries is a particle called the Higgs boson, observed in 2012 by the world's largest particle accelerator – the Large Hadron Collider (LHC) at CERN.

Particle accelerators, which accelerate charged particles (such as protons or electrons) close to the speed of light, are used to study matter on the smallest scale. This enables scientists to better understand the properties of elementary particles, see how they interact and ultimately fathom how the Universe works. The theory that best describes particles and their interactions (all except gravity) is known as the Standard Model of particle physics. Since the model was finalised in the 1970s, it has successfully explained countless experimental results.

The quest is not over, though. It is known that the Standard Model describes only 4% of the Universe. Therefore, more experiments and more powerful tools are needed to explain the remaining 96%, including the enigmatic 'dark matter'. The accelerators that are used to perform these experiments are huge, but you can show their basic operation in your classroom.

Creating a salad bowl accelerator

You may have experienced a shock from static electricity caused by friction, or perhaps seen how a Van de Graaff generator can make your hair stand on end. This device is used to charge a large metal sphere to high voltage. It was invented to supply the high energy required to propel charged particles in early particle accelerators, and the same



- ✓ Physics
- ✓ Static electricity
- ✓ Magnetism
- ✓ Ages 14–19

REVIEW

This article models the operation of a synchrotron particle accelerator. It's great fun to build and even more exciting to operate and watch. A brief history of the use and operation of particle accelerators is included. This would be the perfect way to prepare for a trip to Diamond Light Source in the UK or CERN in Switzerland.

Comprehension questions could include:

- What are fundamental particles?
- Why are particle accelerators important to scientific research?
- Can the cost of particle accelerators be justified?
- Why can the building and operation of a particle accelerator be classed as multidisciplinary?

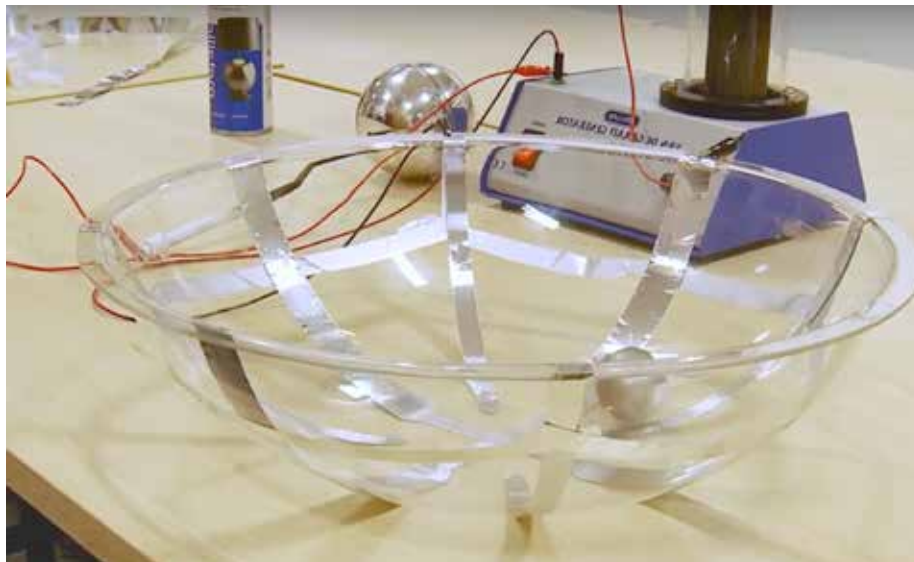
Robert Woodman, head of science, Ysgol Bro Gwaun, UK

principle is still used in electrostatic particle accelerators today.

Most modern large-scale accelerators, however, use changing electromagnetic fields: electric fields accelerate the particles to incredibly high speeds and magnetic fields control the beam of particles and its trajectory. This process can be demonstrated using a small Van

de Graaff generator, a metal-coated ping-pong ball and a salad bowl. Students can construct the accelerator themselves, or the teacher can prepare it in advance of the lesson. A video outlining how to build a salad bowl accelerator (following the method below), and a paper cup accelerator, is available on YouTube^{w1}.

Image courtesy of Cockcroft Institute



The salad bowl accelerator

Materials

- Plastic salad bowl (not glass): it should be smooth and with a shallow curve – any bump or dent will hinder the ball's trajectory
- One ping-pong or polystyrene ball
- Conductive paint: either nickel or graphite (to create the electrically conductive coating)
- Paint brush
- Aluminium (or copper) foil adhesive, at least 2 cm in width
- Van de Graaff generator (or Wimshurst generator)
- Electrical wires, banana plugs, crocodile clips
- Scissors
- Toothpicks (to hold the balls while painting and drying them)
- Newspapers (to protect surfaces when painting)
- Plastic spoons (to manipulate the balls when in the bowl)

Safety note

The voltage generated in a Van de Graaff can be very high (several tens of thousands of volts) but the current is low. That means that the electric shock is not dangerous to a healthy person, but it's still painful and should be avoided. Operation of the Van de

Graaff generator should be supervised by a trained adult (the teacher or demonstrator) and the following rules must be followed:

- Avoid touching or getting too close to the charged surfaces.
- Make sure that the earth clips are firmly attached.
- Always discharge the dome after use by touching it with an earthed object.

Method

1. Prepare the ping-pong ball by coating it in conductive paint. As the paint will need some time to dry, you may want to start painting the ball a few days before preparing the salad bowl.
2. Cut two pieces of aluminium tape. Each should be about 2 cm wide and long enough to go from one rim of the bowl, along the bottom of the bowl and up to the other rim.
3. In the middle of these strips, trim each side so they are narrower (about 1 cm in the centre) than the rest of the strip, as in figure 1.



Figure 1: Two pieces of aluminium tape are cut to the length of the salad bowl and so they are narrower in the centre.

4. Stick the strips onto the bowl: they should be at a 90° angle, forming a cross at the centre of the bowl. The strips should end at the edge of the bowl (figure 2).
5. Cut eight short, narrow strips (about 1 cm wide) from another piece of aluminium tape. They should be long enough for one end of the strip to run over the edge of the bowl when the other end is placed close to the centre of the bowl. Round the ends of the strips as charge may leak from sharp corners. Note that the wider strips in step 3 do not need to be rounded.
6. Using four of the narrow strips, stick one strip in each of the spaces between the cross. They should not be touching the centre. The end of the strips should run over the edge of the bowl and down the outside (figure 3).
7. With the remaining four narrow strips of tape, join all the narrow strips together on the outside of the bowl (figure 4).
8. Use aluminium tape, crocodile clips and banana plugs to connect one of the narrow strips at the edge of the bowl to the earth terminal of the Van de Graaff generator and

Images courtesy of Cockcroft Institute

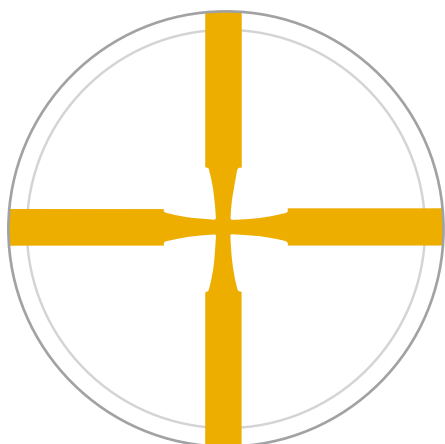


Figure 2: Two aluminium strips are stuck to the bowl to form a cross.

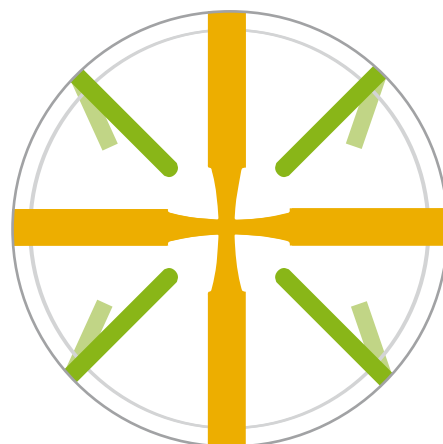


Figure 3: Four narrow strips of aluminium tape are placed in between the cross.



Figure 4: Connect the narrow strips of aluminium tape on the outside of the bowl using the four remaining strips.

Image courtesy of Cockcroft Institute

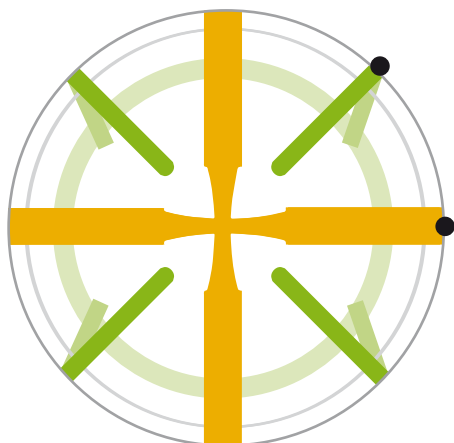


Figure 5: Connect one of the narrow strips at the edge of the bowl (green) to the earth terminal, and connect a point of the cross (yellow) to the high-voltage terminal.

connect the cross to the high-voltage terminal (the dome) of the Van de Graaff generator (figure 5). Make sure the high-voltage and earth leads do not touch each other.

9. Drop the ball into the bowl and switch the generator on.
10. Watch the ball spin inside the bowl. After the experiment, don't forget to discharge the Van de Graaff generator.

Troubleshooting

If the ball does not begin to spin:

- Check that the generator is on
- Nudge the bowl gently to initiate motion

Image courtesy of Cockcroft Institute



Hair-raising experiment with a Van de Graaff generator

- Check the live strips and wires are not touching the earthed ones
- Try using a smaller ball.

How does it work?

The Van de Graaff generator produces static electricity, which builds up a high voltage (over 30 000 volts) on the metal strips forming the cross. This means that these metal strips are charged (either positively or negatively). However, the current that is actually flowing is very small, which makes the whole procedure safe. The other strips are earthed so they hold no charge.

The moment the ball comes into contact with one of the charged strips, it picks up that charge. Because both the ball and the strip now have the same charge, they repel each other: the ball moves away. It then rolls onto an earthed strip, causing the ball to neutralise and lose its charge. The ball is accelerated every time it touches a charged strip and decelerates in between strips due to the friction with the bowl.

How is it similar (and different) to a real accelerator?

The salad bowl accelerator is a simple model for explaining the workings of real particle accelerators, such as the LHC. Although the same principle of the original Van de Graaff accelerator is still used today, modern accelerators have some fundamental differences.

Particle charge and electric fields

Unlike the particles in an accelerator, the ball in the salad bowl has no charge of its own – its charge changes depending on the aluminium strip that it was last in contact with. In CERN's LHC, the protons and ions each have their own charge, which does not change. Instead, specially designed metallic chambers are spaced around the accelerator, which oscillate between negative and positive charge, creating radio waves that push the particles forward in bunches.

In this activity, the ball represents one of the particles that scientists want to accelerate and collide. However, in a real collider, there are billions or even trillions of these, which together form a beam. To avoid collisions with air molecules, the beam travels in a vacuum inside a metal pipe. Monitoring the properties of this beam in real time is extremely important, for example to protect the machine, so scientists use a variety of techniques called beam diagnostics to track every single particle in the beam.

Size and shape

Particle accelerators can be linear, whereby the beam of particles travels in a straight line from one end to the other, or circular, in which the beam of particles travels around in a loop. The advantage of a circular accelerator, such as the LHC, is that with each loop, the particles accelerate a little bit more. This makes it possible to reach high energies, although the particles do lose some energy in each turn due to an effect called synchrotron radiation. The final energy of a circular accelerator is limited by its size, the intensity of the accelerating fields and of the bending magnets which keep the particles on track. A typical salad bowl is about 30–40 cm wide, whereas the LHC has a diameter of 8.5 km. The LHC's huge size is one of the reasons why it can accelerate particles almost to the speed of light.

In the salad bowl accelerator, the speed of the ball is limited by friction and by the rate of charge transfer between the strip and the ball. When the ball moves slowly, it remains on the strips for longer and has more time to charge and discharge, so there is more scope for acceleration. When the ball moves faster, it spends less time on the strips and eventually reaches a constant final velocity.

Magnets

Magnets are essential for controlling the unruly particles that circulate within both linear and circular accelerators. For example, quadrupole and

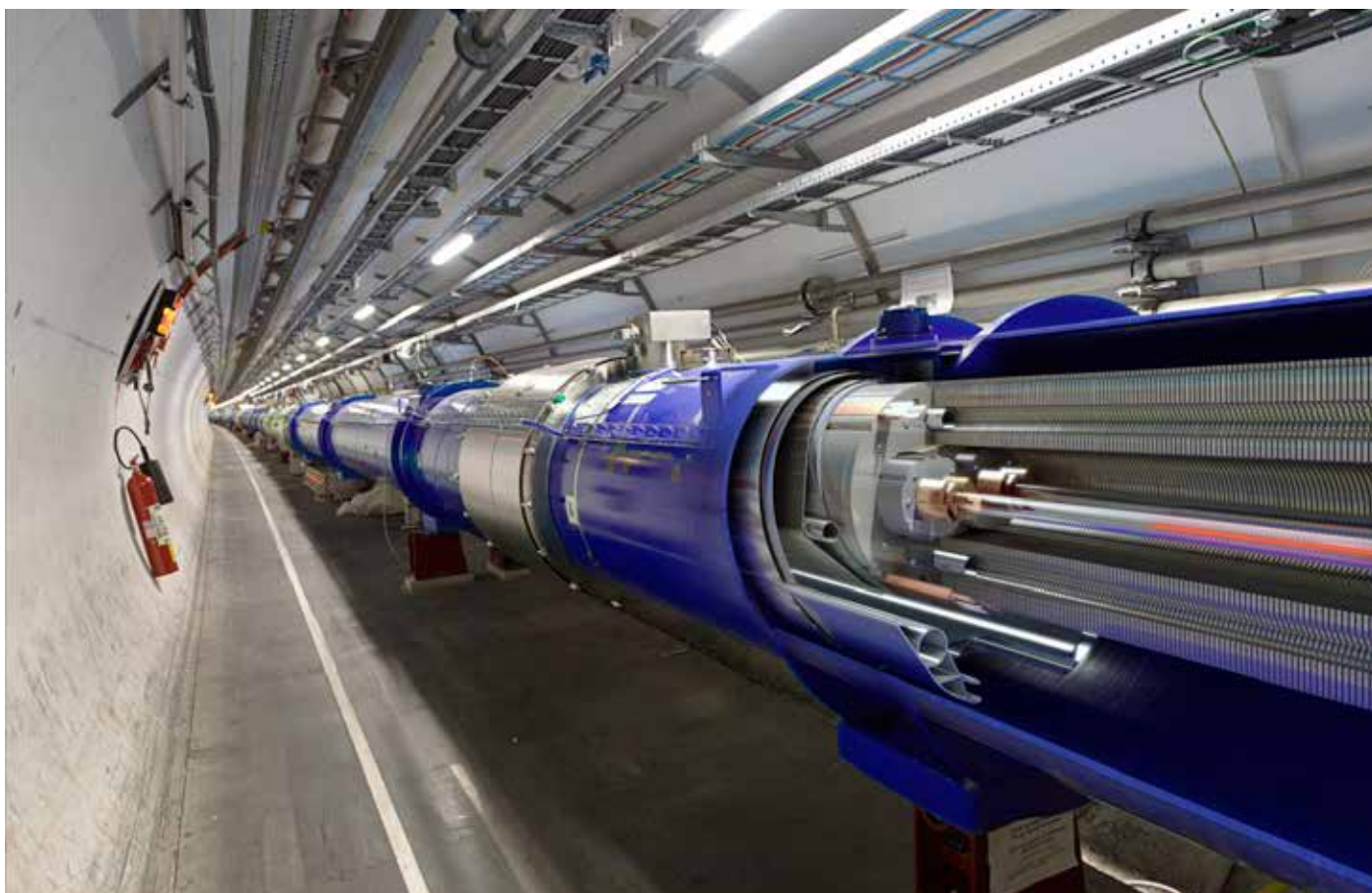


Image courtesy of CERN / Daniel Dominguez

Cross-section of one of the Large Hadron Collider dipole magnets

higher-order magnets are used to squeeze the particles together and to control the size and the divergence (how much the diameter of the beam increases with distance) of the beam. In circular accelerators, the particles also need to travel in a curve rather than a straight line, which is achieved using very strong dipole magnets. The higher the energy of the particle beams, the stronger the magnets need to be. The LHC's main magnets are superconducting, meaning they conduct electric current with zero resistance when they are cooled to sufficiently low temperatures. These magnets operate at a temperature of 1.9 K ($-271\text{ }^{\circ}\text{C}$), which is achieved by pumping 70 000 litres of liquid helium through a closed circuit around the accelerator. The salad bowl itself works like the magnets, constraining the movement of the ball and forcing it to travel in a circle – luckily, this works at room temperature.

Particle detectors

Accelerating particles is only the first half of the story. Particle accelerators increase the speed of particles to high energies before they are directed at a fixed target (such as a thin piece of metal foil) or made to collide by aiming two beams of particles at each other. In accelerators such as the LHC, two particle beams travel in opposite directions, one clockwise and the other anticlockwise, and they are made to collide almost head-on at specific points. Detectors are placed around the target point to gather information about the particles that result from the collision, such as their speed, mass and charge. From this information, scientists may discover new particles or find out how the particles interact with each other. This was how researchers at CERN discovered the Higgs boson, a particle believed to give mass to all the other particles in the Universe.

“Detectors are placed around the target point to gather information about the particles that result from the collision, such as their speed, mass and charge.”

Questions for the students

Why is the ball spinning in a particular direction?

Whether the ball spins in a clockwise or anticlockwise direction is determined by the initial impulse given to the ball. If the ball starts at rest, it will move away from the charged stripe in one direction or the other depending on the exact position of the ball, so it is difficult to predict. After a few random movements, a general direction sets in and the ball starts to accelerate.

Could you make the ball spin the other way around? How?

Just take the plastic spoon and give it a push in the opposite direction.

How could you make the ball spin faster?

The speed of the ball is limited by friction and by the rate of charge transfer between the strip and the ball. Having a smoother ball and bowl would allow the ball to reach final velocity more quickly, but it would not change the final velocity itself. The shape of the bowl is important because the final trajectory of the ball is determined by the balance between gravity, the centrifugal force and the normal force. The normal force prevents the ball falling through the plastic bowl, and because the force is perpendicular to

its surface, it depends on the shape of the bowl.

What happens if you use an uncoated ball? Why?

Without the conductive coating, the ball could neither charge nor discharge, so it would not accelerate.

Next generation colliders

Particle accelerators are complex and cutting-edge machines whose development usually requires collaborations between people from different countries, working in very different fields. It took almost 30 years for thousands of scientists, engineers and technicians to plan and build the LHC.

While the world's largest particle accelerator still has several decades left of activity, researchers from institutions all over the world are already putting their heads together to design the next generation of colliders. The replacement for the LHC will probably enter service in the 2040s, so most of the scientists who will operate it are currently in school. The salad bowl accelerator may just give them a head start.

Acknowledgement

The inspiration for this activity came from physicists Todd Johnson (Fermilab) and Suzie Sheehy (Oxford University) who work in the field of particle acceleration.

Web references

- w1 Watch a video from the Cockcroft Institute showing how to build salad bowl and paper cup accelerators. See: www.youtube.com/watch?v=8NQtjvGQA18 or use the direct link: <http://tinyurl.com/yjddmgx>
- w2 Connect with the University of Liverpool Physics Department and discover their outreach opportunities. See: www.liverpool.ac.uk/physics/outreach/
- w3 The Cockcroft Institute is an international centre for accelerator science and technology in the UK. It is a joint venture between the universities of Lancaster, Liverpool and Manchester and the Science and Technology Facilities Council (STFC) at the Daresbury and Rutherford Appleton Laboratories. See: www.cockcroft.ac.uk

Resources

- Explore how accelerators work and what their main components are using AcceleratAR, an augmented reality app. See: <http://acceleratar.uk>
- Discover what accelerators are used for and why they are important by watching this series of talks from the University of Liverpool. See: www.liverpool.ac.uk/physics/outreach/public-engagement/
- Visit the CERN website to learn more about the LHC. See: <https://home.cern/topics/large-hadron-collider>
- Watch a webinar from the Institute of Physics on the top five static electricity demos, including the salad bowl accelerator. See: www.talkphysics.org/articles/webinar-top-five-static-electricity-demos/
- Further information and alternative instructions for the salad bowl accelerator activity are available from the Science & Technology Facilities Council and the International Particle Physics Outreach Group. See: www.royalholloway.ac.uk/physics/documents/pdf/outreach/saladbowlacceleratorbackground.pdf and <http://ippog.org/resources/2014/salad-bowl-accelerator>
- To learn how to build your own Van de Graaff generator and linear accelerator, watch these videos on YouTube from the Cockcroft Institute. See: www.youtube.com/watch?v=EnRbHK8zlyE&t=9s and www.youtube.com/watch?v=wO4MeVwbwAo
- Read more about the LHC, the building blocks of matter and the standard model. Landau R, Rau M (2008) The LHC: a step closer to the Big Bang. *Science in School* **10**: 26–33. www.scienceinschool.org/2008/issue10/lhcwhy

Image courtesy of CERN / Maximilien Brice



Three scientists with one of the end-caps of the ATLAS detector, which will be used to detect particles produced in proton-proton collisions

Learn more about how the LHC works and read about some of the experiments being carried out at CERN.

Landua R (2008) The LHC: a look inside. *Science in School* **10**: 34–45. www.scienceinschool.org/2008/issue10/lhchow

Read the story behind the Higgs boson.

Hayes E (2012) Accelerating the pace of science: interview with CERN's Rolf Heuer. *Science in School* **25**: 6–12. www.scienceinschool.org/2012/issue25/heuer

Create a particle accelerator using a cathode ray tube to explore the principles of the LHC.

Brown A, Merkert J, Wilson R (2014) Build your own particle accelerator. *Science in School* **30**: 21–26. www.scienceinschool.org/2014/issue30/accelerator

A physics teacher explains how his time as a teacher in residence at CERN has inspired both him and his students.

Watt S (2012) Nuclear options: a teacher at CERN. *Science in School* **23**: 57–60. www.scienceinschool.org/2012/issue23/Bachmann

Bring particle physics to life in the classroom with the aid of a homemade particle detector.

Barradas-Solas F, Alameda-Meléndez P (2010) Bringing particle physics to life: build your own cloud chamber. *Science in School* **14**: 36–40. www.scienceinschool.org/2010/issue14/cloud

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