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Cells: why shape matters

INSPIRE

Art meets molecular biology

TEACH

Track inspection: how to spot subatomic particles

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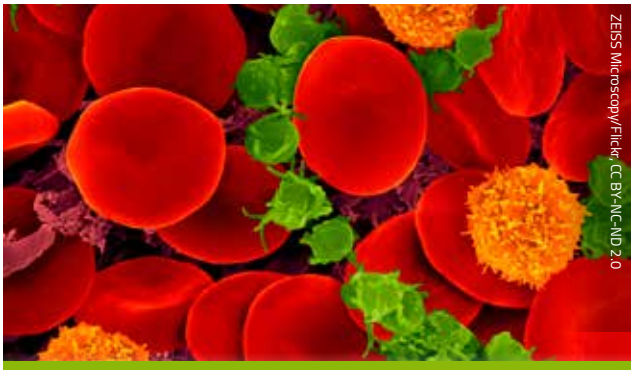
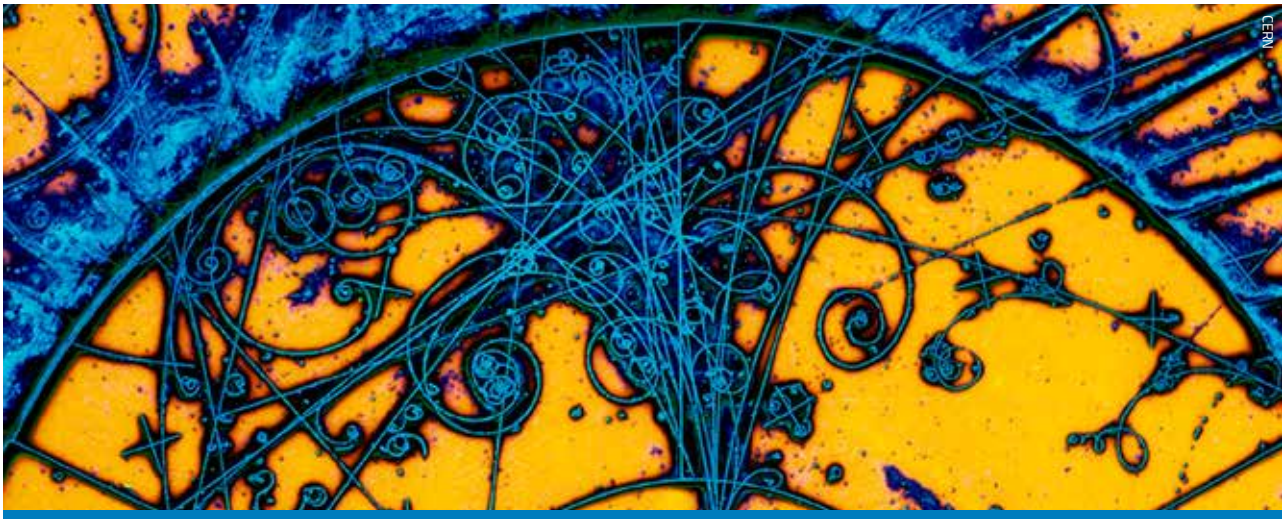


CELLS: WHY SHAPE MATTERS 08

New techniques are revealing how cells control their shape – and the changes that could give an early warning of disease.

ART MEETS MOLECULAR BIOLOGY 29

Step inside a science-inspired art exhibition where students bring biological molecules to life.



TRACK INSPECTION: HOW TO SPOT SUBATOMIC PARTICLES 40

Identify tracks of subatomic particles from their 'signatures' in bubble chamber photos – a key 20th century technology for studying particle physics.

UNDERSTAND

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EDITORIAL

Hannah Voak
Editor
Science in School
editor@scienceinschool.org

Teaching science often involves explaining things that are invisible to the naked eye: from the huge variety of microorganisms that are visible only under a microscope, to distant stars explored using powerful telescopes. The ability to reach into these remote worlds is one of the things that makes science so fascinating.

In this issue, we share an array of articles to help bring these hidden worlds into view. In the chemistry classroom, we investigate the benefits of the enzymes that lurk in your laundry detergent (page 34) and find out how scientists design molecules to make new drugs (page 25). In biology, we create living 'agar art', painting with the tiny microbes that live around us (page 48), and a researcher tells us how newly discovered bacterial communities on leaf surfaces can benefit the health of trees and forests – and can also help the environment (page 20).

For physics students, we reveal how they can identify subatomic particles by looking closely at the tracks seen in bubble chamber photographs from CERN (page 40). Venturing above Earth, we take a look at Aeolus, a new satellite launched by the European Space Agency, which promises improvements in global weather forecasting by delivering detailed data on Earth's winds (page 14).

Finally, we showcase how images and ideas from science can really spark the artistic imagination, with some striking artworks created by students. Starting with images of biological molecules usually reserved for the eyes of scientists, the students explore and reimagine these 3D structures to create their own artistic interpretations, adding some profound cultural reflections to the mix (page 29).

Whatever your area of science, we hope that this issue will inspire you to introduce some fresh activities into your teaching – just in time for spring.

Hannah Voak

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

Mercury's mysteries, astronomy education and a new generation of X-ray science

CERN

Catch cinnamon powder in a particle trap

CERN is synonymous with accelerators designed to boost subatomic particles to almost the speed of light. But to study a particle in detail, scientists must trap it and hold it in place for long enough to do so. To achieve this, CERN's experiments use devices called particle traps, which suspend particles using electromagnetic fields.

Now, thanks to 3D-printing technology, you can build your own particle trap that works in a similar way – although not quite for subatomic particles – using an open-source design developed by the S'Cool LAB team at CERN. This home-scale particle trap is best suited for suspending particles such as ground cinnamon powder, which are slightly charged. Its design principles, however, have a lot in common with the larger devices used in particle physics laboratories.

At the heart of its design is an electric quadrupole, a configuration of positively and negatively charged electrodes. Electromagnetic fields are generated by connecting these electrodes to an AC power supply. The fields limit the direction in which the electrically charged particles can travel, trapping them in the middle.

Particles suspended in a 3D-printed particle trap

Janna Zoe Vischer/Julia Wolthe/CERN

Visit the S'Cool LAB website to learn more about their activities. See: https://cern.ch/scool

The CERN laboratory sits astride the Franco-Swiss border near Geneva, Switzerland. It is the world's largest particle physics laboratory. See: www.cern.ch

EMBL

Interactive protein map brings cell division to life

One of the fundamental processes of life is mitosis, whereby one cell divides to form two identical daughter cells. It is a complicated process that involves hundreds of proteins within the cell. For mitosis to happen successfully, the activities of all these proteins must be tightly coordinated. When it goes wrong, it can result in defects such as infertility and cancer.

Thanks to a new interactive map developed by scientists at the European Molecular Biology Laboratory (EMBL), it is now possible to track these mitotic proteins in real time. "Until now, individual labs have mostly been looking at single proteins in living cells", says Jan Ellenberg, who led the project. "We are now able to take a systems approach and look at the bigger picture by studying the dynamic networks that many proteins form."

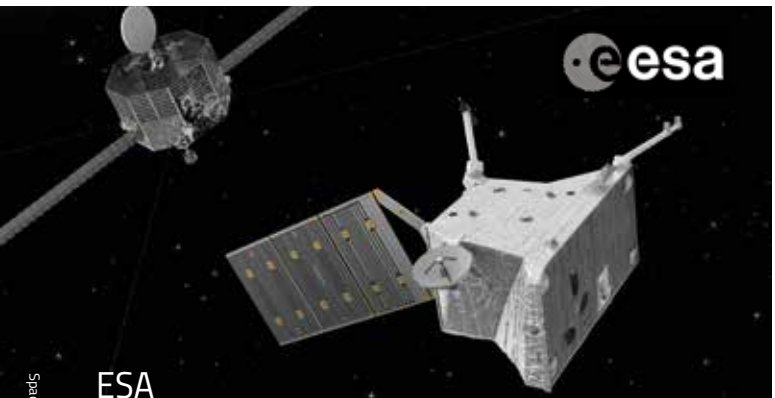
The publicly available Mitotic Cell Atlas allows users to select any combination of proteins and see how they work together to drive cell division.

Aleksandra Krolik/EMBL

Use the Mitotic Cell Atlas to observe the proteins involved in mitosis. See: www.mitocheck.org/mitotic_cell_atlas/

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

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



Spacecraft: ATG medialab/ESA; Mercury: NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington

ESA
New space mission on the way to investigate Mercury's mysteries

Mercury is the smallest and least explored planet in the inner Solar System. Its proximity to the Sun makes it difficult for spacecraft to be placed into orbit around it, because of its extreme temperature and the Sun's enormous gravity. In October 2018, however, the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) launched a new joint mission to uncover the mysteries of this enigmatic planet.

The BepiColombo mission is the first European mission to Mercury. Its first flyby will be of Earth, followed by two of Venus and six of Mercury, before entering orbit around Mercury in late 2025.

The two spacecraft that comprise BepiColombo will study Mercury in detail, including the structure and composition of its interior and exosphere, and the chemical composition of the planet's surface. The spacecraft will also take images of the surface, to better understand the geological processes that have taken place and how the surface has been modified over time.

Follow the mission and find out more on the ESA website. See: www.esa.int/Our_Activities/Space_Science/BepiColombo

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

An artist's impression of BepiColombo orbiting Mercury

ESO
Inspiring schools with astronomy

P Horálek/ESO

A view from inside the planetarium at the ESO Supernova Planetarium and Visitor Centre

Since its opening in April 2018, the Supernova Planetarium and Visitor Centre at the European Southern Observatory (ESO) has welcomed over 60 000 visitors. Of those, more than 6000 have been school students of all ages from Austria, Denmark, Germany, Italy, Switzerland and the UK.

The centre's education programme is free of charge for schools, and consists of age-appropriate activities including a tour of the interactive exhibition, a planetarium show and a hands-on workshop. A temporary exhibition entitled 'Lasers, Light, Life' will run until summer 2019. All materials and activities are available in German and English. In addition, since ESO staff come from more than 40 countries, programmes may sometimes be offered in other languages.

The Supernova Planetarium and Visitor Centre is also developing a teacher training programme, which will welcome its second group of science teachers in 2019.

Find out more about the education programme and how to make a booking by visiting the Supernova website. See: https://supernova.eso.org/education

If you are interested in arranging a teacher training workshop, email education@eso.org

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. See: www.eso.org

ESRF
Next-generation synchrotron to light up in 2020

In 1988, 11 European countries joined forces to create the world's first third-generation synchrotron light source at the newly established European Synchrotron Radiation Facility (ESRF). Now, over 30 years later, the beam has been switched off for the last time, and its flagship storage ring will be dismantled to make way for a new synchrotron – the Extremely Brilliant Source (EBS).

Since its establishment, ESRF has broken records with its scientific output, publishing over 32 000 scientific papers and giving rise to four Nobel Prize laureates. And with EBS – the world's first high-energy fourth-generation light source – ESRF will continue to lead the way.

EBS is a 150 million euro project funded by the 22 partner countries of ESRF. Opening to users in 2020, the new X-ray source will be 100 times brighter than before and will allow scientists to probe complex materials at the atomic level in greater detail.

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

Stef Candé/ESRF

ESRF has begun disassembling the current synchrotron storage ring to make way for the Extremely Brilliant Source.

EUROfusion
On track to a steady state of plasma fusion

A stellarator is a fusion device that confines hot plasma using a complex configuration of magnetic fields. Just like its cousin, the tokamak, a stellarator is designed to harness the energy of fusion – the same process that powers the Sun and stars. The world's largest stellarator is the Wendelstein 7-X, housed at the Max Planck Institute for Plasma Physics (IPP) in Greifswald, Germany.

Currently, fusion researchers are running experiments to see if the design of Wendelstein 7-X will be suitable for use in fusion power plants of the future. One important feature of the stellarator is that it is designed to maintain the fusion plasma at a steady state for longer than a tokamak. Researchers are aiming to sustain plasmas for 30 minutes in Wendelstein 7-X, and a series of experiments conducted in 2018 indicate that the device is well on its way to this goal.

The IPP is a consortium member of EUROfusion. Visit their website for more information on the experiments conducted in 2018. See: www.ipp.mpg.de/4550215/11_18?c=14226

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

Bernhard Ludewig/IPP

A view inside the plasma vessel of the Wendelstein 7-X fusion device

European XFEL

Bringing new experiment stations to the X-ray light

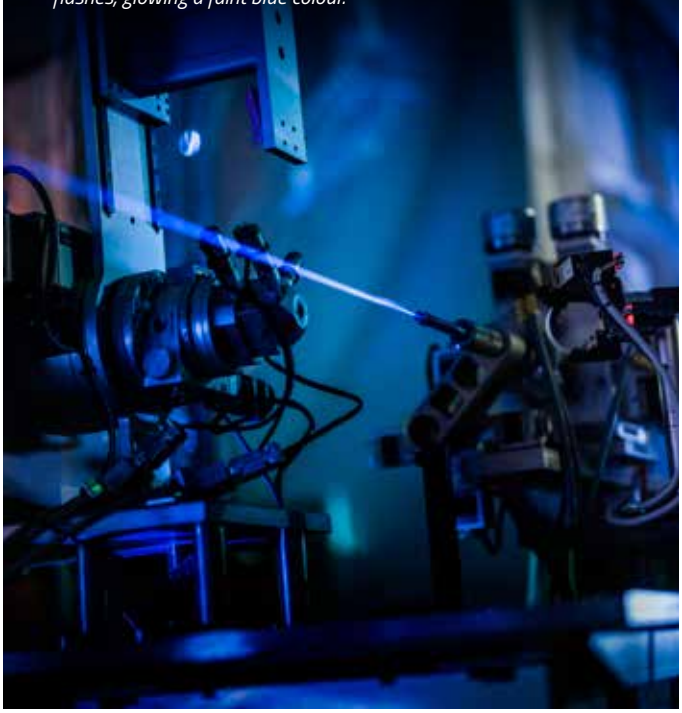
Scientists, engineers and technicians at the European X-Ray Free-Electron Laser (European XFEL) have been working hard to open more experiment stations at the facility, where researchers can use new instruments to perform experiments using pulses of X-ray laser light.

In November and December 2018, two new experiment stations – SCS and SQS – hosted their first users. These instruments use longer-wavelength 'soft' X-rays to probe samples, allowing scientists to study characteristics such as magnetism and the fundamentals of chemical bond formation. They join two other operational stations (SPB/SFX and FXE), which opened in the underground experimental hall in late 2017.

Scientists are now busy preparing the last two of six initially planned experiment stations for user operation in early 2019. These will include instruments for studying materials science and extreme states of matter. Once all six stations are in place, scientists will continue to discuss constructing additional stations in the experiment hall.

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

A long exposure shows the X-ray laser beam in open air at the FXE instrument. Nitrogen molecules in the air are excited by the X-ray flashes, glowing a faint blue colour.



Jan Hosan/European XFEL

ILL

Neutrons unlock the secrets of limoncello

A Chezière/ILL

The D11 neutron scattering instrument, which was used to study the molecular structure of limoncello

If you're looking for a liquid to study with neutron scattering, lemon liqueur probably isn't your first thought. But for Dr Leonardo Chiappisi – a researcher from Sicily, Italy – it was an obvious choice.

Limoncello is among a group of liqueurs that show a reaction known as the 'ouzo effect'. These liqueurs are normally clear, but they turn milky and opaque when water is added. The reason is due to their mix of alcohol, oil and water. To understand this effect, Dr Chiappisi used neutron scattering at the Institut Laue Langevin (ILL) to look at the molecular structure of this popular Italian liqueur.

The results showed that limoncello is formed from tiny oil droplets, around 100 nanometres in radius, suspended in an alcohol-water mix. Although oil and water usually repel each other, the alcohol in the limoncello keeps the oil and water together in an emulsion. It is this property that interests the chemical industry, and Dr Chiappisi hopes his study will help with the development of surfactant-free emulsions in the future.

To learn more about the study, visit the ILL website. See: www.ill.eu/news-press-events/news/scientific-news/neutrons-unlock-the-secrets-of-limoncello/

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

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

Cells: why shape matters

New techniques are revealing how cells control their shape – and the changes that could give an early warning of disease.

By Priyamvada Chugh

Billions of years of evolution have given living organisms an amazing diversity of shapes and forms, from the amorphous irregularity of simple animals such as sponges, to the sculpted and symmetrical shapes of more complex creatures, including ourselves. But it is not just organisms' bodies that have a great range of shapes: their cells do, too.

The shapes of cells usually relate to their function. The neurons in our brains, for instance, have star-like branches to network with other neurons, and red blood cells have the form of biconcave discs to maximise their oxygen-carrying capacity while allowing them to squeeze through the narrowest blood vessels. In contrast, macrophages (a type of white blood cell) have changing, amoeba-like shapes that help them engulf foreign bodies. In the plant world, cell shapes vary from the elaborate spiny forms of pollen grains – adapted to catch the wind or adhere to pollinating insects – to the expandable kidney shape of guard cells, which open and close pores in leaves. Cells can also take more complicated shapes, like twisted prisms or 'scutoids'; these are nature's way of allowing epithelial tissues to curve.

Changing shapes

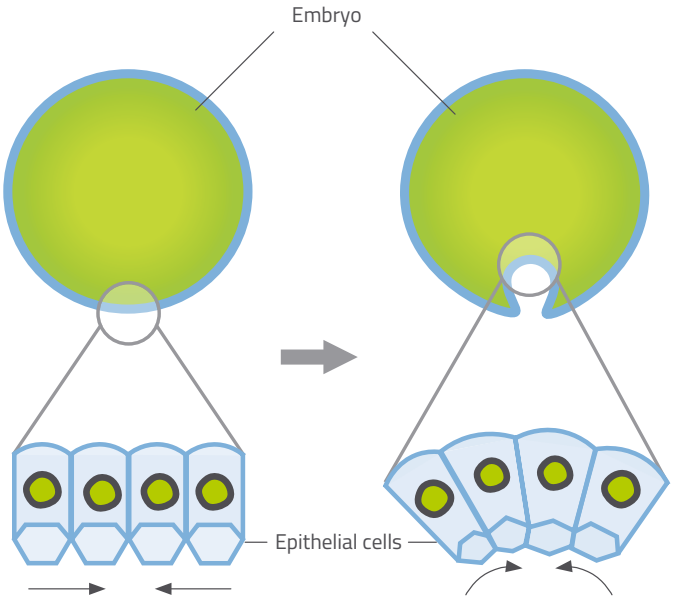
Although a cell's shape is linked to its functional role, many cells have the potential to change their shape. This ability is critical in embryonic development, when tissues undergo

Nico Cavallotto/Flickr, CC BY-NC-ND 2.0

Kirt L Onthank/Wikimedia Commons, CC BY-SA 3.0

Some organisms, like the freshwater sponge, Spongilla lacustris *(above), have an asymmetric, amorphous body form, while others like this romanesco cauliflower (left) have a highly symmetrical form.*

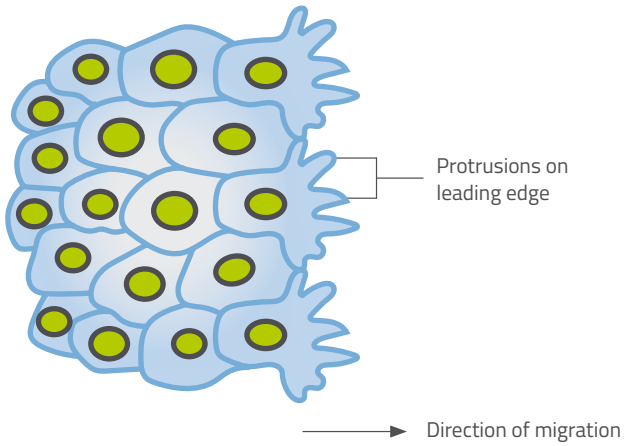
dramatic folding, furrowing and bending transformations as organs are generated. In fruit fly embryos, for example, the process of gastrulation – during which an embryonic ball of cells begins to differentiate into distinct tissues – is driven by a change in cell shape known as apical constriction. Epithelial cells on one side of the embryo change from column-shaped to bottle-shaped, causing the epithelium to wrap itself into a tube (figure 1).



Priyamvada Chugh/Nicola Graf

Figure 1: Gastrulation in fruit fly embryos: epithelial cells change shape, causing folding.

Major changes in cell shape also occur when clusters of cells migrate from one part of an embryo to another. In zebrafish embryos, cells involved in the development of the 'lateral line' (a sensory organ found in fish) grow tiny mobile protrusions called filopodia and lamellipodia. They appear on the leading edge of the cluster and seem to lead the entire cluster in a particular direction (figure 2).



Priyamvada Chugh/Nicola Graf

Figure 2: Migrating cell cluster, showing cell shape changes on leading edge

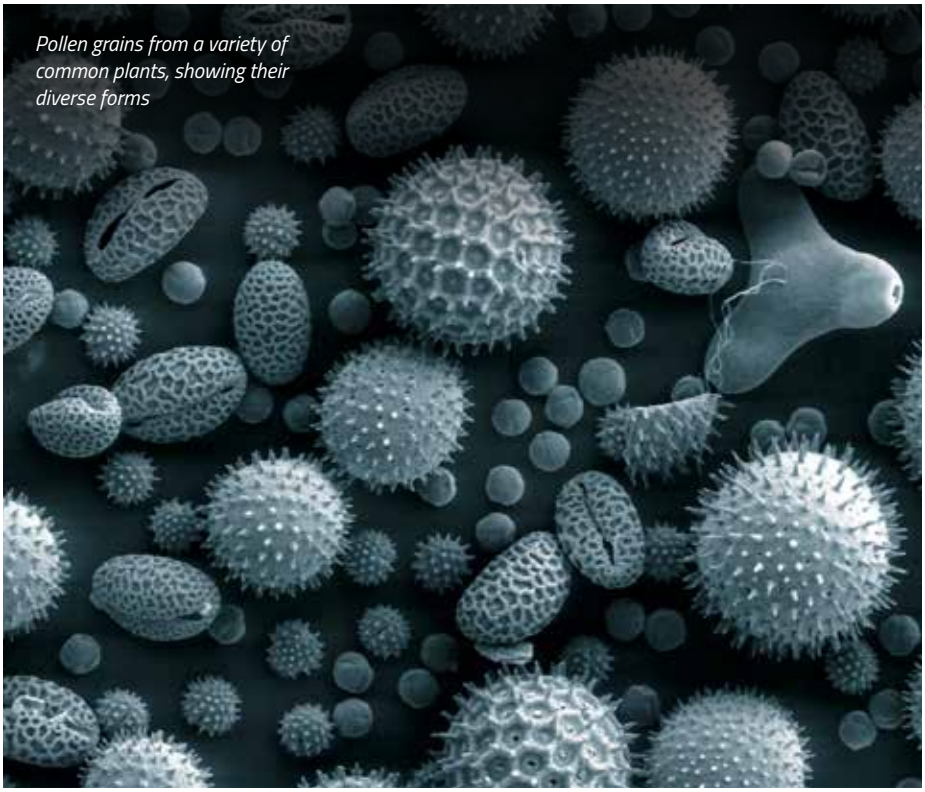
REVIEW

- ✓ Cell shape and function
- ✓ Differentiation
- ✓ Ages 16–19

The link between cell shape and function is fundamental to understanding cell and tissue biology. This article offers a glimpse into the world of cell biology, showing how important cell shape is in the development of organisms, tissue shape and function, and as a disease marker.

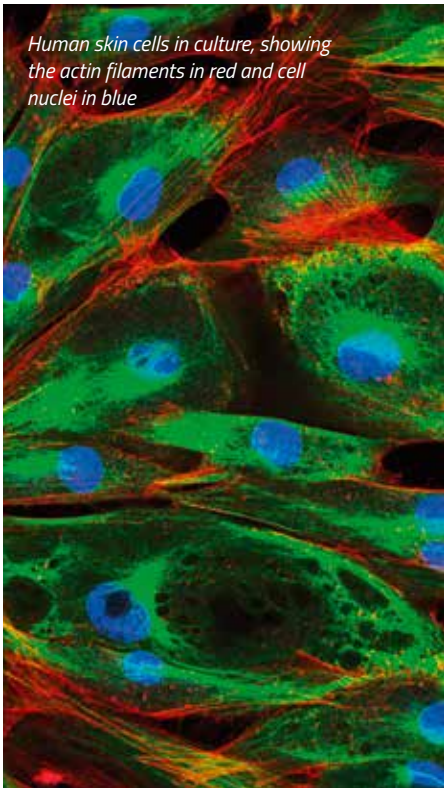
The article would be useful as wider reading in cell biology for older students. This could be linked to observing cells and tissues under the light microscope. The introduction of more molecular biology into higher-level school curricula gives an opportunity to introduce the functions of siRNA molecules, which are mentioned in the article. Finally, students could use the idea of cell shape as a disease marker to develop a poster of cell types and shapes, showing how cell shape changes with disease and how this is used in diagnosis.

Dr Shelley Goodman, college lecturer in applied science, UK



Pollen grains from a variety of common plants, showing their diverse forms

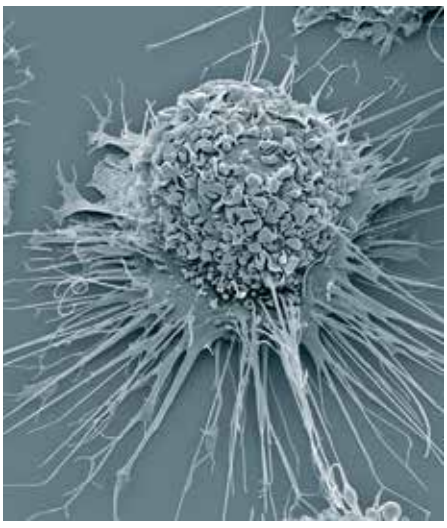
Dartmouth College Electron Microscope Facility/Wikimedia Commons, CC0



Human skin cells in culture, showing the actin filaments in red and cell nuclei in blue

Vshivkova/Shutterstock.com

Shape change is also important in cell division, which plays a crucial role in many developmental processes. When mitosis (cell division) begins, cells change from flat to spherical. Experiments that confined dividing cells inside microscopic channels, restricting their dimensions, revealed that the spherical stage is essential for chromosomes to be distributed equally among daughter cells. If this shape change is prevented, the cell division fails (Lancaster et al., 2013).



Steve Gschmeissner/Science Photo Library

Macrophage (white blood cell) in active state, showing extensions that the cell uses to seek out and engulf foreign bodies

Controlling cell shape

But what exactly is it that controls cell shape? Although we don't yet have a comprehensive understanding, we have discovered some of the molecular and mechanical processes that determine a cell's shape. These findings come largely from familiar laboratory organisms such as fruit flies and zebrafish, or from cancer cells grown in culture, but many of the processes involved are likely to be universal.

One important part of a cell that influences its shape is the cortex – a network of structural proteins that forms a layer beneath the cell's outer membrane. The physical properties of the cortex determine how rigid or soft the cell's surface is and thus how malleable the cell is as a whole. The cortex consists mainly of two kinds of protein that are closely related to the proteins that make muscle fibres contract: actin, which forms long microfilaments; and myosin, which binds to the actin microfilaments and uses chemical energy to pull them, acting like a motor. This system generates contraction in a similar way to the actomyosin system in muscles.

Scientists have also identified hundreds of regulatory proteins that interact with the actin microfilaments in the cortex. Finding out how these proteins affect the cortex, and thus the cell's shape, is an active area of research. One common technique used to study them is to block the production of regulatory proteins one at a time using siRNAs (small interfering RNA molecules), which silence particular genes. Other experiments have investigated how switching off the myosin 'motors' or chopping actin microfilaments into fragments affects cell shape.

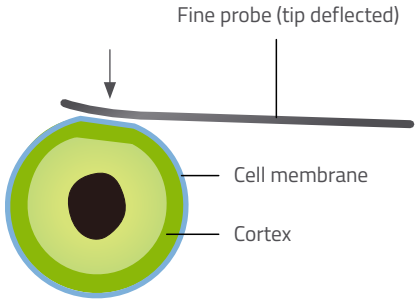
> **"The physical properties of the cortex determine how rigid or soft the cell's surface is."**

Human blood, showing biconcave red blood cells, T cells (orange) and platelets (green)

Cell shape technology

New technologies have made it possible to measure the tension in the surface of individual cells, which in turn tells us how much tension there is in the underlying cortex. The three most common techniques for measuring cell surface tension are atomic force microscopy, micropipette aspiration and laser ablation.

Atomic force microscopy uses a tiny metal tip, finer than a hair, to probe the cell surface (figure 3). The amount of deflection in the probe reveals how stiff the surface is. Using this technique, scientists discovered that an increase in tension drives the change in shape from flat to spherical in the early stage of cell division. Micropipette aspiration involves measuring the force required to suck a portion of a cell into a microscopic pipette (figure 4). Laser ablation involves severing the network of actin microfilaments in the cortex with a laser and measuring the subsequent recoil as the two sides of the cortex snap back like cut rubber bands.



Priyamvada Chugh/Nicola Graf

Figure 3: Atomic force microscopy

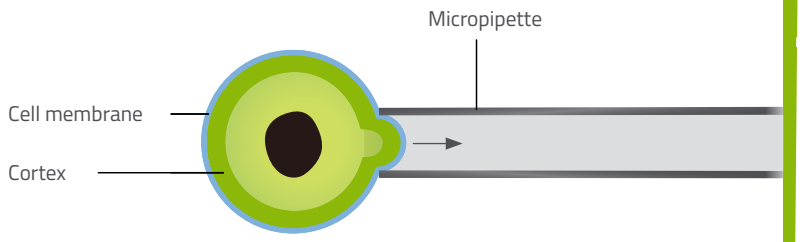


Figure 4: Micropipette aspiration

Although these three methods are all effective, they assess only one cell at a time. Another technique, real-time deformability cytometry (RTDC), can assess hundreds of cells per second (Otto et al., 2015). In RTDC, a suspension of cells is pumped by syringe through a microscopic channel. Forces in the flowing liquid cause abnormally soft cells – such as cancer cells – to deform, while more rigid cells are less affected. A camera hooked up to a microscope records images of the passing cells, and these are processed by software.

Advances in optics have also made it possible to capture detailed 3D images of living cells and even see individual protein molecules inside them, using laser-scanning microscopes. These super-resolution microscopes have revealed that the actin filaments of the cortex organise themselves into parallel bundles at the cell equator during mitosis, maximising the tension they generate and so pinching the cell into two daughter cells.

A key finding is that the actomyosin cortex controls cell shape by creating tension in the cell surface, rather like the tension in the skin of a balloon. If the myosin motors are inhibited or the actin filaments are broken down, the tension is lost and the cell surface forms bulges, disrupting its shape.

In many cases, the shapes of cells are dictated by external forces. For instance, epithelial cells within the wing of a fruit fly form hexagonal shapes because they are packed together in a tight honeycomb, with each cell surrounded by six or so neighbours. Similarly, the cells that line our blood capillaries are sculpted by the flow of blood, causing them to become elongated and lined up parallel to the flow.

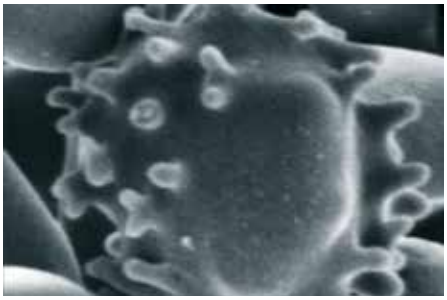
Cell shape and disease

Changes in cell shape have a key role in the development of many diseases, including those caused by infectious organisms and others triggered by faulty genes. For example, cancer-causing mutations can make cells lose the adhesions that bind them to neighbouring cells, making them amorphous and deformable – and thereby helping them to travel to and grow in other parts of the body. In Alzheimer's disease, mutations affect the twig-like dendrites that wire brain cells together, making them shorter or less finely branched. In sickle cell anaemia, a mutation gives red blood cells a curved, sickle shape, while in malaria – a disease caused when the *Plasmodium* parasite infects red blood cells – the cells become stiffer and less deformable.

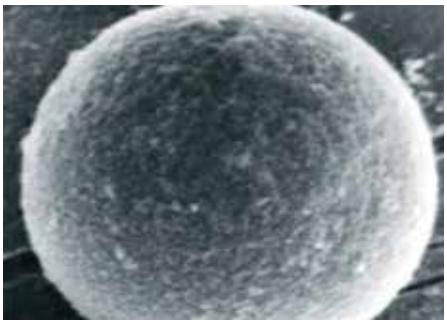
Although we now know that abnormalities in cell shape are seen in some of the most common and hard-to-treat diseases (such as cancer and Alzheimer's disease), it is not always clear whether these defects have a causal role or are merely symptoms of disease. However, the study of cell shape, and new techniques that support this, offer a new line of enquiry for investigating how such diseases develop.

For example, collaboration between biologists and physicists has yielded a

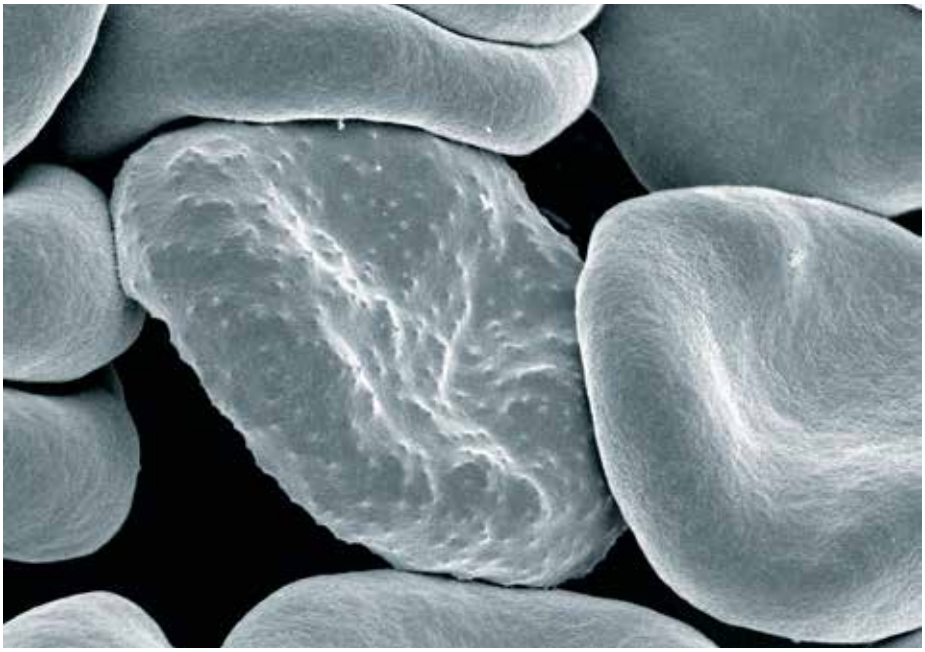
Ibrahim Mustafa et al./BioMed Research International



Ibrahim Mustafa et al./BioMed Research International



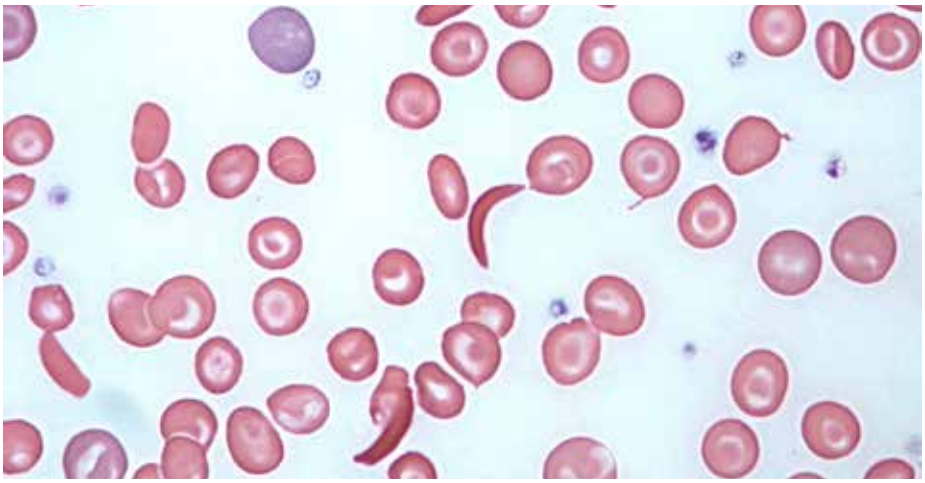
Red blood cells that have changed shape due to damage: an echinocyte (spiky form, top) and a spherocyte (spherical form, above)



Rick Fairhurst/Jordan Zuspann/National Institute of Allergy and Infectious Diseases/National Institutes of Health/Flickr, CC BY-NC 2.0

Red blood cells, one (centre) with change of shape due to malaria

technique called real-time deformability cytometry, or RTDC (see text box). As well as advancing our understanding of cell shape and its role in development and disease, this new technique may prove to be an effective way of detecting cancer cells at an early stage. Such techniques offer the hope of new diagnostic methods that could save lives by detecting disease earlier, when treatment has a much better chance of success.



Viv Caruna/Flickr, CC BY-2.0

Red blood cells, some showing the characteristic curved shape that causes sickle cell anaemia

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Resources

Read about the newly discovered 'scutoid' cell shape on the *New Scientist* website. See: www.newscientist.com/article/2175297-a-new-shape-called-the-scutoid-has-been-discovered-in-our-cells/

Watch a video of a neutrophil (a type of white blood cell) changing shape as it chases bacteria. Visit the Embryology education and research website: https://embryology.med.unsw.edu.au/embryology/index.php/Movie_-_Neutrophil_chasing_bacteria or use the direct link: https://tinyurl.com/yc89uyy6

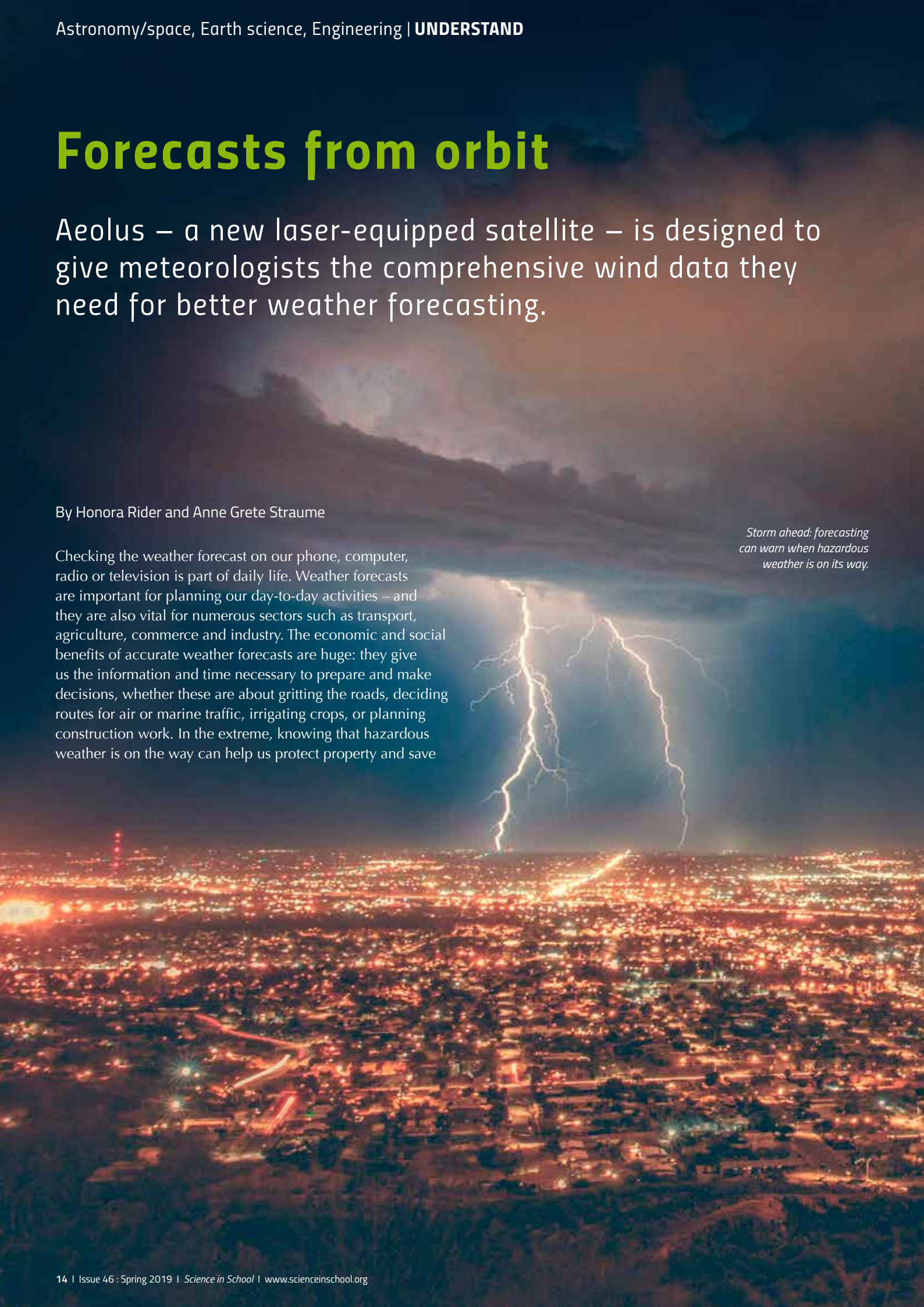
Read an accessible overview of the many shapes and sizes of neurons, the signalling cells of the nervous system, from the *Scientific American* blog. See: https://blogs.scientificamerican.com/brainwaves/know-your-neurons-classifying-the-many-types-of-cells-in-the-neuron-forest/ or use the direct link: https://tinyurl.com/y4gm7574

Priyamvada Chugh was born in Delhi, India. As a researcher working in laboratories in India, Germany and the UK, she has studied cell shape changes using model systems including stem cells, fruit flies and cancer cells. Currently working as an editor for a scientific journal, she is passionate about communicating science and its excitement to a diverse audience.

Forecasts from orbit

Aeolus – a new laser-equipped satellite – is designed to give meteorologists the comprehensive wind data they need for better weather forecasting.

By Honora Rider and Anne Grete Straume



Storm ahead: forecasting can warn when hazardous weather is on its way.

Checking the weather forecast on our phone, computer, radio or television is part of daily life. Weather forecasts are important for planning our day-to-day activities – and they are also vital for numerous sectors such as transport, agriculture, commerce and industry. The economic and social benefits of accurate weather forecasts are huge: they give us the information and time necessary to prepare and make decisions, whether these are about gritting the roads, deciding routes for air or marine traffic, irrigating crops, or planning construction work. In the extreme, knowing that hazardous weather is on the way can help us protect property and save

lives. But what role does scientific knowledge of our planet have in such predictions?

Bringing in the data

Creating weather forecasts is a complex process that involves collecting as much measurement data as possible about the state of the atmosphere – particularly temperature, pressure, humidity and wind. This data is obtained from a global network of weather stations and other monitoring sources, from weather balloons to ships and scheduled airlines – and also satellites.

Attempts to forecast the weather go back to the time of the ancient Greeks, but the systematic collection of information to use in weather forecasting started in the 19th century. The advent of the satellite era around 50 years ago has led to enormous improvements in the accuracy of weather prediction and our understanding of climate. Today, about 90% of data used by numerical weather models comes from satellites. This includes global observations of snow and ice, microwave and infrared radiances, winds derived from motion of the sea surface, and clouds. Data

REVIEW

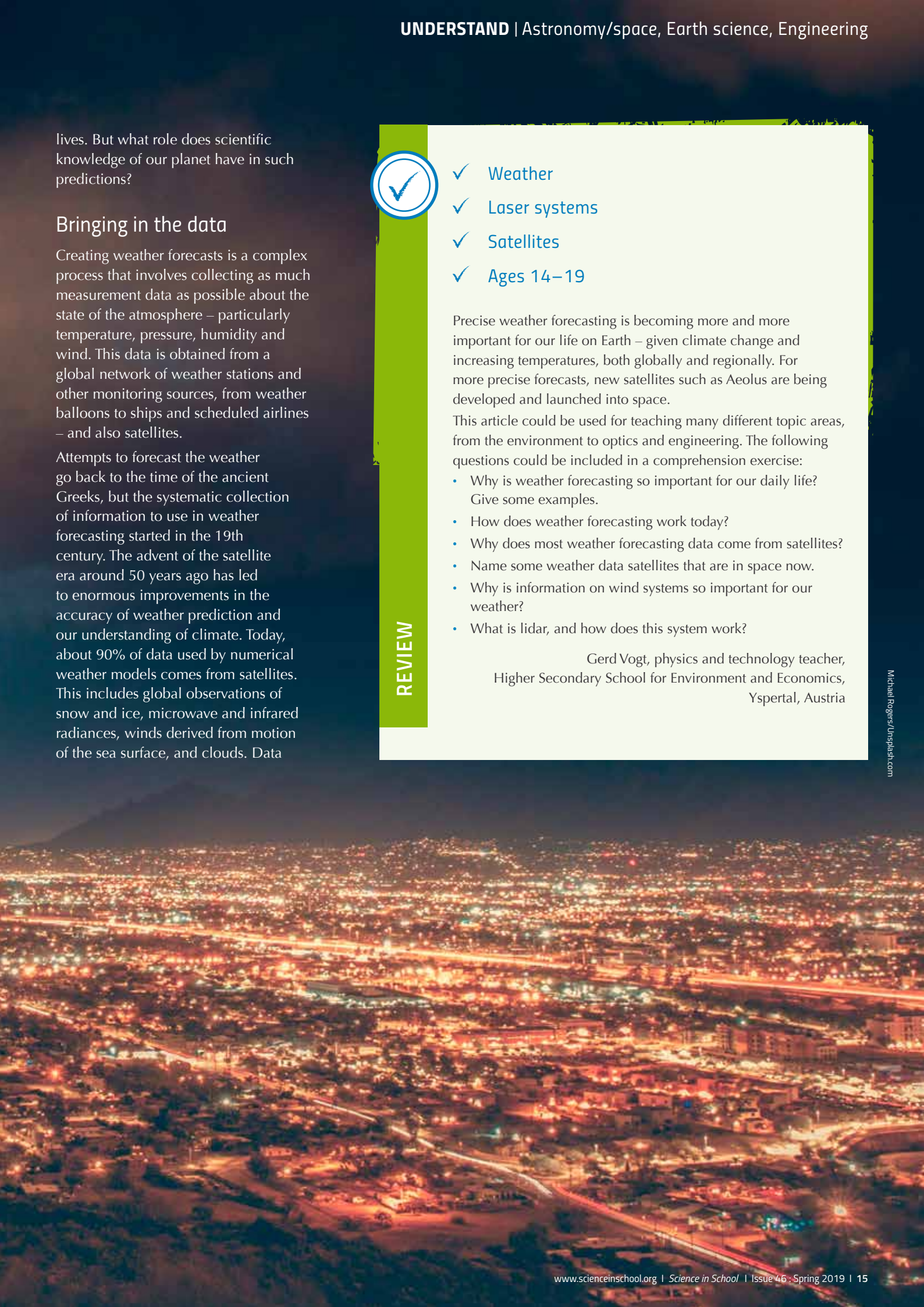
- ✓ Weather
- ✓ Laser systems
- ✓ Satellites
- ✓ Ages 14–19

Precise weather forecasting is becoming more and more important for our life on Earth – given climate change and increasing temperatures, both globally and regionally. For more precise forecasts, new satellites such as Aeolus are being developed and launched into space.

This article could be used for teaching many different topic areas, from the environment to optics and engineering. The following questions could be included in a comprehension exercise:

- Why is weather forecasting so important for our daily life? Give some examples.
- How does weather forecasting work today?
- Why does most weather forecasting data come from satellites?
- Name some weather data satellites that are in space now.
- Why is information on wind systems so important for our weather?
- What is lidar, and how does this system work?

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

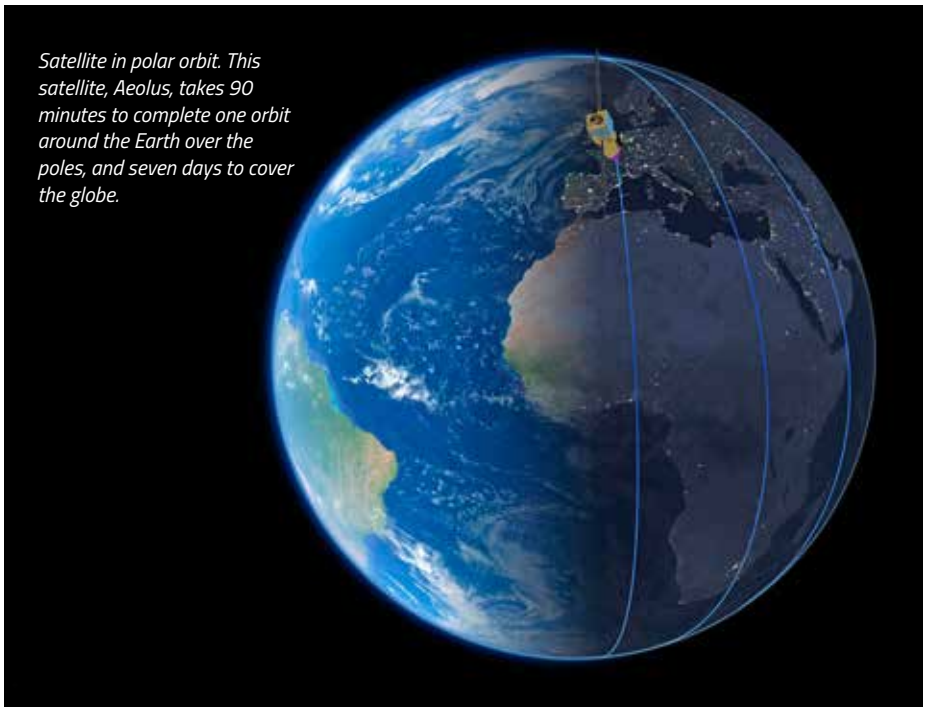


Michael Rogers/Unsplash.com

NOAA, CCO

Image from a NOAA GOES satellite showing a storm approaching the southeastern coast of the USA, September 2018

remotely sensed by satellites, along with other measurements, is used in numerical prediction models, which are run on supercomputers in meteorological centres around the world to forecast the weather. For example, the weather forecasting system at the European Centre for Medium-Range Weather Forecasts (ECMRWF) in the UK processes 40 million individual observations every day and integrates this data into their weather model.



Satellite in polar orbit. This satellite, Aeolus, takes 90 minutes to complete one orbit around the Earth over the poles, and seven days to cover the globe.

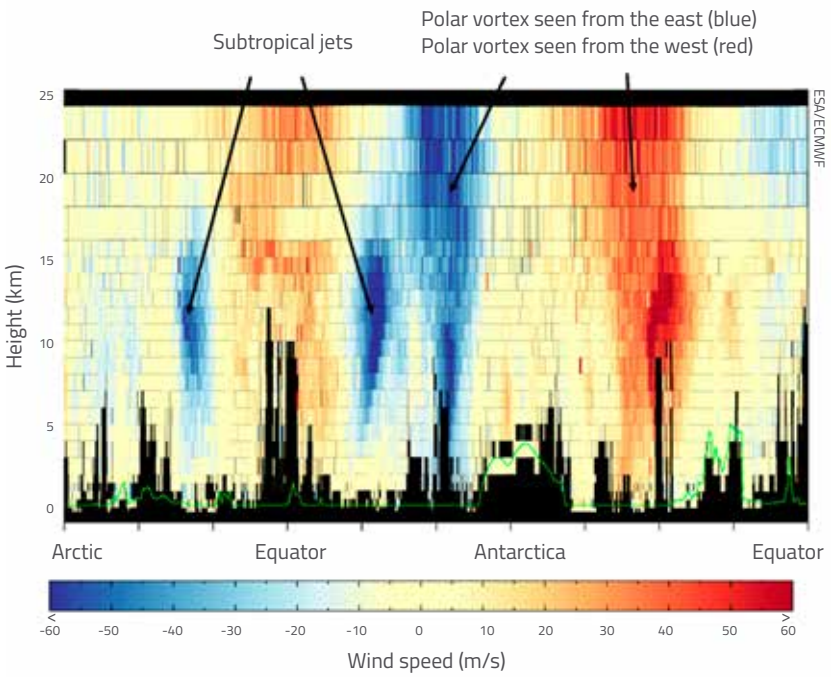
ATG medialab/ESA

Highs and lows

Forecasts rely on data from satellites in two different types of orbit, which offer complementary perspectives of the Earth and evolving weather systems. Satellites in geostationary orbit hover around 36 000 km above the equator, while satellites in polar orbit circle the Earth above both poles at the much lower altitude of a few hundred kilometres above the surface.

The high-altitude geostationary orbit allows a large portion of Earth's surface to be in constant view. For example, Europe's geostationary Meteosat weather satellites constantly observe Europe and Africa, while the USA's NOAA GOES satellites do the same for the Americas. This high vantage point enables rapidly evolving events to be monitored continuously, providing advance warning of continental-scale thunderstorm fronts, hurricanes and other destructive weather phenomena.

However, there are some parts of the planet that geostationary satellites never view, and their greater distance from Earth's surface limits the resolution of



Global wind data from Aeolus, showing the speed, height and location of winds

their data. In contrast, polar-orbiting satellites collect data over the entire planet in a matter of days, and their lower orbit yields much higher-precision data than can usually be gained from the high geostationary satellites. There are a fleet of weather satellites operating in polar orbits, including Europe's MetOp and the USA's JPSS satellites.

Room for improvement

Although our weather forecasts are more accurate than ever before, there is still the wish to improve them further, especially for long-range forecasting. The chaotic nature of the atmosphere, and the need for a more detailed understanding of the processes involved, mean that there is a constant drive for new information. This will not only help forecasting, but also aid our scientific understanding of how the atmosphere works and the longer-term implications of climate change.

Over the past few decades, meteorologists have argued that, in particular, there is a lack of accurate global wind data, which is needed to improve forecast accuracy. In response, the European Space Agency (ESA) launched a new satellite in 2018 specifically to provide better wind information. The satellite is named after Aeolus, who in Greek mythology was appointed 'keeper of the winds' by the gods. So how will this satellite help with forecasting?

> **"There is a lack of accurate global wind data, which is needed to improve forecast accuracy."**

The Aeolus satellite is designed to acquire wind data from across the globe, using innovative 'lidar' technology.

S Corvaja/ESA

Wind profiles are an essential element of accurate medium- to long-term weather forecasting, as well as a key input for modelling climate change. This is because the wind is an important component of the Earth's energy balance. Essentially, some areas of Earth receive more heat from the Sun than other areas, leading to differences in air temperature, density and pressure. These differences in turn cause the air to move, creating wind. Wind transports heat away from equatorial regions towards the poles and returns cooler air to the tropics. The Earth's rotation also results in large-scale wind systems such as the jet stream. These effects form the basis of atmospheric circulation, which governs the weather and climate.

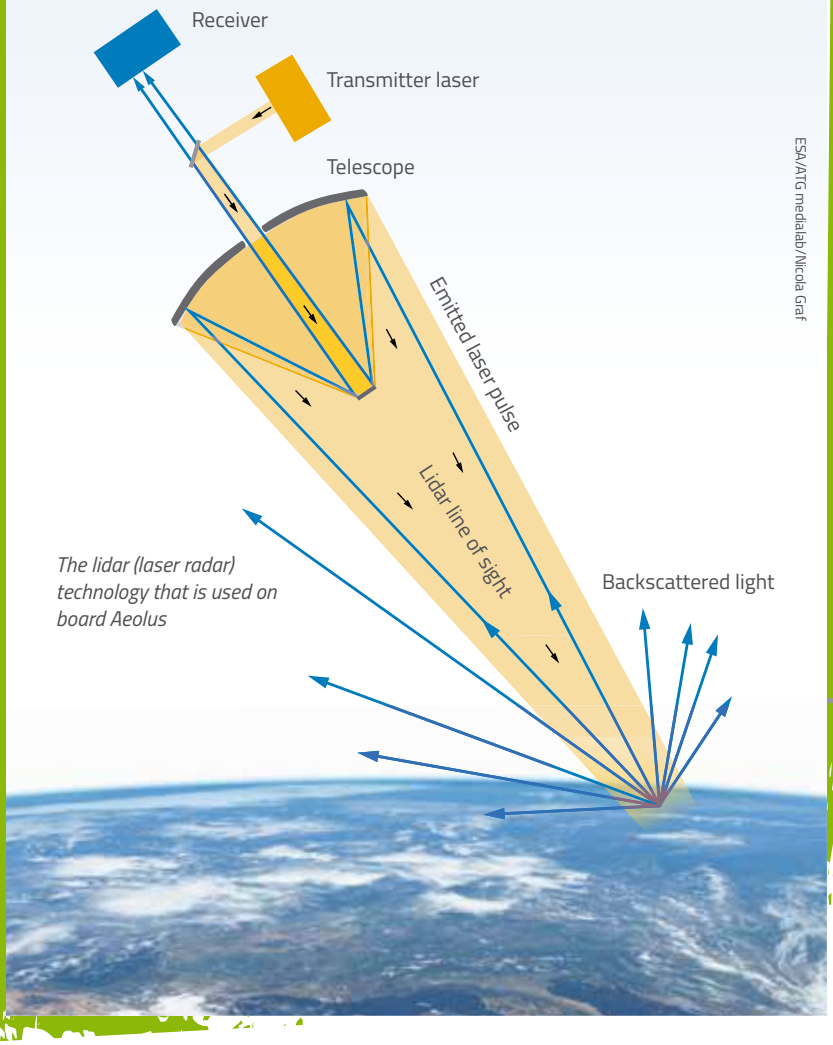
There are a variety of sources that provide wind information: weather stations, weather balloons or aircraft, and satellite observations of moving clouds and ocean roughness. But until recently, large parts of the

Aeolus: lasers in space

Launched on 22 August 2018, the Aeolus satellite carries one of the most sophisticated instruments ever to be put into orbit. At the heart of Aeolus is a highly sophisticated Doppler wind 'lidar', which can be thought of as a laser (i.e. light) radar. One of the aims of the Aeolus mission is to test this novel technology – which comprises a powerful laser, a large telescope and a very sensitive receiver – in space.

From its 320 km high orbit, the laser emits short but powerful pulses of ultraviolet light (355 nm wavelength) 50 times per second. This light travels down through the atmosphere, and a tiny fraction is backscattered from particles moving with the wind – air molecules, dust, ice particles and droplets of water. The backscattered light is collected by the telescope and detected by the receiver, which is incredibly sensitive: it can pick up as few as four photons per metre, along the line of the laser beam.

Just like the radar that police use to catch speeding motorists, the backscatter from the moving particles results in a small 'Doppler shift' between the light frequencies that Aeolus emits and receives back. From this shift, the wind velocities along the satellite's direction of view can be derived, to an accuracy of some 2 m s^{-1}.



ESA/ATG medialab/Nicola Graf

The lidar (laser radar) technology that is used on board Aeolus

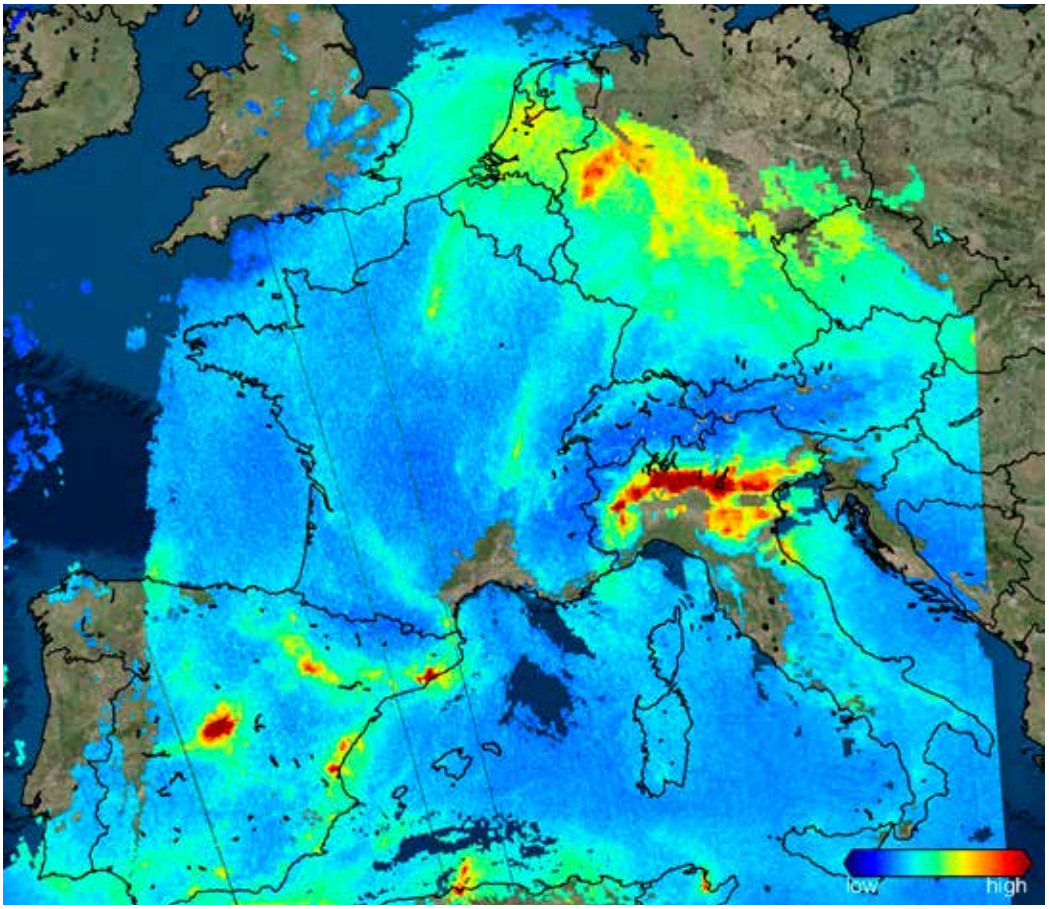
atmosphere were not well observed – in particular, the tropics, over the oceans, in the southern hemisphere, above polar regions (where there are few weather stations or balloons) and in the higher atmosphere. Direct wind observations covering the full extent of the atmosphere – both horizontally and vertically – were therefore needed to better predict the weather.

> **"The troposphere is where the weather that affects our lives is formed."**

The Aeolus satellite is equipped with breakthrough laser technology (see text box). This allows wind fields to be mapped globally up to an altitude of 30 km for the first time, including in areas that are not well covered by existing observation systems. This height includes the troposphere, where the weather that affects our lives is formed. Although the mission is scheduled to last only three years initially, Aeolus is expected to lead to a new generation of satellite instruments designed for routine weather forecasting.

Beyond weather forecasting

Satellite data is becoming increasingly important in many everyday applications other than weather forecasting. With air pollution a major environmental health problem, daily forecasts now often include warnings on poor air quality, and satellite data is used to ensure that these forecasts stay as close to reality as possible. For example, the EU's Copernicus Sentinel-5 Precursor satellite maps a multitude of pollutant gases such as nitrogen dioxide, methane, carbon monoxide, ozone and sulfur dioxide. This satellite gives decision-makers the information they need to fight air pollution and also provides data to help scientists understand atmospheric processes linked to climate change



KNMI/ESA

Image from the Copernicus Sentinel-5 Precursor mission showing nitrogen dioxide over Europe in November 2017. High emissions can be seen over northern Italy and western Germany.

– for example, why holes form in the stratospheric ozone layer.

To monitor our changing world in the light of climate change, satellites track changes in many factors: the dynamics and composition of the atmosphere, ice cover and volume, the height and temperature of the sea surface, the way land is used and urbanisation, and more. This is the only realistic way of observing the Earth as a whole and generating the information we need to understand how Earth works as a system – and, of course, the impact humans are having on natural processes.

Resources

Learn more about the mission of the Aeolus satellite on the ESA website. See: www.esa.int/Aeolus and http://m.esa.int/Our_Activities/Observing_the_Earth/Aeolus/Documents_publications

Learn about the roles of satellites in numerical weather prediction with an interactive module from the European Centre for Medium-Range Weather Forecasts (ECMWF). See: www.ecmwf.int/assets/elearning/satellite/satellite-obs/story_html5.html

The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) operates a complement of meteorological satellites to monitor the climate and developing weather situations. Learn more about its mission and activities on the EUMETSAT website. See: www.eumetsat.int

Watch a short video from the UK's National Meteorological Service explaining how weather forecasts are created. See: www.metoffice.gov.uk/learning/making-a-forecast

Resources to teach students about monitoring Earth and its climate are available on the ESA Education website. See: www.esa.int/Education/Climate_detectives/Classroom_resources_for_Climate_Detectives

The EO Browser and Sentinel hub are online tools that allow all users to access current satellite images. See: http://esamultimedia.esa.int/docs/edu/EO_Browser_guide.pdf and www.sentinel-hub.com/explore/eobrowser

Honora Rider has worked for ESA since 2002. She is the editorial consultant for ESA's Earth Observation Programmes Directorate. She holds a degree in environmental science from the Open University, UK.

Anne Grete Straume has worked at ESA since 2004 and is the ESA mission scientist for the Aeolus mission. She has a PhD in meteorology from the University of Bergen, Norway, and worked as a researcher in the fields of air-pollution transport, atmospheric circulation and atmospheric remote-sensing of trace gases before she joined ESA.

The secret life of forests

New research is revealing the previously unknown beneficial effects of tree canopies – and the secret life within them.

By Rossella Guerrieri

When you walk through a forest, what is it about the trees that most impresses you? For me, it's the green canopy of leaves, with branches reaching out towards the sky. I remember when I saw a giant sequoia tree for the first time, at the Calaveras Big Trees State Park in California, USA. What really impressed me was the high evergreen canopies of these trees – which can be up to 3500 years old – receiving water from roots almost 100 metres below. In my career as a tree ecophysiologist, I am fascinated by tree canopies, which are important not only for single trees, but also for forests – and for all of us.

Tree canopies make a huge contribution to mitigating global warming and climate change by taking in carbon dioxide through their leaves, which they use in photosynthesis to produce sugars. Thanks to this activity, forest canopies worldwide remove around 30% of the carbon dioxide emitted by fossil fuel combustion. At the same time, trees lose water through their leaves, which they take from the soil and return to the atmosphere through transpiration. This is a familiar story, but what is less well known, and is only beginning to be understood, is that trees also have an effect on other gases in the air, beyond carbon dioxide, oxygen and water vapour – in particular, on nitrogen and its compounds.

Nitrogen cycling

Tree canopies are continuously exposed to changes in the composition of the atmosphere, including those due to pollutants. Some of these pollutants are reactive nitrogen compounds, including ammonia (NH_3) and its compounds, and various oxides of nitrogen known as NOx (NO, NO_2 and NO_3). Over the past century, there has been a rapid increase in atmospheric nitrogen compounds due mainly to global increases in industrial activity, traffic emissions, intensive

The author (Rossella Guerrieri) amid giant sequoia trees at the Calaveras Big Trees State Park in California, USA

Katie Jennings/Rossella Guerrieri

bibiphoto/Shutterstock.com

Traffic emissions are a major source of air pollution from nitrogen compounds known as NOx.

livestock farming and fertiliser use in agriculture, and burning biomass for energy (Galloway et al., 2004).

As with increases in atmospheric carbon dioxide, forests have a stabilising effect here, because they store some of the extra nitrogen compounds from the atmosphere. One of the key questions scientists have tried to answer since the 1980s is whether it is the trees themselves that have this role or only the soil beneath. Earlier studies assumed that the extra nitrogen compounds reach the soil directly and that there is no interaction with tree canopies, but more recent research shows this assumption may not be true.

Tree canopies and pollution

At several forests across Europe and the USA, atmospheric nitrogen compounds have been monitored over several decades. Studies using this data have

REVIEW

- ✓ Environmental chemistry
- ✓ Nitrogen cycle
- ✓ Microbiology
- ✓ Ages 16–19

This article is about tree canopies and their importance as agents of atmospheric change. The author describes the aims of her own research: to understand the diversity and function of the microbes living in and on the leaves of Scots pine and beech forests.

The article could be used as a stimulus for teaching topics such as cell metabolism, biological reactions, the nitrogen cycle and, more generally, ecosystems.

It could also be used as a basis for comprehension questions such as:

- Which compounds are involved in the exchange between trees and the atmosphere?
- What is the impact of sulfur dioxide on plants?
- How do trees reduce pollution from nitrogen compounds?

The article could also be useful to show the application of techniques used for bacterial recognition, in particular DNA analyses. More generally, it highlights the sheer excitement of scientific research, and the enthusiasm of the researcher for this new area of study.

Monica Menesini, science teacher, Italy

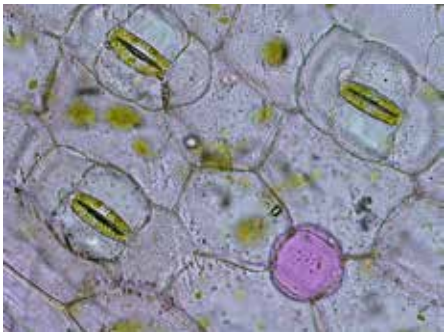
Oak tree (Quercus), *a species that can take up ammonia from the atmosphere*

Yuriy Vahlenko/Shutterstock.com

Right: Black elder (Sambucus nigra), *which can take up airborne NOx compounds*

Far right: Leaf surface showing stomata – pores guarded by elongated cells (shown green) that let gases pass in and out of the leaf

Forest and Kim Starr/Flickr, CC BY 2.0



BlueRidgekitties/Flickr, CC BY-NC-SA 2.0

shown that tree canopies have an active role in removing air pollution by retaining some of the nitrogen compounds and altering others that reach the soil. But how do they do this? It seems that, like carbon dioxide, these nitrogen compounds are able to penetrate the leaf surface through the stomata, and be taken up and absorbed by the plant. Other studies have revealed that tree canopies can transform ammonia and its compounds, converting them to nitrate, which is washed off into the soil to be taken up by the roots as a nutrient. These processes explain another finding: airborne nitrogen compounds can actually benefit trees, as they increase the growth rate in some forests where the availability of nitrogen can be a limiting factor (Magnani et al., 2007).

Of course, trees can also be damaged by air pollution, particularly by ozone and sulfur compounds such as sulfur dioxide – which has been known since the 1980s. These gases damage the leaf cuticle and stomata, causing an imbalance in the plant's gas exchange with the air. However, thanks to regulation, emissions that cause air pollution have decreased since the 1980s, especially with regard to sulfur compounds.

Trees thus act as filters and contribute to improved air quality, even in cities. In general, how effective a tree is at removing pollutants depends on the structure of the tree canopies (their shape, leaf and branch density) and of their leaves (e.g. surface roughness and waxiness). Tree species that are particularly effective at taking up NOx compounds through their leaves include birch (*Betula*), poplar (*Populus*) and black elder (*Sambucus nigra*) species, while oak (*Quercus*), beech (*Fagus sylvatica*) and hornbeam (*Carpinus betulus*) are good at taking up ammonia.

Microbial protectors

Current research is revealing another factor in how tree canopies have these remarkable effects on the atmosphere. This is the 'leaf microbiome' – the microbial life forms found inside or on the surfaces of leaves, rather like the gut microbiome within our own bodies. It's now well known that our health and even our happiness may be significantly affected by our gut microbiome. Remarkably, there seems to be a rather similar effect for trees, with the leaf microbiome influencing how trees respond to environmental changes.

But while DNA sequencing analyses have enabled scientists to compile a global atlas of bacteria living in the soil, we have only started to learn which classes of microbes are living in tree canopies. There are many questions still to answer: for example, are these microbial species similar across different forests and tree species? And which microbes are responsible for taking up atmospheric nitrogen within tree canopies, and which for transforming it?

In 2015, I received a research grant to try to answer these questions. My aim was to investigate the secret life of the tree canopies of mature Scots pine and beech forests across Europe, from Sweden and Finland in the far north to Mediterranean Italy and Spain in the south. Six months after I started my fellowship, I had a lab full of soil, leaves and bottles containing water collected from underneath tree canopies. It was amazing to discover that just a few grams of leaves hide an incredibly diverse bacterial community (Guerrieri et al., 2017), and through the microscope I could see how beautifully the microbes line up along the leaf nerves.

> **"It was amazing to discover that just a few grams of leaves hide an incredibly diverse bacterial community."**

With my colleagues, we began to work out which leaf microbes are doing what – for example, we found that there were more archaea than bacteria involved

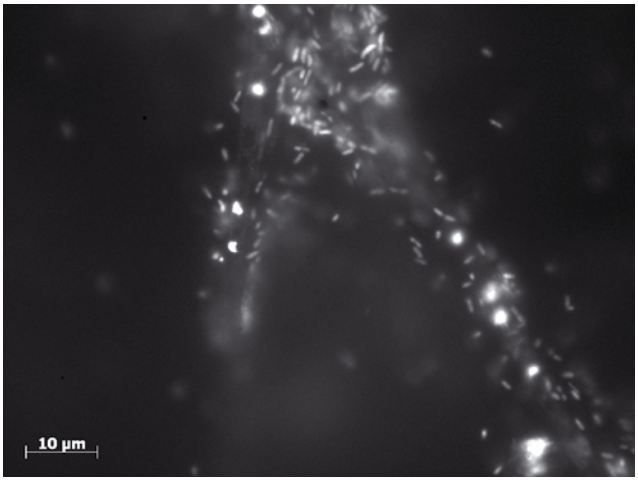
Julia Vorholt/ETH Zurich

Bacterial colonies grown by imprinting a leaf onto a culture medium, showing how the bacteria line up along leaf structures

Takashi Images/Shutterstock.com

The canopy of a primeval beech forests at Hainich National Park, Germany

Rossella Guerrieri



Rossella Guerrieri

A single beech leaf (left), and bacteria seen on the leaf surface using fluorescence microscopy (right)

in converting atmospheric ammonia into nitrate. Other studies have shown that some bacteria remove pollutants from the atmosphere by using them in their metabolism (Wei et al., 2017). But we have a lot more to do in this new research area, to understand the effects of particular microbes within the leaf biome.

Leaf biomes and forest health

Like humans, it seems that trees themselves benefit from their microbial lodgers. Recently, scientists have found that bacterial diversity in tree canopies helps improve resistance to pests and contributes to better forest health generally. And a group of scientists in the USA have found bacteria in sequoia leaves that protect against pathogenic fungi (Carrell & Frank, 2015) – so maybe this is the secret that has allowed these beautiful giant trees to resist disease and survive for centuries, or even millennia.

In any case, after more than 20 years of observations in European forests, we can say for sure that tree canopies – and the invisible life forms they hide – are an important piece of the complex and incomplete puzzle of how nitrogen is cycled between land, air and living species.

Acknowledgements

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Magnani F et al. (2007) The human footprint in the carbon cycle of temperate and boreal forests. *Nature* **447**: 849-851. doi: 10.1038/nature05847

Wei X et al. (2017) Phylloremediation of air pollutants: exploiting the potential of plant leaves and leaf-associated microbes. *Frontiers in Plant Science* **8**: 1318. doi: 10.3389/fpls.2017.01318

Resources

Find out more about the author's research from her own website. See: www.rossellaguerrieri.com

Experience what the Earth would look like from space over a year of seasonal changes in this NASA movie. See: https://svs.gsfc.nasa.gov/4596

Watch a video about nitrogen in the environment and why we should care about it. See: www.youtube.com/watch?v=gED5f_g20_Y

Get to know your nitrogen footprint. See: www.n-print.org

Read about an ongoing project to monitor the effects of air pollution on forest health. See the European ICP Forests website: http://icp-forests.net

Find out about trends in air pollution within Europe. See the website of the European Environment Agency: www.eea.europa.eu/highlights/air-pollution-agriculture-and-transport and www.eea.europa.eu/data-and-maps/indicators/main-anthropogenic-air-pollutant-emissions/assessment-4

Rossella Guerrieri is a plant physiologist and forest ecologist. Her main research interest is understanding how forest functioning varies in relation to major environmental and anthropogenic changes. After receiving her PhD from the University of Basilicata, Italy, she did research at the universities of New Hampshire, USA, and Edinburgh, UK, and then at CREAF (Centre for Ecological Research and Forestry Applications) in Barcelona, Spain. She has been involved in outreach activities for forests and climate change, including at the Edinburgh Science Festival and the Barcelona Centre of Contemporary Culture.

Orawan Pattarawimonchai/Shutterstock.com

The changing technologies of drug design

Over several decades, the search for new medicines has progressed from mimicking natural molecules to screening many millions of compounds.

By Sarah Houlton

The first medicines that chemists designed were inspired by nature. Aspirin was derived from an extract of willow; belladonna came from deadly nightshade; opioid medicines such as morphine have their origins in the opium poppy. Later, more medicines were found in other natural materials – notably penicillin, which was isolated from a mould.

While nature has continued to be a rich source of ideas for new drugs, there are many diseases for which no natural compounds are available as treatments. Scientists now have a key role in designing new compounds that can lead to effective pharmaceutical treatments. This has required the adoption of new approaches and techniques – from

automated screening to genetic engineering – to develop a drug discovery process that is more complex and precise than ever before.

Designing modern medicines

Understanding how biochemical processes work is central to modern medicine design. By studying the biochemistry of a particular effect, scientists can design molecules that either mimic the effect or stop it from happening. Since most of the processes in our bodies involve proteins, scientists want to create drugs that alter the behaviour of the proteins associated with a particular disease.

The first new medicine to be invented in this way, in the early 1960s, was the beta-blocker propranolol. When a patient takes propranolol, the drug sits in the beta receptors of cells and stops adrenaline from binding. Because it blocks the natural activity of adrenaline, propranolol has a range of uses – from lowering blood pressure to preventing migraines.

> **"Understanding how biochemical processes work is central to modern medicine design."**

By the late 1980s, scientists could isolate individual proteins using new molecular biology techniques. This allowed them to study and measure the strength and nature of the binding interactions between proteins and potential drug molecules. Techniques included adding fluorescent tags or radiolabels to the protein or the drug molecule, enabling them to be tracked. The inspiration was the chemical structure of the natural hormone that fits into the target receptor: its shape, and its functional groups, provide clues about the shape that a drug molecule must have in order to fit into the receptor. Chemists could also design modifications to that natural structure

REVIEW

- ✓ Biochemistry
- ✓ Health
- ✓ Ages 16–19

The design of new drugs is an exciting subject of chemistry in the 21st century. Research in this field involves designing specific molecules that act locally at the molecular level.

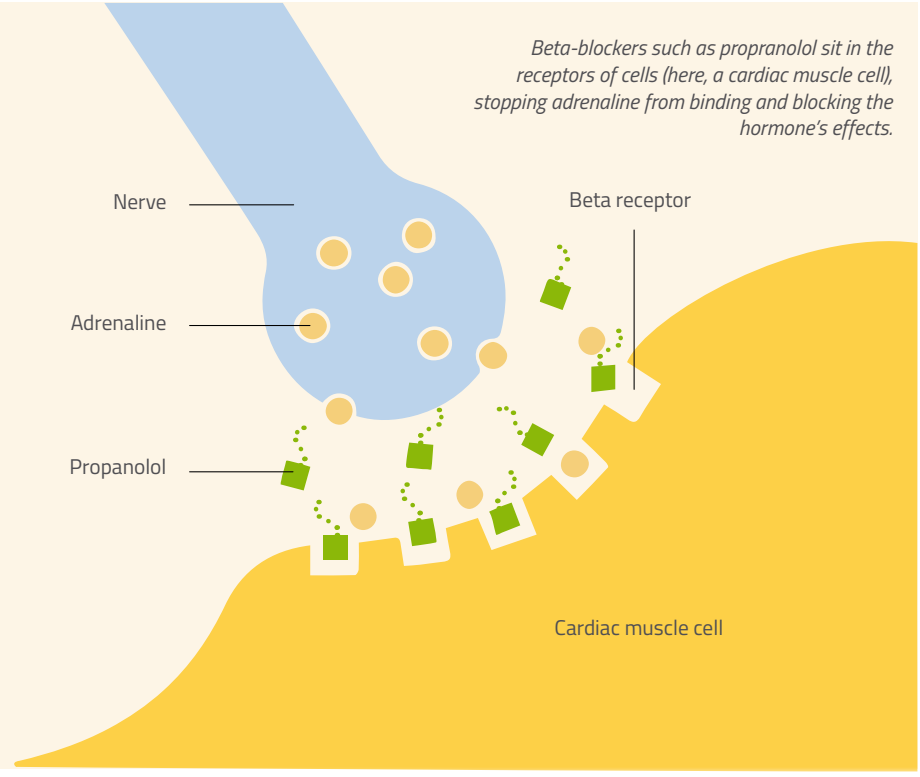
This article can be used to introduce current methods of searching for and designing new drugs, particularly to advanced students. Teachers can use the article to discuss the methods from different fields of science that are now being used to modify the mechanisms of human body function.

Through these methods, the article makes links between chemistry, biology and even philosophy. It could also be used to prepare secondary school science students for future university courses, or as a complementary lecture for their final courses.

Comprehension questions that teachers could use include:

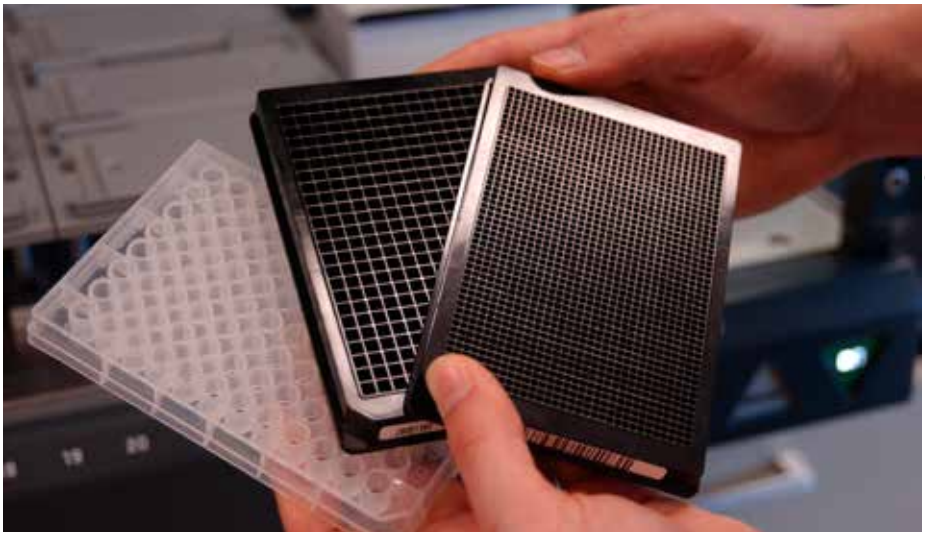
- Today, where do the first ideas come from in designing new drug molecules?
- Why is combining different techniques a good way to design new drug molecules?
- Side-effects are not desirable when we take drug treatments. How can chemists help to avoid side-effects in new drugs?

Manuel Hernández Rodríguez, chemistry teacher,
Ies Pedro Mercedes school, Cuenca, Spain



Beta-blockers such as propranolol sit in the receptors of cells (here, a cardiac muscle cell), stopping adrenaline from binding and blocking the hormone's effects.

Nicola Graf



National Center for Advancing Translational Sciences/Flickr, CC BY 2.0

In high-throughput screening, compounds are added to plates with multiple wells that act as small test tubes.

that might alter its activity as required.

At first, this process was very much a case of trial and error. But over time, much knowledge has been built up about how different functional groups can affect activity at cell receptors. Today, chemists can predict what changes they need to make to a molecule's structure to achieve the desired response. By accurately modifying the design of natural molecules, chemists can improve their affinity (how well they bind to the receptor), activity (how well they work) and selectivity (so they do not act at other receptors as well). The chemists will also do their best to tweak molecules so they are less likely to cause side-effects.

Molecular starting points

Nowadays, however, chemists don't always use a natural hormone as their molecular starting point. Instead, they test the target receptor against huge 'libraries' of different compounds. In an automated process called high-throughput screening, tests are carried out to find molecules that have the desired activity in the receptor. In this very rapid process, screening a million compounds in a week is not unusual. The results of these tests then provide chemists with an all-important starting point for designing drugs.

High-throughput screening finds molecules that interact reasonably strongly with the protein target, but they are often fairly large. To identify small chemical fragments – which typically produce a weaker effect – scientists instead use a similar process called fragment-based drug discovery. Rather than looking for molecules that already resemble drugs, like the molecules in a normal compound library, the idea is to use smaller, simpler molecules that can be developed into more complex molecules later on. This approach can give a better insight into which functional groups have a biological effect, because a small molecule has fewer parts to interact with the target. Also, attributes from more than one fragment can ultimately be combined into a single complex molecule.

Two anticancer drugs derived from fragment-based drug discovery have made it to market – vemurafenib and venetoclax. Several more are undergoing clinical trials.

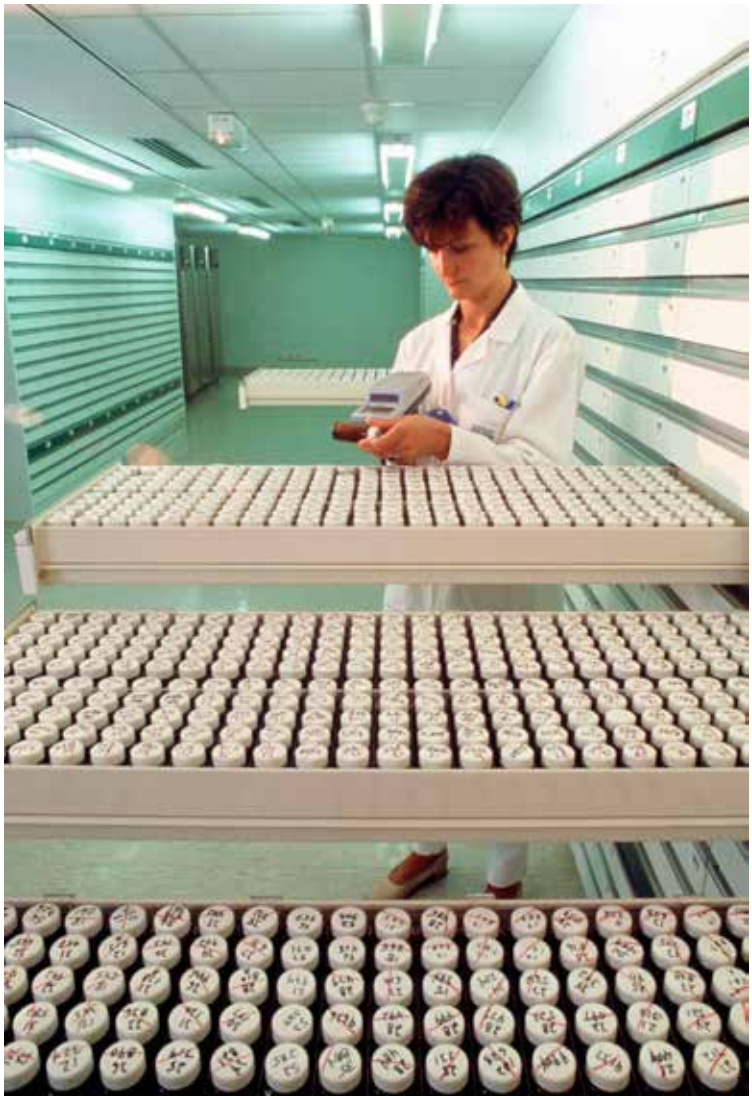
Phenotypic screening

In recent years, there has been something of a return to the old approach to drug discovery: identifying a physiological effect and then working out which biological process caused it. Instead of an isolated protein, chemists use a cell, a tissue, or even a whole organism. This is known as phenotypic screening, because it identifies the molecules that alter the phenotype of that cell, tissue or organism.

For example, in cancer, the physiological effect is cells multiplying, and the phenotype to change is cell

Daniel Sone Photography, LLC/National Center for Advancing Translational Sciences/Flickr, CC BY 2.0

Plates are placed in a robot carousel to be rapidly tested using high-throughput screening.



P Dumas/EURELIOS/Science Photo Library

A technician catalogues a library of drug compounds, which are stored for screening and for potential future drug development.

> **"Advances in chemical biology now allow us to look inside the cell and see how the molecules bind to proteins within it."**

growth, so a suitable drug molecule will kill cancer cells or arrest their growth. Or in diabetes, researchers might take a pancreatic islet cell and look for molecules that alter glucose-stimulated insulin secretion.

Once the molecules have been identified, the next step is to work out what happens when they are added to the cell, tissue or organism. Advances in chemical biology now allow us to look inside the cell and see how the molecules bind to proteins within it. Today, multiple molecular processes can be observed and studied at the same time, whether they are taking place within cells or on their surface.

Extremely sensitive mass spectrometry and fluorescence methods are the key to these advances, as they help to detect individual proteins among the thousands expressed by a cell.

Modern genetic techniques

Advancements in genetic engineering and gene editing have also helped to progress the discovery of new drugs.

Using modern DNA editing techniques, such as TALENs and CRISPR, scientists are able to remove, insert or replace genes in a very precise way. Scientists can use these very targeted genetic modifications to edit the genome of cells, giving them confidence that what they see as a result of phenotypic screening is the effect they want to see and not something else.

Gene editing can also be used to modify a binding site and see if it stops the original biological process from happening. Combinations of these new techniques have sped up research that, in the past, would have taken many years, if not decades. Genetic engineering thus has the potential to transform the way scientists search for drugs in the future.

Acknowledgement

This is an edited version of an article first published in the magazine *Education in Chemistry* in May 2017[w1].

Reference

w1 *Education in Chemistry* is a magazine for chemistry teachers, published by the Royal Society of Chemistry in the UK. To see the original article, visit the EiC website. See: https://eic.rsc.org/feature/searching-for-a-cure/3007211.article

Resources

Learn about the steps in the drug development process from molecule screening to marketing in an article from *Tomorrow's Pharmacist*. See: www.pharmaceutical-journal.com/publications/tomorrows-pharmacist/drug-development-the-journey-of-a-medicine-from-lab-to-shelf/20068196.article or use the direct link: https://tinyurl.com/yy76m6bc

Watch a TED-Ed video about the discovery of aspirin. See: https://ed.ted.com/lessons/how-aspirin-was-discovered-krishna-sudhir

Explore the trial-and-error process of chemical modification in drug design with a printable drug discovery game. See: http://drugdiscoverygame.com/

Dr Sarah Houlton is a science writer based in Hertfordshire, UK.

Art meets molecular biology

Step inside a science-inspired art exhibition where students bring biological molecules to life.

By Oana Stroe

Inspiration can come from the most unexpected places. Often it springs from things we can't see with the naked eye, like outer space, the depths of the oceans – or even the structure of molecules. This was one of the ideas behind a recent science-inspired art project launched by the Protein Data Bank in Europe (PDBe)[w1] at the European Bioinformatics Institute (EMBL-EBI)[w2], located near Cambridge, UK.

PDBe is an open repository for molecular structures, so anyone with an internet connection can visit the website and search through thousands of 3D representations of proteins and other biological molecules, from haemoglobin (which carries oxygen around our bodies) and oxytocin (dubbed the 'love hormone'), to components of deadly viruses and beyond.

Once reserved for the eyes of scientists, such images are now easily accessible to the public. And for the past two years, students aged 12–18 in local Cambridgeshire schools have used the images as the inspiration for creating stunning artworks. Working with scientists, students begin by exploring the huge diversity of biological molecules, understanding their 3D structures and what they do. The students are then encouraged to create their own artistic interpretations, which are presented at an exhibition in central Cambridge.

PDBe aims to grow the art project in the coming years, both to encourage more students to participate, and to attract different audiences to enjoy the artwork. Using active learning processes such as art to teach scientific concepts may also encourage more students to pursue science subjects in the future. With this in mind, PDBe hopes to reach students in younger age groups, from both science and art subjects, to help improve the uptake of scientific subjects at later stages of education.

For now, we are pleased to share some of the highlights from the 2018 PDBe art exhibition, accompanied by a description written by each student explaining the ideas behind their artwork. This selection illustrates the enormous potential for science-inspired creativity, and it is clear that these artworks have the potential to impress people everywhere with the wonders of the molecular world.

Rodion Kutsaev/Unsplash.com

Agents of disease

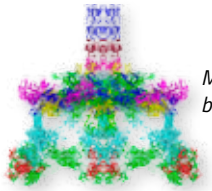
By Katherine Prince

This piece of art captures the dark side of a type of virus called a bacteriophage. They get inside bacteria, replicate and can then break open and kill the bacterium. This is what gave them the name of bacteriophage, which means 'bacteria eater' in Greek. In some cases, they don't destroy the bacteria, but can turn them into agents of disease.

PDBe/EMBL-EBI

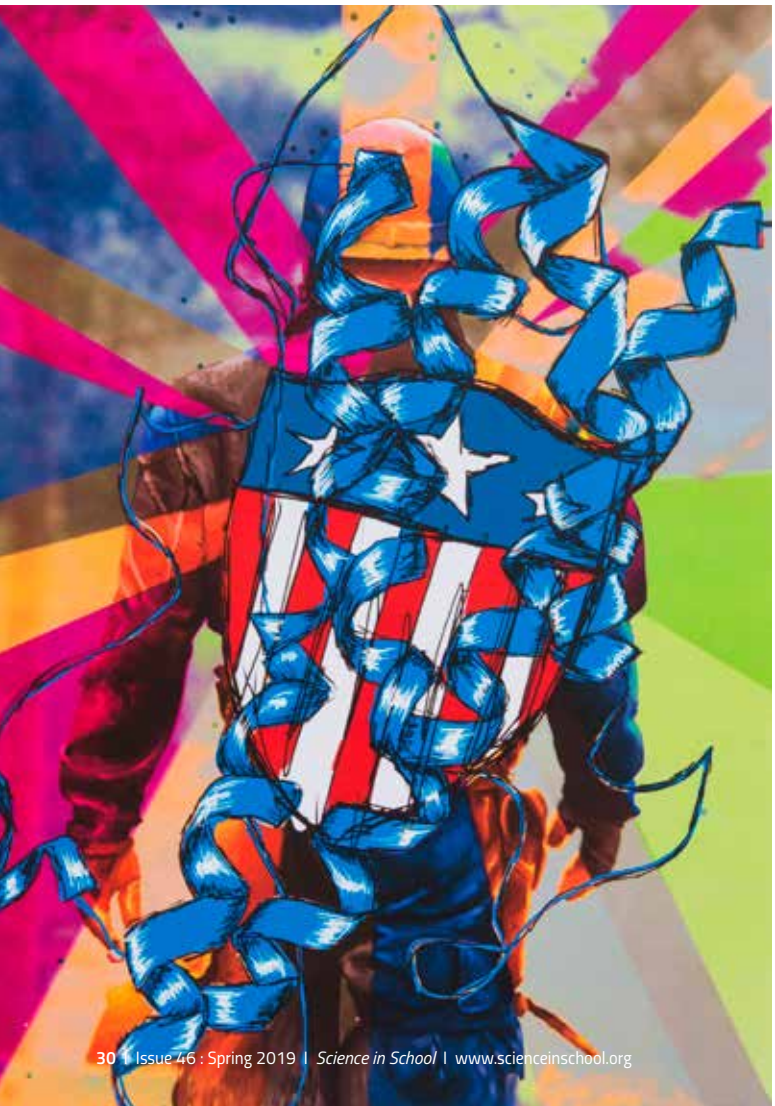
Resources

For information on the structure and function of a T4 bacteriophage, and to observe the 3D molecular structure, visit the PDBe website. See: www.ebi.ac.uk/pdbe/entry/pdb/5vf3 and www.ebi.ac.uk/pdbe/entry/pdb/5iv5



PDBe/EMBL-EBI

Molecular structure of a T4 bacteriophage baseplate

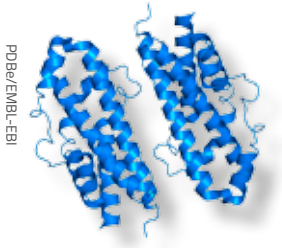


PDBe/EMBL-EBI

Marvel's Captain America

By Emi Rush

This artwork explores the idea of greatness, both of individuals and of a nation, by referencing the superhero Captain America, who is a symbol of hope and strength. The public perceives him as great because of his strength and physicality. This piece of art questions whether his greatness comes from the man behind the superhero identity or from the serum that gave him his superpowers. The shield represents the person, while the cartoon coils of somatotropin – a growth hormone – represent the serum. The colours (blue, pink and orange) represent the fractured state of masculinity and femininity and ask whether masculinity equates to greatness.

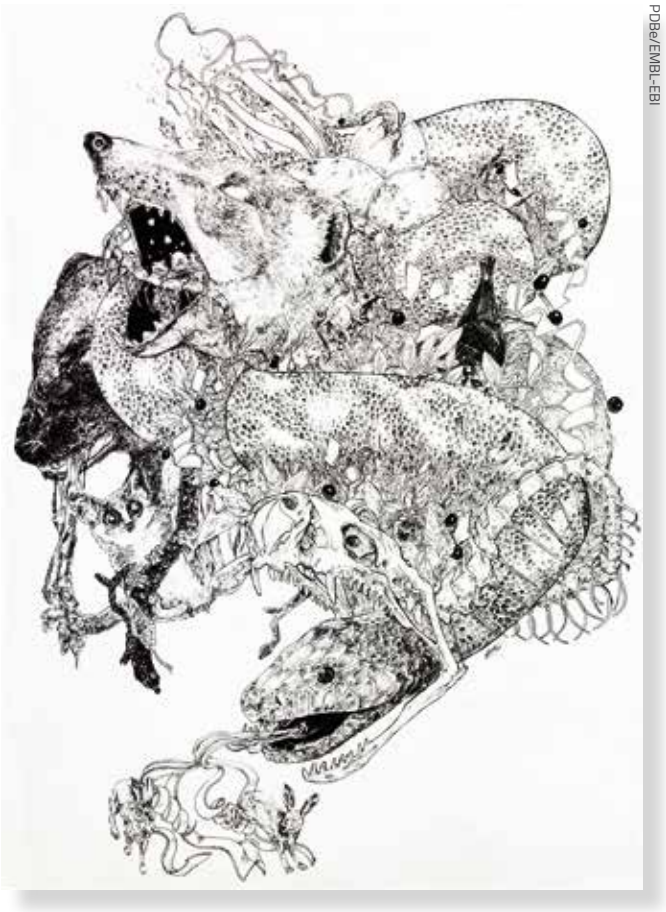


PDBe/EMBL-EBI

Molecular structure of somatotropin

Resources

For information on the structure and function of somatotropin, and to observe the 3D molecular structure, visit the PDBe website. See: www.ebi.ac.uk/pdbe/entry/pdb/1huw



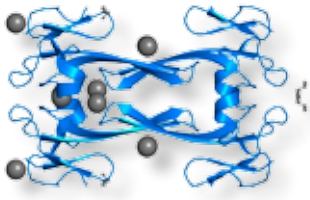
PDBe/EMBL-EBI

Toxins

By Ayshini Senadeera

Venomous creatures such as snakes, jellyfish and scorpions generate a sense of fear – but they also intrigue us. Why would such small animals develop such harmful toxins? Why don't most mammals and birds have access to the biological weapons that venomous creatures use?

The vast number of toxins accessible through PDBe are fascinating. One such toxin is mambalgin-1, which is a pain-relieving peptide isolated from black mamba snake venom. This artwork represents the evolution of biological weapons that venomous creatures call upon.



PDBe/EMBL-EBI

Molecular structure of mambalgin-1, a toxin found in black mamba snake venom

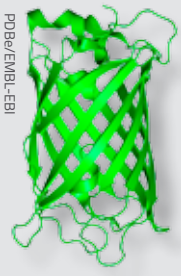
Resources

For information on the structure and function of mambalgin-1, and to observe the 3D molecular structure, visit the PDBe website. See: www.ebi.ac.uk/pdbe/entry/pdb/5do6

Dressed to fluoresce

By Rachel Glinsman

Fluorescent proteins emit light in some living organisms, such as deep-sea fish and jellyfish. The molecular pattern of this dress is based on the green fluorescent protein from the jellyfish *Aequorea victoria,* printed on cartridge paper and coated with glow-in-the-dark paint. The molecules were cut using a laser cutter and assembled into a mesh layer of material around the black body of the dress. The molecules 'float' around the dress, mirroring jellyfish movement underwater. In the dark, the dress glows green, much like fluorescent proteins in deep-sea organisms.



PDBe/EMBL-EBI

Molecular structure of the green fluorescent protein

PDBe/EMBL-EBI

Resources

For information on the structure and function of the green fluorescent protein, and to observe the 3D molecular structure, visit the PDBe website. See: www.ebi.ac.uk/pdbe/entry/pdb/1ema

PDBe/EMBL-EBI

Liver fluke thioredoxin

By Anna Valchanova

Air-breathing freshwater snails of the *Lymnaeidae* family are the intermediate host for the liver fluke parasite, *Fasciola hepatica*. When the parasite infects humans or ruminants (such as cattle and sheep), it causes fasciolosis, a disease with painful symptoms including abdominal pain, inflammation of the gall bladder and even fibrosis.

Thioredoxin is an antioxidant found in liver fluke, which aids in the removal of potentially harmful free radicals. In this artwork, the molecular structure of thioredoxin is repeated throughout the spiral of the shell, and its increasing size reflects the parasite's growth and development inside the snail.

PDBe/EMBL-EBI

PDBe/EMBL-EBI

Molecular structure of thioredoxin

Resources

For information on the structure and function of thioredoxin, and to observe the 3D molecular structure, visit the PDBe website. See: www.ebi.ac.uk/pdbe/entry/pdb/2vim

PDBe/EMBL-EBI

Molecular structure of an AMPA-type glutamate receptor

Connection

By Natalia Heirman

Relationships require strong bonds to function; otherwise, they fall apart. The aim of this artwork is to compare the bonds between both proteins and people. For humans, these links allow us to function and be our happiest and healthiest selves. Similarly, many proteins must work in groups to carry out their functions. Proteins must have physical contact between them for larger structures to form, unlike in humans, where a physical interaction is not needed for a relationship to exist.

The protein shown is an AMPA-type glutamate receptor, which mediates neurotransmission and synaptic plasticity in nerve cells, allowing communication between them.

Resources

For information on the structure and function of AMPA-type glutamate receptors, and to observe the 3D molecular structure, visit the PDBe website. See: www.ebi.ac.uk/pdbe/entry/pdb/5ide

Icosahedron assembly

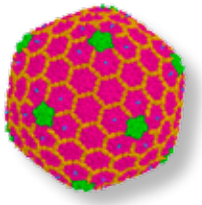
By Rebecca Sheng

PDBe/EMBL-EBI

The structure depicted here is a virus that commonly infects honey bees, causing deformed wings. Like many other viruses, the deformed wing virus is made up of repeating symmetrical units that self-assemble into a 3D object. The shapes that viruses form are often similar to the Platonic solids. The ancient Greek philosopher Plato wrote about these shapes in his work *Timaeus*, in which he linked four of them to the classical elements: earth, air, water and fire. The deformed wing virus has the symmetry of one of these solids: the regular icosahedron, which has 20 faces, 30 edges and 12 vertices.

Resources

For information on the structure and function of the deformed wing virus, and to observe the 3D molecular structure, visit the PDBe website. See: www.ebi.ac.uk/pdbe/entry/pdb/5mv5



PDBe/EMBL-EBI

Molecular structure of the deformed wing virus

Acknowledgement

The 2018 PDBe art project was a collaboration with four Cambridgeshire schools: the Leys School, the Perse School, Impington Village College and the Stephen Perse Foundation Sixth Form College.

Web references

w1 The Protein Data Bank in Europe (PDBe) is a database for 3D structural data relating to large biological molecules, such as proteins and nucleic acids. The models are made freely available worldwide. See: https://PDBe.org

w2 The European Bioinformatics Institute (EMBL-EBI) hosts and shares data from life science experiments performed all over the world, and its scientists carry out basic research in computational biology. See: www.ebi.ac.uk/about

Resources

Find out more about the PDBe art project in the following articles:

'PDB Art' from the PDBe website: https://PDBe.org/art

'Art meets structural biology' from *EMBLetc.*: https://news.embl.de/science/pdbe-art-exhibition-2018/

View more molecular inspired artworks by visiting the 'Featured structures' page on the PDBe website. See: www.ebi.ac.uk/pdbe/featured-structures

Printable teaching materials, including a protein colouring book, are available on the PDBe website. See: www.ebi.ac.uk/pdbe/training/teaching-materials

Oana Stroe is a communications officer at EMBL-EBI. After completing a master's degree in communication, culture and media, Oana worked in technology and engineering public relations for a number of years before joining EMBL-EBI.

Bowonpat Sakaew/Shutterstock.com

Which laundry enzymes work best?

Investigate how enzymes in your laundry detergent get rid of stains – and which are most important for keeping clothes clean.

By Mariona Lladonosa Soler

Supermarket shelves are stocked with an overwhelming variety of laundry detergents, with many products promoting the 'powerful' performance of enzymes for 'superior' stain removal. But beyond the eye-catching claims, how does one laundry detergent really differ from another? And is there an advantage to using those that contain enzymes?

The composition of laundry detergents

Detergents are made up of a mixture of substances, but most importantly contain chemicals called surfactants that break up and remove dirt. Surfactants – which include common hand soap – are usually amphiphilic, meaning that one

end of the molecule is hydrophilic (it is attracted to water) and the other is hydrophobic (it repels water). The hydrophobic end sticks to the surface of oily dirt, while the hydrophilic end attaches to water. Water molecules pull the surfactant away from the clothes – taking the dirt with them – to be washed away at the end of the washing cycle.

Surfactants alone, however, are not enough to keep clothes clean and smelling fresh, so laundry detergents often contain a host of other ingredients, such as optical brighteners, perfumes and enzymes. To distinguish between a detergent that contains enzymes and one that does not, products use the terms 'biological' and 'non-biological' respectively. But do enzymes really improve cleaning power?

Enzymes provide extra help to break down stains that are otherwise hard to remove. The main advantage of using a biological detergent is that it is effective at lower temperatures and in quick washes, which saves time, energy, water – and money. There are four major classes of detergent enzymes, each with a different use: proteases remove protein stains; lipases break down fatty materials; amylases remove stains from starch-based food; and cellulases break down the small cotton fibres that form on the fabric surface during use, helping to release dirt and keep the fabric smooth. Most biological detergents combine enzyme types – often using proteases and lipases – to improve their overall performance.

If small amounts of biological detergent remain on clothing, however, they can irritate sensitive skin. For this reason, the use of non-biological detergent is preferred in some situations, particularly for washing clothes for babies. For tackling tough stains, however, non-biological detergents often need to be used at a higher temperature.

REVIEW

- ✓ Chemical bonding
- ✓ Solutions and mixtures
- ✓ Catalysis
- ✓ Enzyme kinetics
- ✓ Biotechnology
- ✓ Ages 16–19

Enzymes are a key topic in both biology and chemistry lessons, but its complexity can mean that it is sometimes perceived as difficult or boring, especially if addressed with a traditional theoretical approach. The activity outlined in this article, however, is quite the contrary. Using the simple everyday task of laundry washing, the author addresses the topic of enzymes in an engaging way, with students carrying out their own investigation into the action of enzymes on different substrates.

Teachers may be familiar with similar enzyme-based practical activities, but this article is comprehensive and well-structured, resulting in an activity that is perfectly suited for an enquiry-based approach to enzyme chemistry.

The activity uses simple laboratory equipment, but requires enzymes to be ordered from specialised supply companies. If your school does not have access to isolated enzymes, the activity could be adapted to use different store-bought detergents.

Giulia Realdon, natural sciences teacher and education researcher, Italy

Investigating the effectiveness of enzymes

This activity helps students to learn about different enzymes and their properties, and encourages them to evaluate the use of enzymes in laundry detergents. By washing a variety of stains with detergents to which they have added different 'mystery' enzymes, students guess the enzyme type based on the effectiveness of the detergents they have created. In addition, students test their detergents at three different temperatures to examine how this affects the performance and to see that some enzymes are denatured (and therefore no longer work) at high temperatures.

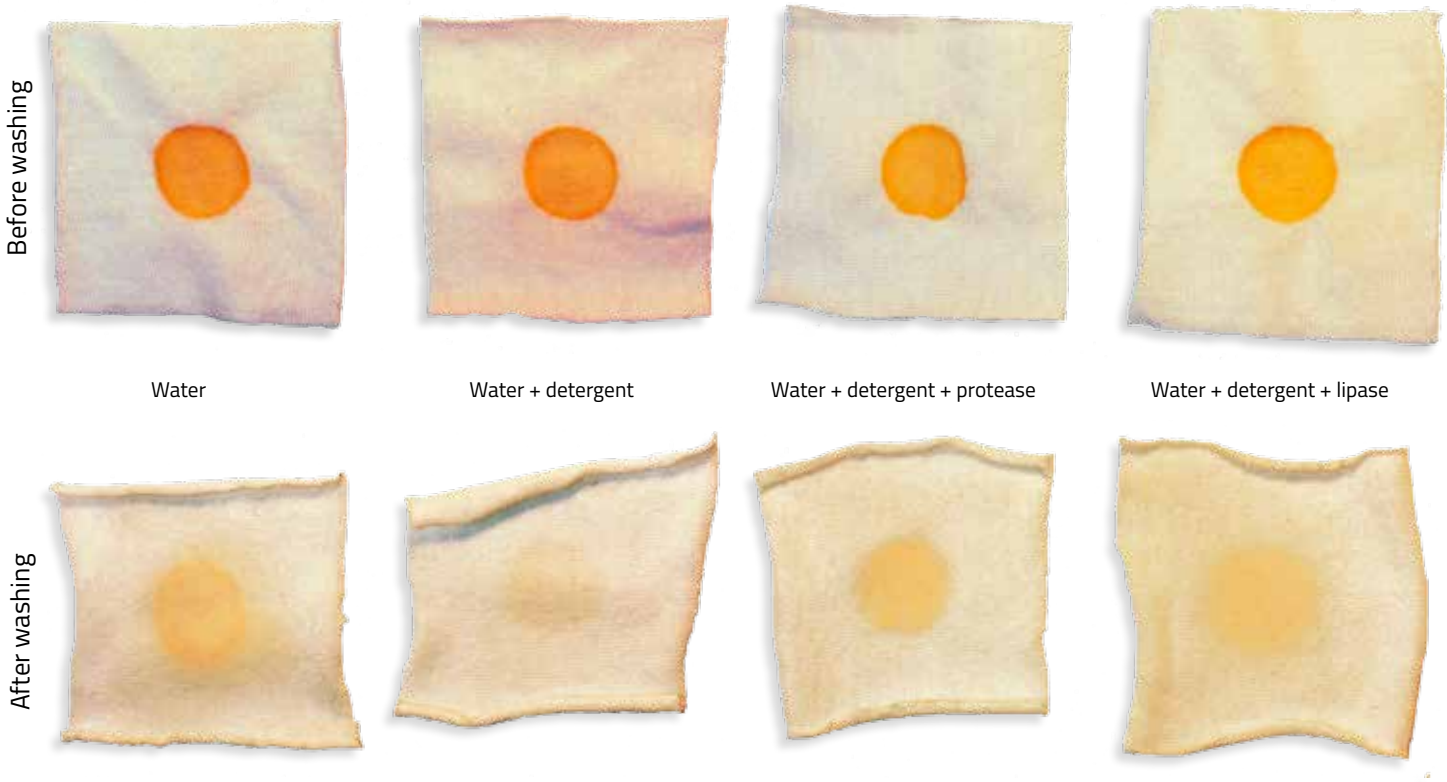
For the enzymes, we suggest using protease, lipase, amylase and cellulase. The enzymes can be ordered from a scientific laboratory supply company. To keep the enzymes secret from your students, label them A–D before the lesson.

We recommend that students work in groups of eight. Within each group, students work mostly in pairs, with the group combining their results at the end of the activity to draw their conclusions. Students can check these conclusions by completing the extension activity (testing for the presence or absence of particular enzymes) or, if time is limited, you can simply reveal which enzymes are which.

Once you have introduced the investigation to your students, they can work through the instructions set out in the following activities.

Activity 1: Making the stains

Start by creating some stained samples of fabric. You will use these samples in activity 2 to test the effectiveness of various detergents. Ideas for staining substances include beetroot juice, coffee, lipstick, starch solution, paint, permanent marker, olive oil, egg, wine and melted chocolate. This part of the activity takes approximately 30 minutes.



Materials

- White cotton fabric (e.g. old white T-shirts or muslin cloths)
- Staining substances
- Scissors
- Pipette or dropper (optional)

Procedure

1. Within your group, choose four different staining substances to test and assign each one to a pair of students. Make sure to include substances to test for protease, lipase and amylase, such as egg, olive oil and a starch solution, respectively.
2. In your pairs, cut up the cotton fabric to create 24 pieces. With these pieces, you will test four separate enzymes, two enzyme mixtures, and two control solutions, all at three different temperatures. Make each piece roughly 5 cm x 5 cm. To distinguish your samples from those of other pairs in your group, cut them into a distinct shape.
3. In your pairs, stain all 24 pieces of fabric with your assigned staining substance. Your stains (and the stains of your whole group) should all be a similar size, using the same amount of each substance. For greater precision, use a pipette or dropper for liquid substances.

Activity 2: Testing the detergents

Within your group, create the biological detergents by mixing the enzymes with non-biological detergent and water. You should test each of the four enzymes separately (e.g. A only, B only, C only, D only), and also create two additional biological detergents by mixing enzymes together (e.g. A and B, or B and C).

To predict which enzyme is which, test the performance of each enzyme-containing detergent on each of the stained fabrics. Each detergent should be tested at room temperature (around 20°C), and at 40°C and 70°C. In addition, carry out two more tests to act as controls: one using only water, and one using a solution of water mixed with non-biological detergent (i.e. no enzymes). In total, this part of the activity takes approximately 1 hour.

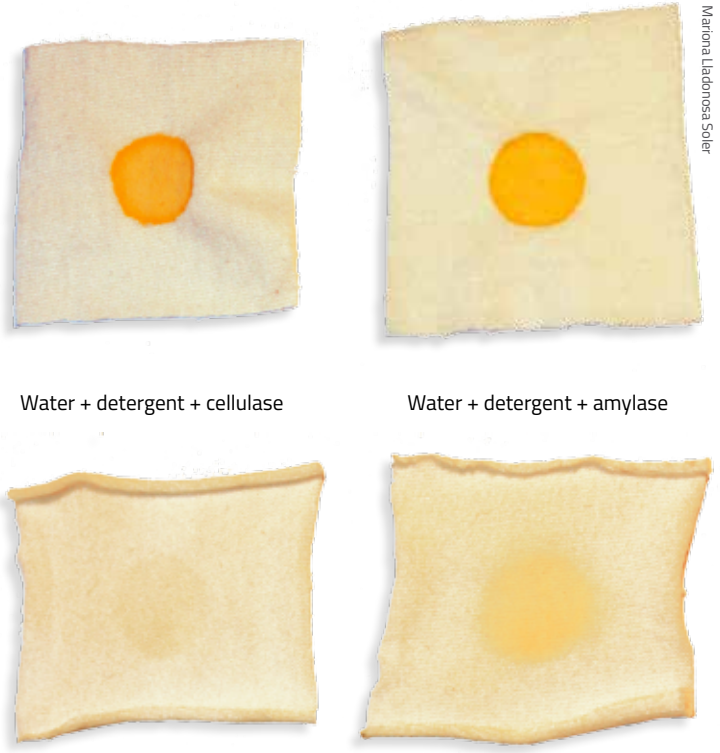
Materials

- Stained fabric samples
- Non-biological detergent
- Enzymes A–D
- Water
- 1 litre beakers
- Weighing scales
- Stopwatch
- Water bath or hot plate
- Thermometer
- Glass stirring rod
- Magnetic stirrer (optional)
- Hair dryer (optional)
- Permanent marker

Safety note: A lab coat, gloves and goggles should be worn. Take care when handling the solutions at high temperatures.

Procedure

1. Within your group, create three 1-litre solutions for your first biological detergent: mix 3 g of non-biological detergent and 1 g of enzyme A in a beaker of 1 litre of water. Also create three batches each of the control solutions: 1 litre of water with 3 g non-biological detergent; and 1 litre of plain water.
2. Starting with a solution of enzyme A at room temperature, place one of each of the different stained fabric



Mariona Lladonosa Soler

Water + detergent + cellulase

Water + detergent + amylase

samples (e.g. four in total) into the beaker.

3. Start the stopwatch, and stir the solution as consistently as possible with a glass stirring rod for 5 minutes. Alternatively, you could use a magnetic stirrer, if available.
4. After 5 minutes, pour out the solution, squeeze any excess water out of the fabric samples and leave them to dry. If needed, use a hair dryer on the cool setting to speed up the process. Using a permanent marker, label each piece of fabric to indicate the detergent that was used (e.g. with the letter A), and note what temperature they were tested at (e.g. room temperature).
5. Repeat the procedure at 40°C and 70°C by heating two other beakers of enzyme A solution in a water bath or using a hot plate. Check the temperature is correct using a thermometer before adding the stained fabrics and stirring. Remember to label the fabric samples accordingly.

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Students cut the fabrics into different shapes to distinguish between the stains.

Mariona Lladonosa Soler

Figure 1: The solution on the left contains protease, which results in a visible decrease in the level of the gel in comparison to the test on the right, which contains no enzymes.

Mariona Lladonosa Soler

Figure 2: pH indicator strips show a decrease from 7 (neutral) to 6 (slightly acidic) between the test on the right (without enzymes, the green indicator strip) and the lipase-containing test on the left (the yellow indicator strip).

6. Repeat steps 1–5 for each of the detergents for enzymes B–D, your two control solutions, plus your two chosen enzyme 'cocktails'.
7. Once you have tested all of the solutions, compare your results.

For each stain, which detergents work best? What does this tell you about the enzymes you used? Keep a note of which enzymes you think were in each detergent, so you can check against the answers later.

Discussion

Discuss some of the following questions in your groups:

- What is the effect of enzymes on the performance of laundry detergent?
- Is detergent more effective with or without enzymes?
- Why were some detergents not effective at removing the stains?
- Which stains were hardest to remove? Why might that be?
- How does water temperature affect the performance of detergents?
- What are the advantages of using enzymes in detergent?
- Why can biological detergents remove stains from fabric at lower temperatures than normally used with non-biological detergents?
- What are the advantages and disadvantages of using biological detergents?

Extension activity: Detecting enzymes

The following procedures can be used to test which enzyme is which. Each procedure takes approximately 15 minutes to prepare.

Method 1: Protease

Protease catalyses the breakdown of long protein molecules into shorter fragments called peptides. When protease is added to gelatine (a protein commonly used as a gelling agent in food), the protein molecules are broken up into peptides, so they no longer intertwine to create a semisolid structure.

Materials

- Enzyme solutions A–D (1 g of enzyme per 500 ml of water)
- Test tubes (one for each enzyme)
- Gelatine
- Water
- Permanent marker

Procedure

1. Prepare the gelatine gel by mixing 50 g of gelatine with 500 ml of boiling water.
2. Fill the test tubes each with 10 ml of the gel and place them in a fridge.
3. When the gel has solidified (usually after approximately 2 hours), mark the level of the gel on the test tubes using a permanent marker.
4. Add 5 ml of enzyme solution to the test tubes (one enzyme per tube) and label each test tube according to the enzyme (e.g. A, B, C and D).
5. Return the test tubes to the fridge for 24 hours before marking the level of the gel again.
6. Compare the levels before and after adding the enzymes to determine which one is protease. If protease is present, the level of gel in the test tube will decrease noticeably (see figure 1).

Method 2: Lipase

Lipase breaks up lipids into fatty acids and glycerine, which causes the pH of the solution to decrease. The easiest way to prove the presence of lipase is to identify this decrease using pH indicator strips.

Materials

- Enzyme solutions A–D (1 g of enzyme per 500 ml of water)
- Test tubes (one for each enzyme)
- pH indicator strips
- Double cream or whipping cream (a high fat content is best)
- Dropper
- Permanent marker

Procedure

1. Add 10 ml of each enzyme solution to the test tubes and label them accordingly (e.g. A, B, C and D).

Mariona Lladonosa Soler

Figure 3: In contrast to the test on the right (without enzymes), the flan on the left remains liquid due to the presence of amylase.

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Figure 4: The piece of onion on the left was soaked in a solution containing cellulase. The walls of the onion decomposed, in contrast to the test on the right, which contained no enzymes and remained intact.

2. Add 50 ml of cream to each test tube and mix well.
3. Check the initial pH of each mixture with an indicator strip.
4. Wait approximately 2 hours and check the pH again.
5. Compare the before and after pH indicator strips for each enzyme to determine which one is lipase (see figure 2).

Method 3: Amylase

Amylase catalyses the hydrolysis of starch into sugars. You can test for the presence of amylase by adding the detergents to a creme caramel flan mix, which traditionally contains corn starch to act as a thickening agent. If amylase is present, the flan will remain liquid and not set, because the enzyme breaks down the starch, preventing the dessert from thickening.

Materials

- Enzyme solutions A–D (1 g of enzyme per 500 ml of water)
- Test tubes (one for each enzyme)
- Creme caramel flan mix (ensure that the ingredient list includes starch)
- Permanent marker

Procedure

1. Prepare the dessert as per the flan mix instructions.
2. Add 10 ml of each enzyme solution to the test tubes and label them accordingly (e.g. A, B, C and D).
3. Add 50 ml of the flan mixture to each test tube and mix well.
4. Leave the mixture in the fridge to set for approximately one day, or until a change is visible.
5. Compare the test tubes to determine which enzyme is amylase (see figure 3).

Method 4: Cellulase

Cellulase catalyses the decomposition of cellulose into glucose monomers. One way to test for the presence of cellulase is using an onion. Since the cell walls of an onion are composed of cellulose, mixing the onion with detergents that contain cellulase will result in the walls decomposing, turning the onion transparent.

Materials

- Enzyme solutions A–D (1 g of enzyme per 500 ml of water)
- Test tubes (one for each enzyme)
- Onion
- Knife
- Water
- Permanent marker

Procedure

1. Cut the onion into pieces, approximately 3 cm x 3 cm.
2. Place one piece of onion into each test tube.
3. Add 30 ml of each enzyme solution to the test tubes to cover the onion, and label them accordingly (e.g. A, B, C and D).
4. Wait for at least 4 hours.
5. Observe the appearance of the onion pieces to determine which enzyme is cellulase (see figure 4).

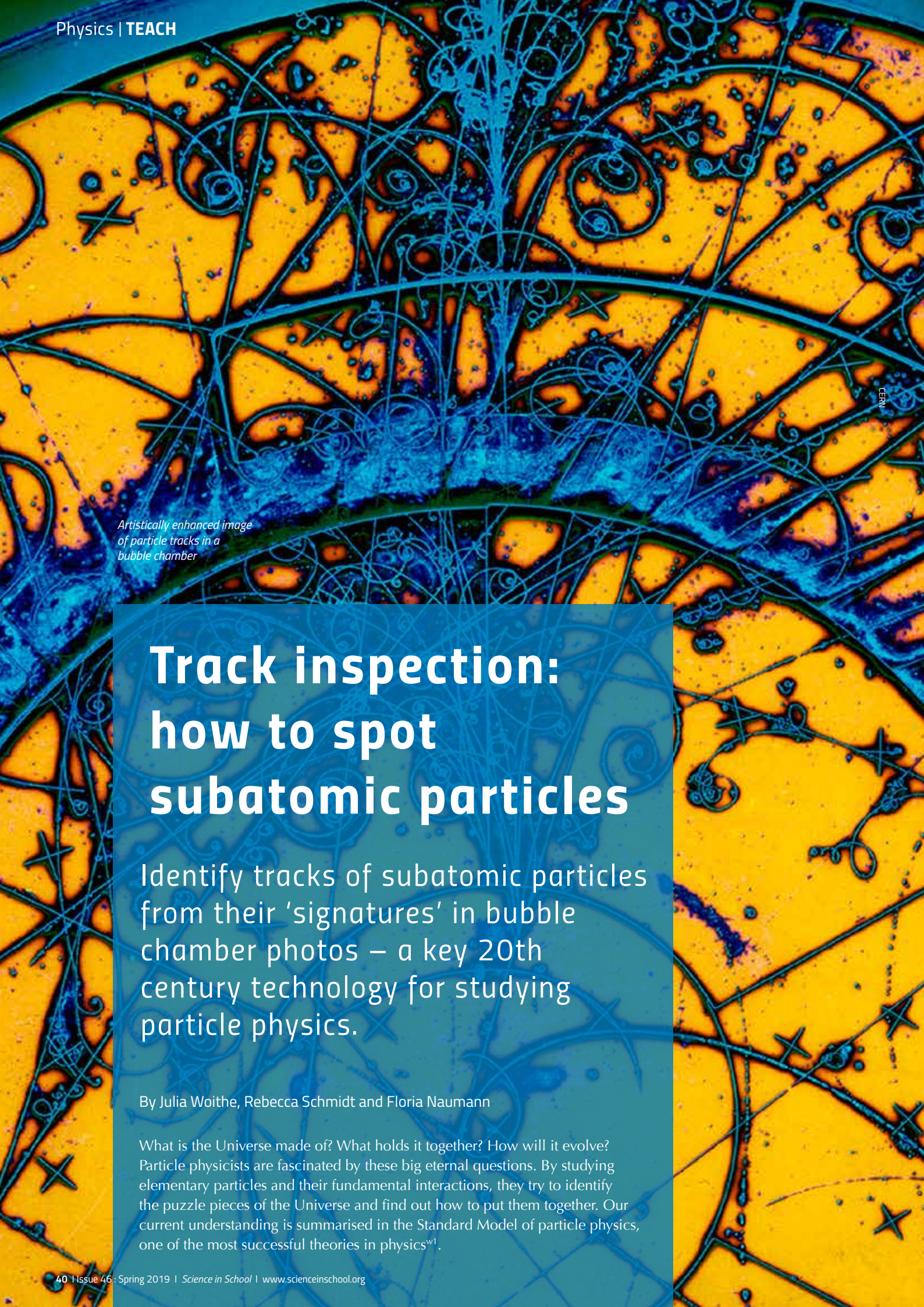
Resources

To learn more about enzymes and for ideas of additional activities, see:

Voak (2016) Energising enzyme activities. *Science in School* **35**. www.scienceinschool.org/content/energising-enzyme-activities

The EMBL-EBI enzyme portal integrates publicly available information about enzymes. Use the search function to find details about enzymes that are of interest to you. See: www.ebi.ac.uk/enzymeportal/

Mariona Lladonosa Soler is a biochemistry student at the University of Barcelona, Spain. Inspired by her research, she developed and presented her activities on enzymes and detergents at the Hands-on Science conference in Barcelona in 2018.



CERN

Artistically enhanced image of particle tracks in a bubble chamber

Track inspection: how to spot subatomic particles

Identify tracks of subatomic particles from their 'signatures' in bubble chamber photos – a key 20th century technology for studying particle physics.

By Julia Woithe, Rebecca Schmidt and Floria Naumann

What is the Universe made of? What holds it together? How will it evolve? Particle physicists are fascinated by these big eternal questions. By studying elementary particles and their fundamental interactions, they try to identify the puzzle pieces of the Universe and find out how to put them together. Our current understanding is summarised in the Standard Model of particle physics, one of the most successful theories in physics[w1].

But how do we know anything about these particles, all of which are much smaller than the atom? From the 1920s to the 1950s, the primary technique used by particle physicists to observe and identify elementary particles was the cloud chamber (Woithe, 2016). By revealing the tracks of electrically charged subatomic particles through a supercooled gas, with cameras used to capture the events, researchers could work out the particles' mass, electric charge and other characteristics, along with how they interacted. However, in 1952 the bubble chamber was invented, and this soon replaced the cloud chamber as the dominant particle detection technology. Bubble chambers could be made physically larger, and they were filled with a much denser material (liquid rather than gas), which made them better for studying high-energy particles.

Today, both cloud chambers and bubble chambers have largely been replaced by other types of detector that produce digital signals and work at a much faster rate. So while photos from bubble chambers are no longer the technology of choice for professional physicists, they can still enrich the discussion of particle physics in the classroom.

REVIEW

✓ Subatomic particles

✓ Ages 16–19

This article provides the opportunity to use photographs produced by a bubble chamber at CERN in 1972 to analyse particle tracks and get to know the typical characteristics of these subatomic particles.

The tasks are inspiring and detailed, and they allow for self- or peer-assessment to be used. The historical aspects of the topic as well as the images could appeal to science teachers running science clubs. The tasks are also very suitable for use in class, as a follow-up to theoretical teaching on this topic, such as when discussing evidence for subatomic particles. For the more creatively inclined, the article could provide a basis for cross-curricular projects – perhaps using the tracks or images as inspiration in an art or craft lesson, for example.

Comprehension exercise could relate to the introductory part of the article. Some suggested questions could be:

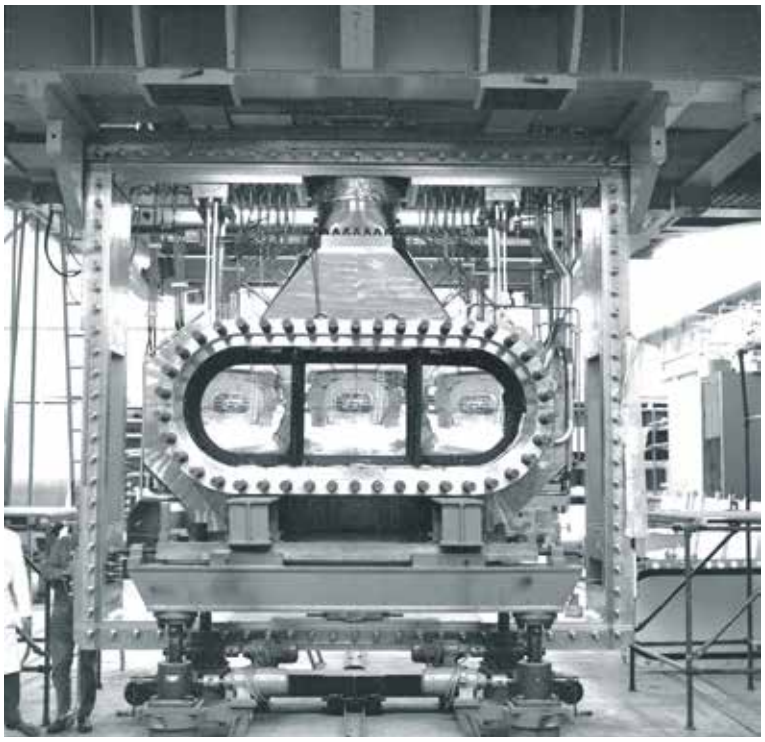
- What events do bubble chamber pictures show?
- Why have cloud and bubble chambers been replaced today?
- List three subatomic particles.

Stephanie Maggi-Pulis, head of physics department, Secretariat for Catholic Education, Malta

How does a bubble chamber work?

The key component of a bubble chamber is a superheated liquid. When electrically charged particles pass through a bubble chamber, they ionise the molecules in the chamber medium. The ions trigger a phase transition and the superheated liquid vaporises, creating visible tracks as bubbles form along the particle's path. Once the newly formed bubbles have grown large enough, cameras mounted around the chamber capture the event.

Importantly, a uniform magnetic field runs through the chamber, which produces a force on moving electrically charged particles, making them move in curved paths – and creating 'signature' shapes for different particles. Measuring the radius of curvature allows a particle's momentum to be



CERN

The 2 m bubble chamber during installation at CERN in 1969

calculated, providing further clues to its characteristics.

Analysing bubble chamber tracks in the classroom

We have developed several activities for advanced high-school students, in which they study bubble chamber photographs and try to work out for themselves what they show. You can find our original worksheet describing these activities (including solutions and additional information for teachers) on the CERN website[w2].

The photographs were produced by the 2 m-long bubble chamber at CERN in 1972. This chamber was filled with 1150 litres of liquid hydrogen cooled to 26 K (–247°C). In its 12 years of operation, 20 000 km of photographic film were produced to capture the particle collisions.

In this article, we present three simple but intriguing activities for students aged 16–19 as an introduction to particle track analysis, using the bubble chamber images. Before starting the activities, students should be familiar with the basics of particle physics (especially the properties of protons, electrons, positrons, photons and, if possible, neutrinos).

The first two activities focus on the identification of some typical particle tracks based on the behaviour of electrically charged particles in magnetic fields. Activity 3 builds on these activities to look at particle transformations. Depending on students' prior knowledge, it will take approximately 1 hour to carry out all the activities.

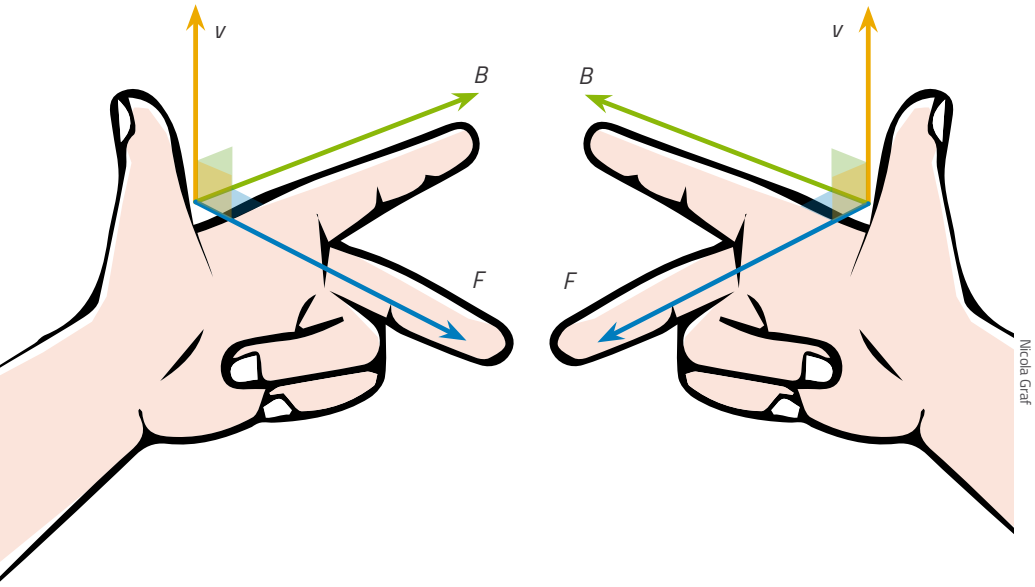
Note: when working with bubble chamber pictures, high-resolution images are crucial to allow the identification of individual tracks. You can find high-resolution versions of the images on the *Science in School* website[w3].

Activity 1: Electrically charged particles in magnetic fields

In this activity, students identify the electric charge of particles based on the direction of curvature of their tracks in a magnetic field. They also compare the speed of electrons, based on the radius of curvature of their tracks.

Left-hand rule for negatively charged particles

Right-hand rule for positively charged particles



Nicola Graf

Figure 1: The left-hand and right-hand rules. v: direction of the particle's movement; B: magnetic field (from north to south); F: force on the particle

As a preliminary to this activity, students will need to understand the following facts relating to particle physics:

- When electrically charged particles move through a magnetic field, they experience a force.
- This force is always perpendicular to the direction of movement of a particle and the direction of the magnetic field. The left-hand (or right-hand) rule tells you in which direction this force points.
- Due to this force, electrically charged particles at constant speed follow circular paths when moving through constant magnetic fields (because the experienced force acts as a centripetal force).
- When several electrically charged particles with the same mass experience a force while moving through a magnetic field, the radius of curvature of their tracks depends on the particles' speed. Tracks of slower particles are more curved than tracks of faster particles with the same mass.

Materials

For this activity, the only materials needed are the images and information in figures 1, 2 and 3. Each student or group of students will need colour printouts of the two bubble chamber photos (figure 2 and figure 3), which can also be downloaded from the *Science in School* website[w3]. In all the bubble chamber images, the particles enter the chamber from the left, and the magnetic field points out of the page.

Procedure

Ask the students to work through the tasks below, using the materials provided.

1. Make sure you are familiar with the left-hand and right-hand rule, which link the following:
   - Direction of movement of an electrically charged particle
   - Direction of the magnetic field (north to south)
   - Direction of the force on the electrically charged particle

   These rules are shown in figure 1.

Figure 2: Bubble chamber photo 1

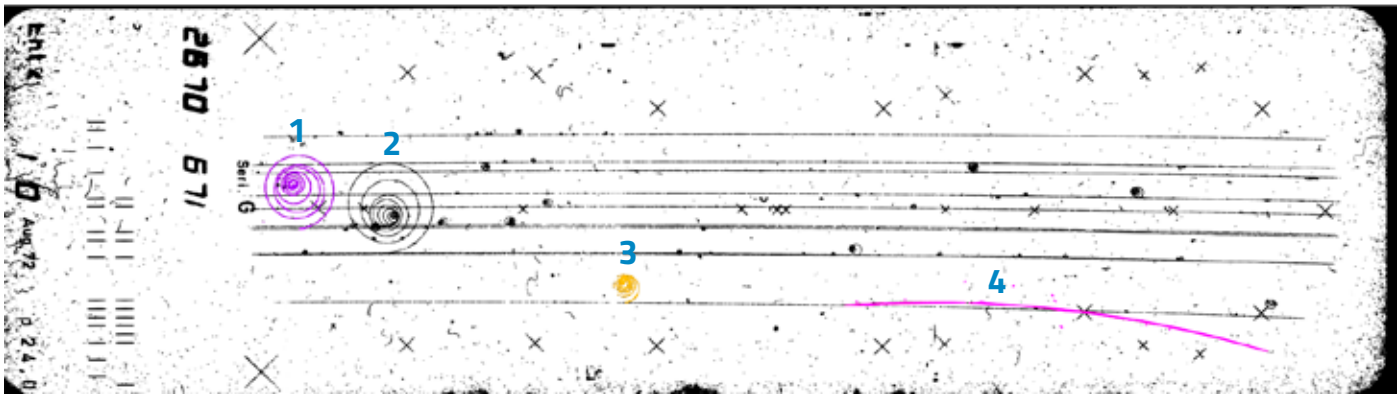


Figure 3: Bubble chamber photo 2

2. Look at the first bubble chamber photo (figure 2) and try to answer the following questions:
   - Which of the two coloured tracks belongs to a **positively** charged particle?
   - Which of the two coloured tracks belongs to a **negatively** charged particle?
   - Why do the particles leave spiral tracks?

Remember, the particles enter the chamber from the left, and the magnetic field points out of the page.

3. Then look at the second bubble chamber photo (figure 3). Again, using the right-hand and left-hand rules, try to answer the following:
   - Which of the coloured tracks in the picture (1, 2, 3 or 4) belong to negatively charged particles?
   - Assume that all tracks belonging to negatively charged particles in the photo are caused by electrons. Place the four tracks in order according to the speed of the electrons, from high speed to low speed.
   - Explain your results.

Discussion

The answers are as follows:

Photo 1 task

Because the blue track curves downwards in photo 1, there must have been a force pointing downwards. Now we try both the left-hand and right-hand rules with the following information taken from the photo:

- Direction of movement of an electrically charged particle (thumb): to the right (as the particles enter from the left)
- Direction of the magnetic field (index finger): out of the page
- Direction of the force on the electrically charged particle (middle finger): downwards

This configuration of fingers works only with the right hand, thus the blue track was caused by a positively charged particle.

The red track curves upwards in photo 1, so there must have been a force pointing upwards, which leads to the following configuration of fingers:

- Direction of movement of an electrically charged particle (thumb): to the right
- Direction of the magnetic field (index finger): out of the page
- Direction of the force on the electrically charged particle (middle finger): upwards

This configuration works only with the left hand, thus the red track was caused by a negatively charged particle.

Why do particles leave spiral tracks in a bubble chamber? On their way through the liquid, electrically charged particles constantly lose kinetic energy – for example, because they ionise the hydrogen molecules on their way. A lower kinetic energy then leads to a progressively smaller track radius in a magnetic field.

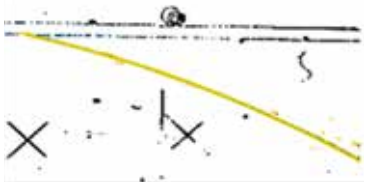
	Electron	Electron-positron pair	Proton
Signature track			
Description	Upward-curving track, starting at another visible particle track	Downward-curving track (positron) starting 'out of nowhere', together with an upward-curving track (electron)	Downward-curving track, starting at the visible track of another particle
Production process	An electrically charged particle enters the chamber and interacts with an electron in the liquid.	A photon transforms into an electron-positron pair. (The photon does not leave a track.)	An electrically charged particle enters the chamber and interacts with a proton in the liquid.

Table 1: Particle signatures and production processes

Photo 2 task

In photo 2, the same procedure identifies tracks 1, 2 and 3 as belonging to negatively charged particles, whereas track 4 was caused by a positively charged particle.

For the speeds, track 2 belongs to the electron (with the highest speed), followed by track 1, then track 3 (with the lowest speed). This is because the lower the speed of the particle, the smaller the radius of curvature of its track. This relationship can be derived for particles as follows:

The force on the electrically charged particle (charge q) moving with speed v perpendicularly to a magnetic field B is described as:

$$F_L = q \times v \times B$$

This force acts as centripetal force, F_c, and leads to a circular particle track with radius r. The centripetal force needed to keep an object on a circular path with radius r depends on the mass m of the object, and the square of its speed v, thus:

$$F_c = m \times \frac{v^2}{r}$$

So $F_L = F_c$

Therefore: $q \times v \times B = m \times \frac{v^2}{r}$

So $r = \frac{m \times v}{q \times B}$

Thus the radius of curvature is directly proportional to the speed of the particle.

Note that we are assuming here that the particles are non-relativistic, i.e. they are moving much more slowly than the speed of light. However, tracks in bubble chamber photos are typically made by relativistic particles moving at speeds close to that of light. In this case, there is a relativistic factor that changes this relationship.

Activity 2: Particle signatures and identification

In the next activity, students use their understanding of track characteristics to identify specific particle 'signatures' (track types) in bubble chamber photos.

Three different types of track are shown in table 1, together with the particle identities, signature descriptions, and explanations in terms of the processes that produced the tracks. This information enables students to identify particles in the bubble chamber images that follow.

	Electron?	Positron?	Proton?	Explanation
Green track				
Upper blue track				
Lower blue track				
Purple track				

Table 2: Identifying particles in figure 4 from their signature tracks

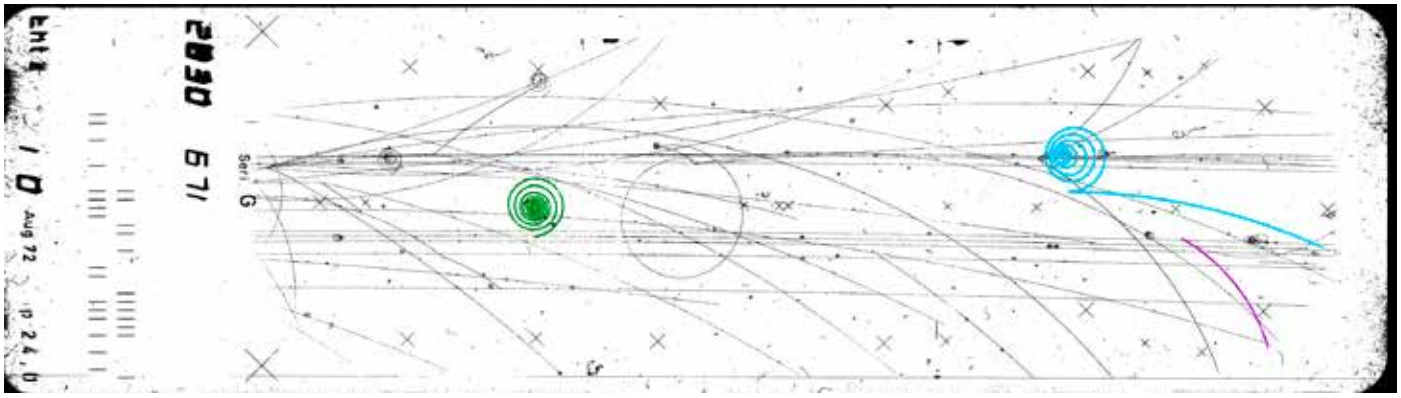


Figure 4: Bubble chamber photo for activity 2

Materials

For this activity, the only materials needed are the images and information in table 1 and figure 4. In all these images, the particles enter the chamber from the left, and the magnetic field points out of the page.

Procedure

Ask the students to tackle the following tasks using the materials provided.

1. Look at the particle signatures shown in table 1.
2. Use this information to identify the tracks highlighted in the bubble chamber image (figure 4).
3. Complete table 2, giving reasons for your choices.

Discussion

The correctly completed table is shown in table 3.

Activity 3: Particle transformations

Interpreting particle transformations is what made bubble chambers famous: many of the particles produced in a bubble chamber are not stable, but transform in time to other particles. However, working out transformation events is usually more difficult for students than simply identifying specific track types, because it requires additional knowledge about the fundamental interactions described by the Standard Model of particle physics.

We suggest using a simple example (figure 5) and providing step-by-step instructions to work through.

Materials

Again, the only materials needed are the image in figure 5 and the information provided previously. As usual, the particles enter the chamber from the left, and the magnetic field points out of the page.

Procedure

Ask the students to answer the following questions using the materials provided.

1. The green track belongs to a type of particle called a pion. There are three types of pions:
   - $\pi+$ (positive electric charge)
   - $\pi-$ (negative electric charge)
   - $\pi0$ (no electric charge)

   Which type of pion caused the green track? Explain your answer.
2. At the end of the green track, the pion transforms into two new particles: a positively charged anti-muon and a muon-neutrino. Why do we only see one track (the blue track) originating from the end of the green track?
3. The anti-muon transforms into a particle that you might be able to recognise. Which particle do you think caused the brown track? (Hint: the new particle has a lower mass than the anti-muon, which has a mass of around 200 times that of an electron.) Explain your answer.

	Electron?	Positron?	Proton?	Explanation
Green track	✓			Track curves upwards.
Upper blue track	✓			Track curves upwards.
Lower blue track		✓		Track curves downwards and appears together with an electron track.
Purple track			✓	Track curves downwards and starts at another track.

Table 3: Identifying particles from their signature tracks: answers

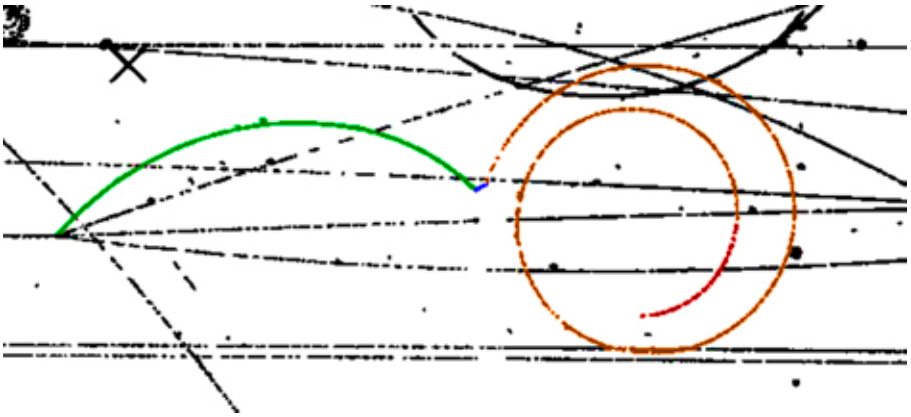


Figure 5: Particle transformations (activity 3)

Discussion

The answers are as follows:

1. The green track curves downwards, so it was caused by a positively charged particle. Therefore, we can identify it as π+.
2. Neutrinos have no electric charge, which means they cannot ionise the molecules in the chamber, so they do not leave visible tracks.
3. The brown track was caused by a positron. It is easy to recognise the positive electric charge because of its downward-curved track. This could therefore be a proton track – except we are told the particle has a lower mass than the anti-muon (because unstable particles typically transform into lighter particles), which itself has a mass of around 200 times that of an electron. This is nowhere near enough to match the mass of a proton, so the track must belong to the only other positively charged particle we have met: a positron. In this situation, the positron track occurs without an accompanying electron track, because the production process is different.

More information about this transformation and the Feynman diagrams that can help to understand this process can be found in the CERN student worksheet[w2].

Bubble chambers: into the future

As these activities show, bubbles chamber images are a great way to

The compact muon solenoid (CMS), a huge modern particle detector at CERN's Large Hadron Collider

Dress inspired by the patterns created by particles in a bubble chamber

Holly Renee/shenovafashion.com

make particle physics accessible to high-school students. Using these images, students can discover the identity of particles by working out their characteristics for themselves.

Meanwhile, the ongoing endeavour to understand the missing puzzle pieces of our Universe continues. And as well as helping to train the particle physicists of tomorrow, bubble chambers have recently found a new role in current research: the detection of dark matter particles – for example, in the PICO project in Canada[w4]. Here, the bubble chamber's relatively slow rate of response (compared to new digital technologies) is not a problem, because – unlike the cascades of particles produced each second at CERN – no signals from dark matter have yet been detected.

Finally, for a completely different approach to particle physics, the unique spirally patterns found in bubble chamber pictures can inspire a range of artistic ideas – from Christmas decorations made using the technique of paper quilling to fabric design. What other fun ideas can your more creative students come up with?

Reference

Woithe J (2016) *S'Cool LAB Cloud Chamber Do-it-yourself manual*. https://cern.ch/s-cool-lab/classroom-activities/cloud-chamber

Web references

w1 Find an accessible and authoritative account of the Standard Model of particle physics on the CERN website. See: https://home.cern/science/physics/standard-model

w2 CERN's worksheet is suitable for advanced high-school students, and it extends many of the ideas in this article. See: https://scool.web.cern.ch/classroom-activities/bubble-chamber

w3 Bubble chamber images for use in activities 1, 2 and 3 can be downloaded from the additional documents section of this article on the *Science in School* website. See: www.scienceinschool.org/2019/issue46/bubblechamber

w4 Find out about recent dark matter detection experiments using bubble chambers. See: www.picoexperiment.com and http://news.fnal.gov/2017/05/sleuths-use-bubbles-look-wimps/

Resources

Watch a demonstration of a superheated liquid produced by microwaving pure water, which is too dangerous for the classroom. See: www.youtube.com/watch?reload=9&v=LpDs7Xm1uLo

The King's Centre for Visualization in Science, Canada, has created applets that can help visualise concepts of modern physics. See: http://kcvs.ca/concrete/visualizations/modern-physics

Download a simulation of electrically charged particle in magnetic fields. See: www.kcvs.ca/site/projects/physics_files/particleMField/pInMagneticField.swf

Download a simulation of a cloud or bubble chamber. See: www.kcvs.ca/site/projects/physics_files/cloudChamber3/cloudchamber.swf

Resources about bubble chambers can be found on the CERN HST Bubble Chambers website, including an introduction to bubble chamber pictures, many images, and practical exercises developed together with teachers at CERN. See: http://hst-archive.web.cern.ch/archiv/HST2005/bubble_chambers/BCwebsite/index.htm

For more educational and accessible online bubble chamber exercises, visit Peter Watkins's website. See: http://epweb2.ph.bham.ac.uk/user/watkins/seeweb/BubbleChamber.htm

Find out how to build a classroom cloud chamber. See: 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

Julia Woithe is a high-school teacher of physics and mathematics. Since 2014, she has been responsible for S'Cool LAB, CERN's hands-on particle physics learning laboratory. She is interested in enquiry-based learning activities in particle physics, students' conceptions and 3D printing.

Rebecca Schmidt and Floria Naumann developed an extensive teaching unit about bubble chambers for their masters' theses at the University of Dresden, Germany. Today, they both work as physics teachers in Dresden.

'Finding Pneumo', a microbial painting of coral by microbiology technologist Linh Ngo

Painting in a petri dish

Create a living piece of 'agar art' to discover the invisible world of microbes living on our hands.

By Aida Duarte and Ana Margarida Madureira

On hearing the word 'bacteria', many pupils might squirm in their seats. But while bacteria are often perceived as bad, linked in our minds to infection or disease, the majority are in fact harmless to humans, and many are even beneficial. Along with other microorganisms (such as viruses and yeasts[w1]), bacteria are too small to see with the naked eye. They are, however, all around us. One way to reveal these hidden microorganisms is to grow them in an agar-filled petri dish (also known as an agar plate), which is a popular activity in schools.

Andrew Simor/Linh Ngo/American Society for Microbiology

- ✓ Microorganisms
- ✓ Bacteria
- ✓ Hygiene
- ✓ Art
- ✓ Ages 11 or under, 11–14

REVIEW

This article provides a great opportunity for interdisciplinary teaching by introducing a playful way of approaching both biology and art. The activity could be used by one teacher teaching both science and art, or through a collaboration between a science teacher and an art teacher.

It is ideal for discussing how bacteria occur and can be cultured, and how they are linked to everyday life. The article could also foster interesting discussions on how science and non-science subjects can work in tandem. I will definitely use it in my classroom.

Dr Christiana Nicolaou, science teacher, Archangelos Elementary School, Cyprus

In recent years, this simple idea has been transformed into an art form: across the world, people are now using bacteria to create beautiful works of 'agar art'[w2]. Using a wire inoculating loop, different species of microorganisms in various colours are carefully painted onto an agar plate. The plate is incubated to encourage the bacteria to grow, in the hope that it will develop into a microbial masterpiece.

Producing agar art at school (albeit using a simplified approach) is a playful way to introduce your pupils to the world of microorganisms. The hands-on activities outlined in this article are suitable for pupils aged 9–11 and are a valuable way to learn about bacteria.

We also provide a simple introductory activity to learn about hand hygiene. Although it is essential to highlight to your class that not all bacteria are harmful, you must also emphasise the importance of thorough hand-washing to control the spread of infectious diseases.

If you choose to carry out the following activities sequentially, keep in mind that you must allow at least two days between each activity for incubation time.

Safety note: For the following procedures, pupils are advised to wear lab coats. Pupils should not eat or drink in the classroom/laboratory or put their fingers or any other matter in their mouths. Once the agar plates have been incubated, pupils should not remove the lids of the plates.

To follow usual guidelines, all contaminated waste (e.g. disposable inoculating loops and agar plates) should be discarded in an appropriate container and collected by a laboratory waste disposal service. If this is not possible, contaminated equipment

A bacterial handprint on agar reveals the variety of microorganisms that are commonly found on our hands.

Tasha Sturm/Cabrillo Collage

could be treated with disinfectant (e.g. bleach) and disposed of in your regular waste.

Activity 1: Bacterial handprints

Washing our hands is the most important means of preventing the spread of infection. In this simple activity, pupils discover the importance of good hand hygiene by comparing two agar plates of their handprints – one before washing, and one after. The activity takes approximately 1 hour, and pupils should work individually.

Materials

Each pupil will need access to the following:

- Two premade agar plates[w3] (standard size of 100 mm in diameter)
- Permanent marker pen
- Hand soap (or antibacterial soap), water and paper towels

"Pupils discover the importance of good hand hygiene by comparing two agar plates of their handprints – one before washing, and one after."

Procedure

Instruct your pupils as follows, demonstrating the procedure if required:

1. Using a marker pen, label the two plates 'before' and 'after' on the underside of each plate, along with your name. When turning a plate upside down, keep the lid pressed down to avoid it falling off.
2. Place the agar plates on the table (the correct way up) and remove the lid of the plate marked 'before'.

Ana Margarida Madureira

Figure 1: Pupils press their fingers onto the agar plate to transfer bacteria to the agar.

3. Press your fingers firmly onto the agar (figure 1) and then remove them.
4. Replace the lid and clean your hands using soap and water. Dry them well using paper towels.
5. Repeat the process for the agar plate marked 'after', pressing your fingers firmly onto the agar.
6. Replace the lid and wash your hands after touching the agar.
7. Leave both plates in a safe area of the classroom to incubate at room temperature (e.g. 20ºC) for 48–72 hours, or until you can see some bacterial colonies.

Observation and discussion

When the agar plates are ready, ask your pupils to compare their 'before' and 'after' handprints (figures 2 and 3). The following questions and tasks can encourage them to analyse the results:

- What do you observe on your agar plates? What are the dots? Are there different types of dots (e.g. different colours and shapes)?
- Is there a difference in bacterial growth between the 'before' and 'after' handprints? What does this show?
- Count the dots on each plate to estimate the number of bacterial colonies. If there are too many dots to count, make an estimate for the whole agar plate based on one section. Record this in a joint classroom table (see table 1).
- Compare your agar plates to those of other pupils in your class. Why do some plates have more growth than others?
- What does this tell you about your hand hygiene, or the hygiene of your peers? What would you suggest to your peers based on these results?

From previous experience, pupils are often surprised by the number of colonies on the plates – and by the variety of colours and shapes of the different bacterial colonies. The activity can also act as a lesson for pupils with poor hand-washing techniques, who see no change (or even an increase in bacteria) between their 'before' and 'after' plates.

Ana Margarida Madureira

Figure 2: 'Before' (left) and 'after' (right) agar plates for pupil 10 (see table 1), showing a reduction in bacteria after handwashing

Ana Margarida Madureira

Figure 3: 'Before' (left) and 'after' (right) agar plates for pupil 8 (see table 1), showing a small increase in bacteria after handwashing – highlighting the importance of an effective hand-washing technique

Pupil	Before	After	Percentage change
1	144	140	–3%
2	424	208	–51%
3	36	18	–50%
4	110	60	–45%
5	138	118	–14%
6	86	98	+14%
7	55	27	–51%
8	449	490	+9%
9	148	96	–35%
10	600	85	–86%
11	125	69	–45%
12	600	289	–52%
13	68	41	–40%
14	600	245	–59%
15	309	261	–16%
16	67	18	–73%
17	132	108	–18%
18	107	120	+12%
19	82	32	–61%
20	348	234	–33%
21	54	6	–89%
22	92	46	–50%
23	125	127	+2%

Table 1: Number of colonies before and after handwashing for 23 pupils who carried out the activity in their classroom

Figure 4: Transferring S. epidermidis *from the agar plate to an inoculating loop*

Ana Margarida Madureira

Activity 2: Microbial 'paint'

Before creating agar art in the final activity, pupils need to grow their chosen bacteria to use as the 'paint' on their blank agar 'canvas'. Inoculating an agar plate to grow the bacteria takes approximately 15 minutes, after which the plate must be incubated.

Materials

Each pupil requires:

- One premade agar plate
- Disposable inoculating loop
- Agar plate labelled 'before', from activity 1 (or alternatively, a purchased culture of *Staphylococcus epidermidis*)

Procedure

Instruct your pupils as follows, demonstrating the procedure if required:

1. Locate the bacterium *S. epidermidis* on the agar plate labelled 'before'. *S. epidermidis* is part of the normal human skin flora and is typically white in colour, forming round colonies with a diameter of 1–2 mm. Alternatively, you can use a purchased culture instead.
2. Transfer *S. epidermidis* to the end of the inoculating loop (see figure 4).
3. Take a new agar plate and, using the loop, spread the bacteria in streaks across the surface of the agar (see figure 5 for the final streaking pattern). Start by drawing lines in the first quadrant of the agar, holding the loop as you would a pen. Do not dig into the agar – only touch the surface.
4. Turn the plate 90° and create streaks across the second quadrant.
5. Turn the plate 90° again and draw a zigzag in between the other streaked quadrants.
6. Place the lid onto the plate and incubate it at room temperature for 48–72 hours or until the plate is sufficiently covered by *S. epidermidis* colonies (figure 6).

Figure 5: Streaking pattern for inoculating the agar plate with S. epidermidis

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Figure 6: Isolated S. epidermidis *for use as the bacterial 'paint'*

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Figure 7: Pupils create microbial art using isolated S. epidermidis.

> **"Your pupils will be amazed to see their invisible drawings come to life."**

If desired, repeat the procedure above for any other bacteria (perhaps of different colours or colony formations) that are present on the 'before' plate, or using purchased cultures. Inoculate each bacteria on a new agar plate using a new loop.

Activity 3: A living masterpiece

Once the incubation period is over, your pupils are ready to start getting creative. We suggest allocating around 30 minutes for pupils to produce their microbial works of art.

Materials

Each pupil requires:

- One premade agar plate
- Disposable inoculating loop (one for each type of bacteria used)
- Agar plate with *S. epidermidis* (and/or other cultures)

Procedure

Instruct your pupils as follows, demonstrating the procedure if required:

1. Transfer *S. epidermidis* from the agar plate onto the end of the inoculating loop.
2. Using the loop as a pen, draw on the surface of the new agar plate (figure 7). You can draw various shapes, write your name, or even sketch a whole scene.
3. When required, collect more bacteria on the loop. This is usually every time you have finished drawing a line. If you are using more than one type of bacteria to create different colours or colony shapes in your drawing, use a new inoculating loop for each culture.
4. Once finished, place the lid onto the plate and incubate at room temperature for 48–72 hours to allow the artwork to develop.

Your pupils will be amazed to see their invisible drawings come to life. And in the process, we hope they discover a new appreciation for the bacterial diversity that surrounds us.

Examples of the pupils' artwork, as seen following incubation of the agar plates

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Web references

w1 Read more about the different types of microorganisms in a resource from The School Run. See: www.theschoolrun.com/homework-help/micro-organisms

w2 Visit the website for the American Society for Microbiology to see beautiful examples of agar art from their annual contests. See: https://www.asm.org/Events/2019-ASM-Agar-Art-Contest/Home

w3 For our experiments, we used petri dishes with a solid culture medium of Columbia ANC agar with 5% sheep blood. See: www.biomerieux-culturemedia.com/product/30-columbia-agar-+-5-percent-sheep-blood

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