



# Science in School

The European journal for science teachers



## Evolution in action

From genetic change  
to new species

**INSPIRE**

Run your coding  
experiment in space

**TEACH**

Look out!  
The physics of  
road safety





Spencer Phillips/EMBL-EBI

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ESA

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Hanna Photo/Shutterstock.com

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## EVOLUTION IN ACTION: FROM GENETIC CHANGE TO NEW SPECIES

How do new species – or completely new types of organism – emerge? Time and separation are the key factors.

08

## EDITORIAL



Hannah Voak  
Editor  
*Science in School*  
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The school year is gradually drawing to a close. Teachers across Europe may soon breathe a sigh of relief as they close their classroom doors for the summer holiday, hopefully leaving the stress of a challenging term behind them.

With demanding workloads throughout the year, it's important that teachers as well as students find time to take a well-earned break over the summer, so everyone can return to school refreshed. And this year, *Science in School* will be taking a holiday of sorts, too – we will step away from our desks to attend conferences and courses over the next few months, and to work on projects behind the scenes. As a result, the next issue of the journal will be published later than usual: you can expect the autumn/winter issue to arrive on your doorstep or in your inbox at the end of November.

But for now, sit back and enjoy what this issue has to offer: in the chemistry lab, we explore biochemistry using bananas (page 28) and have some fun with organic chemistry by extracting essential oils (page 40). For older students, we learn some valuable life lessons (and some physics) about driving and road safety (page 34). We also bring you the third article in the 'evolution in action' series, this time looking at the intriguing – and sometimes contentious – topic of how new species emerge (page 8).

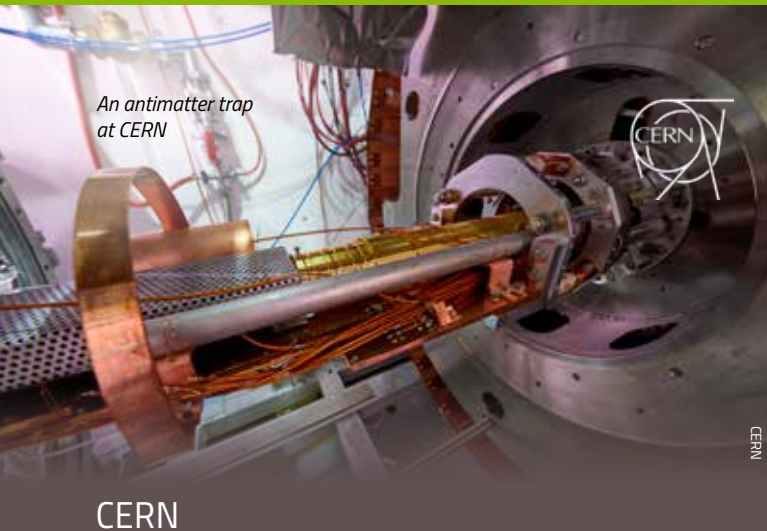
In this issue, three of the organisations comprising EIROforum – which funds *Science in School* – provide features of their own: building the world's largest telescopes (from ESO, page 15); the curation of 'big data' in molecular biology (from EMBL, page 20); and a computer coding challenge to run experiments in space (from ESA, page 25).

We hope you enjoy the summer break and look forward to seeing you in the next academic year.

*Hannah Voak*

Interested in submitting  
your own article? See:  
[www.scienceinschool.org/submit-article](http://www.scienceinschool.org/submit-article)

# Transporting antimatter, attosecond X-ray science and 3D insights into avian evolution



An antimatter trap at CERN

CERN

## CERN

### Antimatter takes a walk

Working with antimatter is no easy task: when it comes into contact with its matter counterpart, it vanishes instantly. Scientists at CERN successfully produce and store antimatter particles in a variety of experiments, but transporting antimatter from one facility to another has so far not been possible. In the next three years, however, transferring antimatter won't just be reserved for fictional Hollywood movies, as a project at CERN plans to make it a reality.

Scientists are designing a special antimatter trap that will be placed inside a 1 tonne superconducting solenoid magnet to enable antimatter to be transported without annihilating during the journey. First, antiprotons will be collected at the GBAR experiment at the ELENA facility at CERN where they are produced, before the whole antimatter trap will be loaded onto a van and transported a few hundred metres to CERN's radioactive ion beam facility, ISOLDE.

There, physicists will insert radioactive exotic nuclei into the trap to observe what happens when they annihilate with antimatter. The project, called PUMA (antiProton Unstable Matter Annihilation), aims to study exotic nuclear phenomena.

Read more about the PUMA project by visiting the CERN website.

See: <https://home.cern/cern-people/updates/2018/03/puma-project-antimatter-goes-nomad>

Based in Geneva, Switzerland, CERN is the world's largest particle physics laboratory. See: [www.cern.ch](http://www.cern.ch)

## EMBL

### Building fluorescence microscopes from scratch



Could you build a fluorescence microscope in under 90 minutes? In March this year, a group of school students aged 15–16 did just that: using research-grade lenses and objectives packaged into a portable kit, the students built fluorescence microscopes capable of imaging biological samples a fraction of a millimetre in size.

The series of hands-on sessions was organised by researchers at the European Molecular Biology Laboratory (EMBL) and the team at the European Learning Laboratory for the Life Sciences (ELLS) in Heidelberg, Germany. Using their microscopes, the students imaged zebrafish embryos and flower pollen, and showcased their work to EMBL researchers and the local press.

The portable kits, which are designed to be loaned to schools in the future, enthused the students about STEM subjects and gave them an insight into real-life laboratory research.

For more information on this outreach project, visit the EMBL news website. See: <https://news.embl.de/?p=12705>

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



Emma Steer/EMBL

Students build a fluorescence microscope as part of an outreach project run by EMBL researchers and the ELLS learning team.

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

ESA



## Atmosphere-propelled satellites for the future

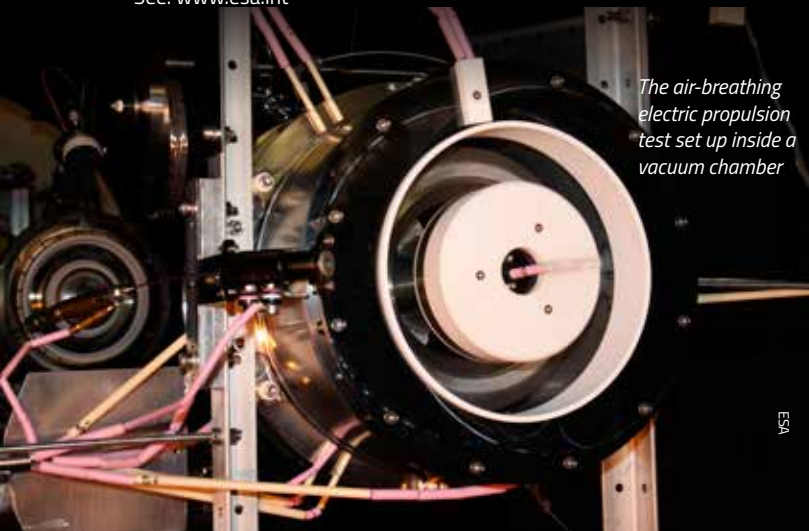
Satellites orbiting close to Earth are subject to a number of perturbing forces, a major one of which is drag. Spacecraft are designed to counteract this drag, but often their working lives are limited by the amount of propellant they can carry on board.

At the European Space Agency (ESA), for example, a novel satellite called GOCE (which provided data about Earth's gravity field) flew as low as 250 km above Earth for over four years thanks to an electric propulsion system – or thruster – that continuously compensated for air drag. But once the propellant was exhausted, the mission was over.

In early 2018, however, an ESA-led team found a way to overcome this challenge. In a world first, they built and tested an electric thruster that ingests scarce air molecules from the top of the atmosphere for propellant. The molecules are given electric charges so that they can be accelerated and ejected to provide thrust.

This technology could open the way for a new class of satellites that could operate in very low orbits for years on end. Air-breathing electric thrusters could also be used in the fringes of atmospheres of other planets, drawing on the carbon dioxide of Mars, for instance.

Learn more about ESA's innovative air-breathing electric thruster on the ESA website. See: [www.esa.int/Our\\_Activities/Space\\_Engineering\\_Technology/World-first\\_firing\\_of\\_air-breathing\\_electric\\_thruster](http://www.esa.int/Our_Activities/Space_Engineering_Technology/World-first_firing_of_air-breathing_electric_thruster)  
ESA is Europe's gateway to space, with its headquarters in Paris, France. See: [www.esa.int](http://www.esa.int)



*The air-breathing electric propulsion test set up inside a vacuum chamber*

ESA

ESO

## Behind the scenes at the European Southern Observatory



Behind the scenes at ESO: Showing you the road to the stars

ESO

*The ESOblog aims to share day-to-day stories of life at ESO with readers from all walks of life.*

The European Southern Observatory (ESO) currently operates an impressive fleet of telescopes, equipped with several dozen instruments. Together, these are pushing astronomy research towards ever more exciting discoveries – but there's more to ESO than the astronomy news announcements we already release.

Hidden behind the scenes are the people that make ESO work, who all have fascinating stories to tell about their day-to-day lives at the world's most productive ground-based observatory. That's why we started the ESOblog, so we can share these stories about our people, technology, and the science they enable. Other items you can expect to read about include quirky and interesting scientific results from our community, updates about famous faces that have recently visited the ESO sites, and features from ESO's public-facing communication department.

Find the blog on the ESO website. See: [www.eso.org/public/blog](http://www.eso.org/public/blog)

ESO is the foremost inter-governmental 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](http://www.eso.org)

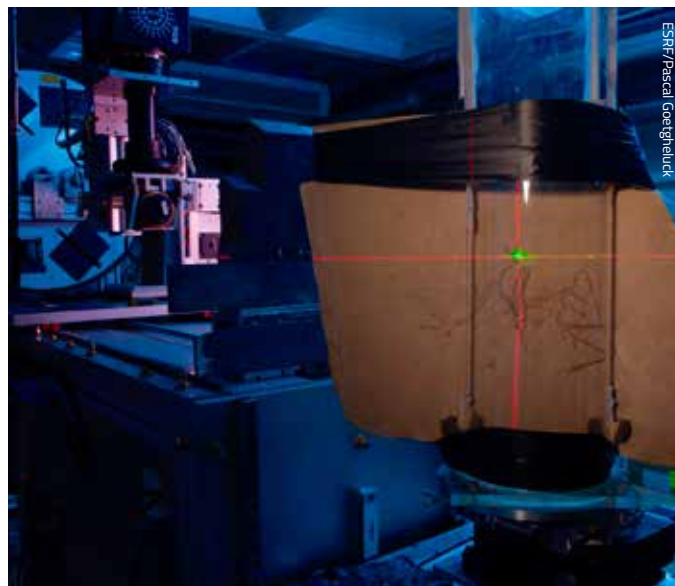
## ESRF New insights into the evolution of flight



It is common knowledge that modern-day birds evolved from extinct dinosaurs (see the article on page 8), but many questions about their early evolution and the development of avian flight remain unanswered. One particular question is whether *Archaeopteryx* (a bird-like dinosaur whose transitional fossils are key evidence in evolutionary debates) was capable of flying, and if so, how?

Archaeologists have so far discovered 12 *Archaeopteryx* fossils, which are preserved in limestone slabs that reveal only part of their morphology. Now, an international team, including scientists from the European Synchrotron Radiation Facility (ESRF), have used synchrotron microtomography to probe inside the fossils and create a 3D model of *Archaeopteryx*.

The scanning data unexpectedly revealed that the wing bones of *Archaeopteryx* share important adaptations with those of modern flying birds. Data analysis also showed that the bones of *Archaeopteryx* are more similar to those of birds (such as pheasants) that occasionally use active flight to cross barriers or dodge predators, rather than to forms that are optimised for endurance flight. It is now clear that *Archaeopteryx* represents part of the first wave of flight-capable dinosaur species, which eventually went extinct.



*A specimen of Archaeopteryx at ESRF's beamline ID19. The beam is centered on the skull using lasers.*

For more information on the study, read the original research paper:  
Voeten D et al. (2018) Wing bone geometry reveals active flight in *Archaeopteryx*. *Nature Communications* **9(923)**: 1–9. doi:10.1038/s41467-018-03296-8

Situated in Grenoble, France, ESRF operates the most powerful synchrotron radiation source in Europe. See: [www.esrf.eu](http://www.esrf.eu)

## EUROfusion A world record in plasma exposure

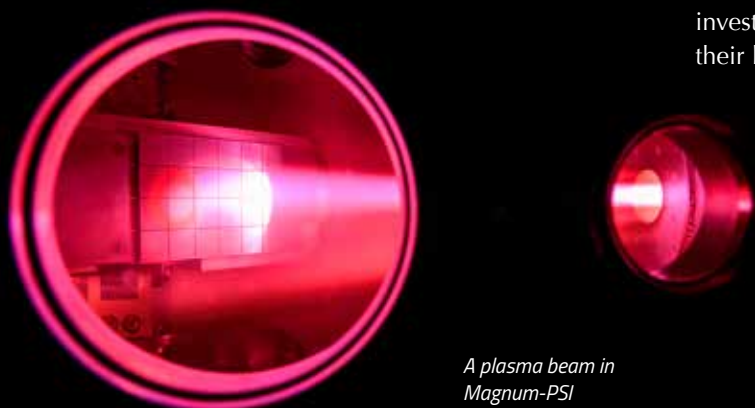


To replicate the process of fusion on Earth, gases are heated to extremely high temperatures inside fusion devices until they turn to plasma. The linear fusion device Magnum-PSI, which is operated by the EUROfusion consortium member, the Dutch Institute for Fundamental Energy Research (DIFFER), is routinely used to test whether materials scheduled for use in future fusion experiments can withstand these extreme temperatures.

In particular, such experiments give insights into the materials that can be used in ITER – the world's biggest fusion device currently under construction in Cadarache, France.

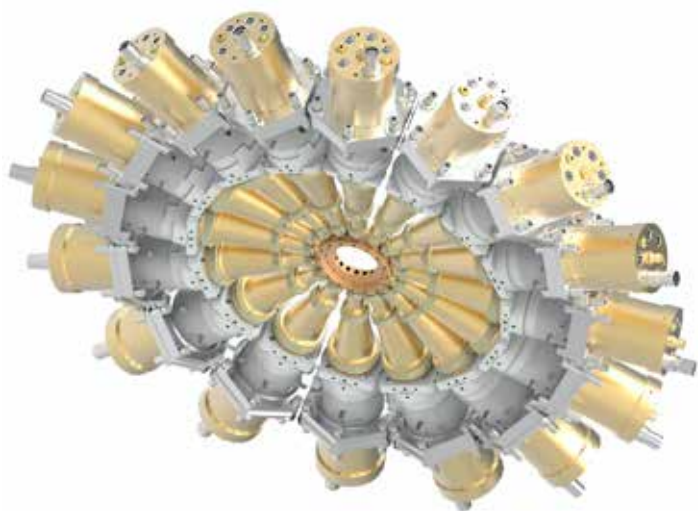
Recently, scientists set a new world record for the longest exposure of a material to the harsh plasma conditions, by exposing tungsten wall components to the equivalent of a full year of high-power fusion operations in the future ITER reactor. Researchers at the facility will now investigate how ITER's wall materials will change during their lifetime in the reactor.

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 the Ukraine. See: [www.euro-fusion.org](http://www.euro-fusion.org)



*A plasma beam in Magnum-PSI*

## European XFEL Entering the realm of attosecond X-ray science



Frank Scholz & Jens Buck/DESY

An illustration of the spectrometer that can reveal information such as the energy and intensity of X-ray pulses

The European X-ray Free-electron Laser (European XFEL) generates X-ray pulses lasting a few millionths of a billionth of a second, or a few femtoseconds ( $10^{-15}$  seconds). These ultrashort flashes help scientists to understand the individual stages of a chemical or biological reaction. But some natural processes are even faster: to observe these, we need even shorter X-ray flashes, at the attosecond timescale (1/1000 of a femtosecond, or  $10^{-18}$  seconds). The technology is almost ready to generate such fast X-ray pulses, but scientists must also be able to record the exact time and energy structure of each pulse to characterise their existence.

With this in mind, an international team of scientists developed a technique to do just that. Using the shortest X-ray pulses available at the Linac Coherent Light Source (LCLS) in the USA, they created a method involving circularly polarised light that acts as a 'clock' by which to sort the resulting experimental data.

Crucial to this method is a spectrometer developed at European XFEL's close partner, the Deutsches Elektronen-Synchrotron (DESY) and adapted by European XFEL for use on hard X-ray free-electron lasers such as European XFEL and LCLS. The spectrometer consists of a ring of individual spectrometers aligned on a plane perpendicular to the X-ray beam. These pick up individual electrons, giving scientists crucial information about features of the beam.

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

## ILL Search continues for fourth neutrino



Neutrinos are notoriously difficult to detect, as these elementary particles do not carry any electric charge and interact only rarely with matter. We know of three types (electron neutrinos, muon neutrinos and tau neutrinos), but are there more?

In 2011, researchers noticed that two unexplained experimental results could be reconciled if a fourth neutrino existed. This hypothetical particle is known as the 'sterile' neutrino, and several experiments have been designed to test its existence.

One such experiment is STEREO, a French-German experiment designed for precisely measuring the rates and energy profiles of the neutrinos generated by the Institut Laue Langevin (ILL) reactor. The experiment released its first results in March 2018, which exclude the presence of a hypothetical fourth neutrino in the region observed. A larger data sample is expected by the end of 2019.

Thanks to the highly enriched uranium fuel in the ILL core, STEREO will also provide a new benchmark for the neutrino spectrum produced by the fission of uranium-235, which is of utmost importance for many other reactor neutrino experiments.

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

*New results from the STEREO experiment are shedding light on a hypothetical fourth neutrino.*



*EIROforum combines the resources, facilities and expertise of its member organisations to support European science in reaching its full potential. See: [www.eiroforum.org](http://www.eiroforum.org)  
For a list of EIROforum-related articles in Science in School, see: [www.scienceinschool.org/eiroforum](http://www.scienceinschool.org/eiroforum)  
To browse the other EIRO news articles, see: [www.scienceinschool.org/eironews](http://www.scienceinschool.org/eironews)*



# Evolution in action: from genetic change to new species

How do new species – or completely new types of organism – emerge? Time and separation are the key factors.



*A complete fossil skeleton of an extinct species, the dinosaur Triceratops. Scientists use both fossil evidence and DNA to track the evolution of extinct species.*

Barks/Shutterstock.com

By Jarek Bryk

When most people think of evolution, they think of Charles Darwin's idea of natural selection, where one kind of organism evolves into a very different kind – such as fish into terrestrial animals, or early primates into humans – over long periods of time. For scientists, however, evolution means something more subtle: a change in the frequency of genetic variants (DNA sequences that vary between individuals) within a population. And – in another contrast with the popular idea of evolution – such changes are driven by many

factors, not just natural selection: mutations, migration and pure chance are all mechanisms of evolutionary change. One issue has become very contentious outside science: what are the processes of evolution that lead to the emergence of new species, and are they any different to those that happen within a species or a population? In this article, we take a look at these questions using insights from both genetics and the fossil record. Genetics alone cannot explain the evolution of now-extinct species, so scientists



rely on fossils to provide snapshots of past evolution. In addition, they can compare the DNA from the surviving cousins of extinct species.

### Why do new species emerge?

For new species to emerge, there seems to be at least one necessary condition: some degree of separation between populations (groups of individuals) of an existing species. This can be physical

**“One issue has become very contentious outside science: what are the processes of evolution that lead to the emergence of new species?”**

separation – a geographical barrier such as a mountain range, or isolation on an island – or it can be ecological, such as having different diets or mating preferences. Over time, the changes in DNA in different populations will eventually make it difficult or impossible for the separated populations



- ✓ Evolution
- ✓ Ages 16–19

The article is interesting and explains evolution in simple words, without difficult or confusing details. Every phenomenon or question mentioned includes clear examples, leaving the reader with the wish to read much more about this dynamic process of evolution. Through this article students can be encouraged to think about evolution as an important principle in the vast domain of biology, and to understand that evolution is achieved through specific mechanisms, acting over longer or shorter timescales, depending on the life cycle of different organisms.

Some comprehension questions that students could be asked include:

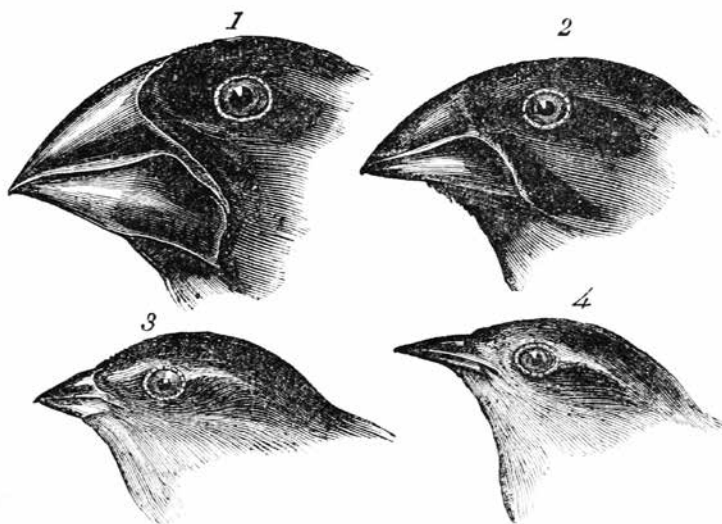
- How do new species arise?
- How is dinosaur evolution connected to the evolution of birds?
- Is evolution in time a slow phenomenon?
- What is a hybrid zone?
- Is evolution connected to diet?
- What does environmental adaptation mean?

REVIEW

Alina Giantsiou-Kyriakou, biology teacher, Lyvadia High School, Cyprus

to interbreed: they will become different species. Instances of this phenomenon are abundant. When groups of fruit flies are housed in different enclosures in a laboratory, for example, flies from different groups eventually stop being able to interbreed or produce offspring

with each other. The ultimate Darwinian example of speciation (one species splitting into several) is the finches of the Galapagos Islands, described by Darwin in *The Voyage of the Beagle*. In that case, separation by both diet and island location led to different species emerging, with a variety of beak shapes reflecting adaptations to their individual diets. We now know that this anatomical variety is mirrored at the genetic level by changes in the genes responsible for beak shape. But what types of genetic changes ultimately lead to a species split, as for Darwin’s finches? Current research in the field is shedding light on this question, allowing scientists to follow the genetic changes happening along the way.



Original drawings of four species of finches found in the Galapagos Islands, discovered by Charles Darwin. The beak shapes evolved to suit the different food supplies on the various islands.

John Gauld/Wikimedia Commons

### The hybrid zone

During the last ice age, many animal populations in Europe became geographically separated when they took refuge in different warmer regions (such as modern-day Spain and the Balkan peninsula). When ice-age



Eri/Shutterstock.com

The carrion crow, *Corvus corone corone*



Stefan Berndtsson/Flickr

The hooded crow, *Corvus corone cornix*

glaciers melted around 10 000 years ago, populations of species that had been separated for a long time came into contact again, as they were able to move out of their refuges and repopulate the continent. But spending many thousands of years apart meant that the different populations acquired some genetic variants peculiar to each, which made it harder for the populations to interbreed when they came back together.

For example, when European crow (*Corvus corone*) populations became separated during the ice age, two visibly different types evolved: the all-black carrion crow (*Corvus corone corone*) in the west, and the black-grey hooded crow (*Corvus corone cornix*) in the east. Today, in the 'hybrid zone' – a narrow strip of land stretching from

Scandinavia to Italy, where crows of both types occur – the two species can interbreed and produce offspring, although with lower success than within their own populations. By analysing the genomes of crows in the hybrid zone, and comparing them to the genomes of crows deep within their own regions, scientists have been able to identify DNA sequences that do not travel across the hybrid zone easily. These fragments of a genome that are specific to one population (here, either hooded or carrion crows), and are very rarely found in the other population, are the key to the emergence of new species. In this case, genes responsible for the differences in plumage are least likely to cross the hybrid zone. This strongly suggests that carrion crows prefer to mate only with other crows that look

like carrion crows and not like hooded crows, and vice versa. If this process continues, the two groups are likely to become completely separate species eventually.

The molecular and demographic processes taking place in crows (or in Darwin's finches), which scientists have been observing and studying for decades, highlight the universal nature of evolutionary processes. Fundamentally, these processes are no different from those occurring in microorganisms – such as when the Ebola virus evolved into a more infectious strain (see Bryk, 2017). The main factor that separates these examples is time: the degree of genetic change that took place in Ebola over a couple of years took thousands of years in birds, reflecting their much longer generation time. In each case, however, when the organism adapts to new environments or random genetic changes occur, the result is that different populations become more and more distinct. In the case of crows or finches, this ultimately leads to complete reproductive isolation – and thus to a new species.

## From dinosaurs to birds – and back

But what about the emergence of seemingly completely new types of organism – such as the evolution of whales from their terrestrial ancestors, or of birds from their dinosaur ancestors? How can we track and understand such major changes in life on Earth, changes that are much greater than the emergence of individual species?

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**“We now know that dinosaurs had feathers a long time before there were any birds able to fly, suggesting that the initial use of feathers was not in flight.”**

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*Illustration showing the feathered but flightless dinosaur Aurornis, which lived around 160 million years ago. Discovered in 2013 in China, Aurornis is considered the oldest known example of a bird-like dinosaur.*

The main challenge in tracking such evolution is that it takes place over an extremely long timescale, so most ancestor organisms are extinct. However, fossils last for hundreds of millions of years and provide detailed information on anatomical changes over these huge swaths of time. In recent

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**“The complete bird body plan emerged gradually over 100 million years of evolution.”**

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decades, thousands of well-preserved fossil specimens have been discovered in northeastern China and have illuminated in great detail the evolution of birds from dinosaurs. For example, we now know that dinosaurs had

feathers a long time before there were any birds able to fly, suggesting that the initial use of feathers was not for flight. Insulation, camouflage and display are all possible alternative advantages that feathers bestowed on these early feathered reptiles (Foth et al., 2014; Zhou, 2014).

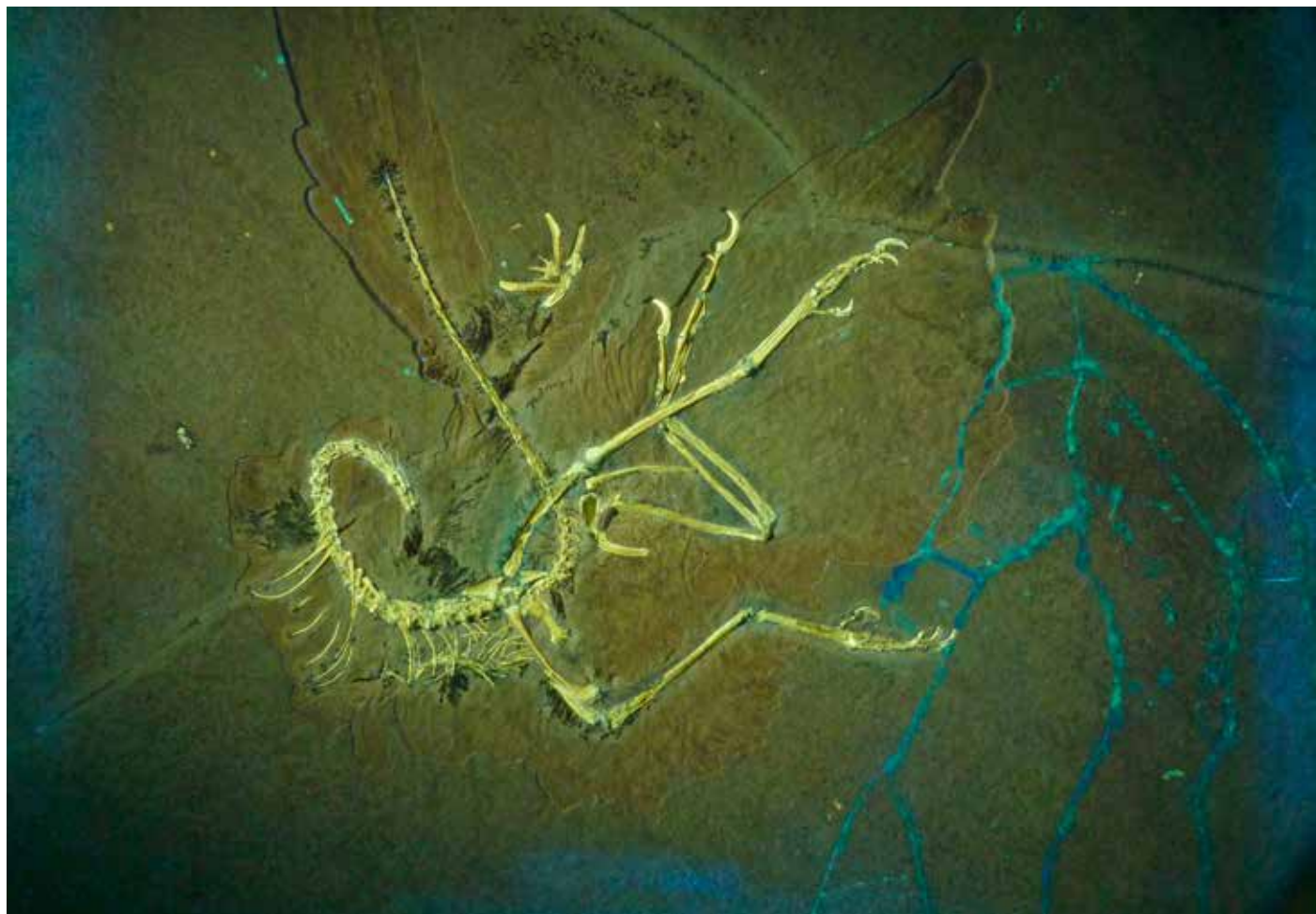
Similarly, flying birds did not emerge suddenly and fully formed. Tracking the different aspects of anatomy needed for wing-powered flight – small size, wings, feathers, fused tail, wishbone and many others – has shown that the complete bird body plan emerged gradually over 100 million years. Once this body plan was complete, birds underwent a massive and rapid divergence into a huge variety of different forms, resulting in the almost 10 000 species we know today (Brusatte, 2015).

The evolution of birds from dinosaurs, then, was a continuous process, without

sudden changes. It has been said that if a time-travelling palaeontologist could sit back and watch the evolution of birds over 100 million years, she would not notice any special moment or event when she could definitely say where the dinosaurs stopped and the birds began. Thanks in large part to the fossil discoveries in China, the previous two decades have seen a shift in our understanding of the evolution of birds, such that birds are now firmly placed within the dinosaurs, making a chicken a distant cousin of a *Tyrannosaurus rex*. Not only that, but *T. rex* is now seen as more closely related to chickens than to many dinosaur species – for example, *Triceratops*.

### Just evolution

Such evolutionary changes above the species level are sometimes called ‘macroevolution’, in contrast to the



Well-preserved Archaeopteryx fossil, showing the impressions of feathers on its tail, wings and legs

Helmut Tischlinger



Ronnie Robertson/Flickr (CC BY-SA 2.0)



Shahin Olakara/Flickr



Barry Badoock/Flickr



Ed Dunens/Flickr

Modern bird species, showing some of their amazing variety. Top left: Atlantic puffin (*Fratercula arctica*); top right: kingfisher (*Alcedo atthis*); bottom left: white stork (*Ciconia ciconia*); bottom right: Alpine chough (*Pyrrhocorax graculus*)

genetic changes that we can observe within a species (sometimes called ‘microevolution’). Unfortunately, this dichotomy suggests that there are two different types of evolution, or that evolution is driven by different mechanisms on the ‘micro’ and ‘macro’ levels. This distinction is often exploited by those who do not accept evolution, and who claim that only ‘microevolution’ ever occurs. But the

dichotomy is false, because there are no mechanisms other than those that change the proportion of genetic variants in a population. There is just evolution, driven by mutation, migration, selection and chance.

#### Author dedication

This is the last in a series of three articles that I would like to dedicate to

Dr Dean Madden (1960–2017), who, in late 2016, prompted me to write about evolution for *Science in School*. Dean was a friend, mentor, colleague, teacher, designer, typographer, beekeeper, cider maker, chilli grower, skinhead reggae lover, grammar policeman, Apple user, Whovian, all-around brilliant mad scientist and partner in mischief. Goodbye, and thanks for all the fish.



Artist's illustration of the feathered dinosaur *Microraptor*, munching a cycad fruit. The legs as well as the wings have long feathers.

Editor's note: Dr Dean Madden was an enthusiastic supporter of *Science in School* from its conception, and a member of the editorial board from 2005 until his death in 2017.

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- Download the *Nature* article free of charge on the *Science in School* website.
- See: [www.scienceinschool.org/2018/issue44/evolution3](http://www.scienceinschool.org/2018/issue44/evolution3), or subscribe to *Nature* today: [www.nature.com/subscribe](http://www.nature.com/subscribe)
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## Resources

- Find out seven important things about evolution from paleoanthropologist/geneticist John Hawks. See: <http://johnhawks.net/explainer/evolution/seven-things-about-evolution-2014.html>
- Read a modern classic book on evolution and speciation. See: Coyne JA (2010) *Why Evolution is True*. Oxford, UK: Oxford University Press. ISBN: 0199230854
- Find out more about the emergence of species from Jerry Coyne's blog. See: <https://whyevolutionistrue.wordpress.com/2011/01/03/more-on-species-part-1/>
- Read an article about new research on *Archaeopteryx* on the website of the European Synchrotron Radiation Facility. See: [www.esrf.eu/home/news/general/content-news/general/the-early-bird-got-to-fly-archaeopteryx-was-an-active-flyer.html](http://www.esrf.eu/home/news/general/content-news/general/the-early-bird-got-to-fly-archaeopteryx-was-an-active-flyer.html) or use the direct link: <https://tinyurl.com/ydckqrr6>

Dr Jarek Bryk is a lecturer in molecular biology at the University of Huddersfield in the north of England, UK. He teaches genomics and evolution and studies how allele frequencies change in wild populations of wood mice and weasels. Find him online at <http://bryklab.net> or on Twitter at @jarekbryk.



# Reflecting the Universe: building the world's largest telescopes

For hundreds of years, telescopes have helped astronomers unravel the mysteries of the Universe. But what's involved in making – and maintaining – the complex instruments of today?

By Nicole Shearer and Tania Johnston

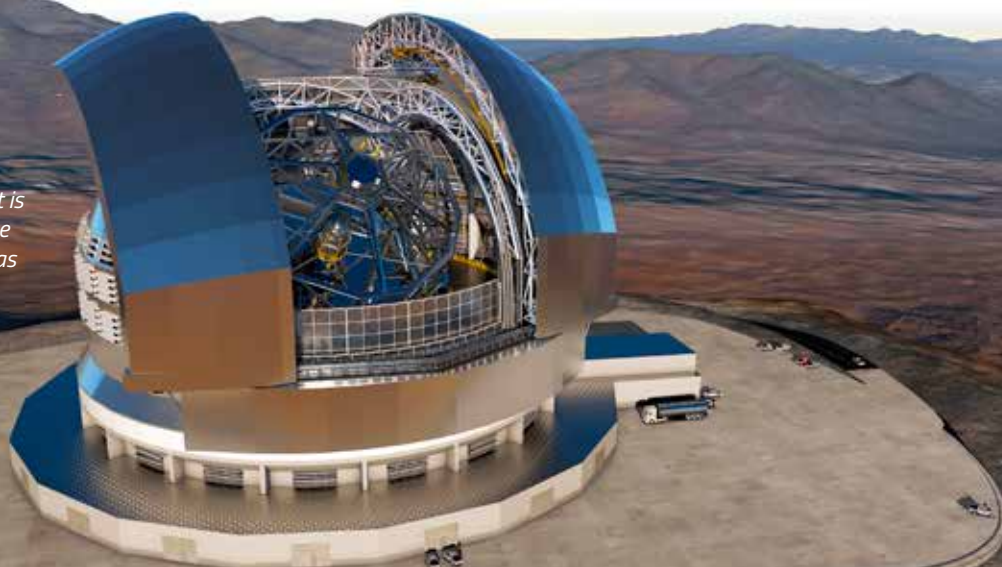
In 1608, a German-Dutch spectacle maker named Hans Lippershey filed a patent for a small device that used lenses to focus light and produce a magnified view of distant objects: it was the earliest known design for a telescope. Shortly after this invention, Galileo famously built one of his own, and was the first to use a telescope for astronomical observations. Four hundred years later, telescopes are still vital for astronomy, but they have evolved from small, hand-held instruments to gigantic, computer-controlled devices. Today, most of the world's largest optical and infrared telescopes – many of which are built and operated by the European Southern Observatory<sup>w1</sup> (ESO) – use mirrors rather than lenses to gather and focus light. The larger the mirror, the more light can be collected, allowing astronomers to see

fainter celestial objects – which are often further away – in greater detail. Although large mirrors are easier to produce than large lenses, producing modern astronomical telescopes is still a real challenge.

## From Newton to today

The first successful reflecting telescope (one that uses mirrors rather than lenses to focus light) was built by Sir Isaac Newton in 1668. The basic Newtonian design uses a concave primary mirror (the first mirror that starlight hits on entering the telescope) and a flat secondary mirror, which is positioned above the primary mirror and angled diagonally to reflect and direct the light to an eyepiece. The same principle is used today in many amateur and professional telescopes.

*Artist's rendering of the Extremely Large Telescope (ELT). Once it is completed in 2024, the dome will be as large as a football stadium.*





- ✓ Waves and optics
- ✓ Space science
- ✓ Ages 11–16

Reflection is a central concept of waves and optics topics in school science curricula. Teachers can draw on this article, which gives up-to-date information about mirrors in large modern telescopes, to bring such topics to life for students. Moreover, it can help to make students aware of the applications of science and the challenges that modern technology can overcome.

Comprehension questions could include:

- Who made the first astronomical observations using a telescope?
- Who built and used the first reflecting telescope?
- Why is glass used to make mirrors found in large astronomical telescopes?
- How it is possible to build telescopes with mirrors greater than 8 m in diameter?

Stuart Farmer, physics teacher, Robert Gordon's College, Scotland, UK

In modern telescopes, mirrors allow the light to be directed to different cameras or detectors in place of the eyepiece, and they also enable telescope designs to be more compact.

Newton's first reflector telescope used a primary mirror measuring 3.3 cm in diameter. Now, the biggest single reflecting telescope mirrors in the world are approximately 8 m in diameter. ESO's Very Large Telescope (VLT) in Chile, South America, for example, consists of four telescopes each with a primary mirror diameter of 8.2 m.

### Making the mirrors

The material of choice for most professional telescope mirrors is glass (such as borosilicate glass, used for 'Pyrex' cookware) or a special

glass-ceramic composite material. Such materials can be ground and polished to exactly the right shape to produce a good image. They also don't change shape or size in response to temperature fluctuations. This is especially important because many telescopes are located high up on mountains or in the desert, where temperatures vary significantly between day and night.

To focus as much of the faint starlight as possible, the surface of primary mirrors must be highly reflective. The reflectivity is created using an extremely thin coating of a light-reflecting material, the identity of which depends on the operating wavelength of the telescope. For example, silver or aluminium is often used on optical and near-infrared telescope mirrors.



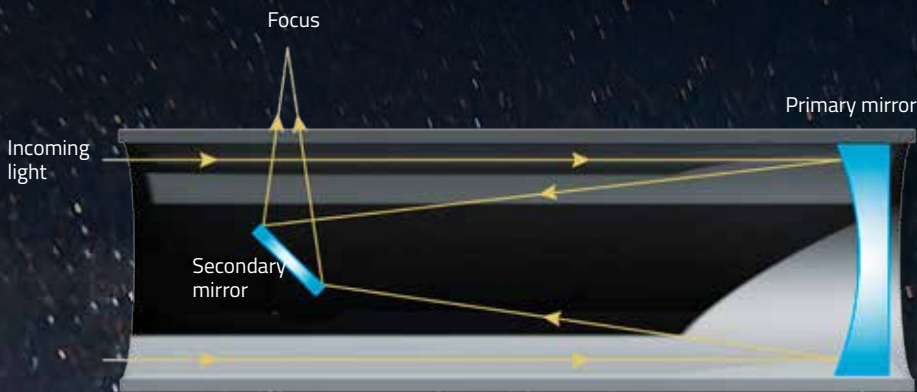
## Bigger and better

The size of telescope mirrors has increased considerably in the past 50 years, but astronomers always want to go bigger. There is still a limit, however: a mirror much larger than 8 m would be incredibly difficult to grind and polish. So, one solution is to build segmented mirrors instead. These consist of individual, often hexagonal, sections that together make up one huge light-collecting area.

**“The size of telescope mirrors has increased considerably in the past 50 years, but astronomers always want to go bigger.”**

Currently, the world’s largest segmented mirror – the Great Canary Telescope, in the Canary Islands, Spain – measures 10.4 m across and comprises 36 segments. But in 2024, it will be superseded by the Extremely Large Telescope (ELT), which is under construction in the Atacama Desert in Chile. The primary mirror, measuring 39 m in diameter, will be made up of 798 segments, each with an area of around 1.4 m<sup>2</sup>. This huge telescope, which will be operated by ESO, will observe the Universe at optical and near-infrared wavelengths.

Further telescopes that are also underway, such as the Thirty Meter Telescope in Hawaii, have adopted a similar approach, using a large number of small segments. Others, such as the Giant Magellan Telescope in Chile, will comprise fewer – but larger – segments.



*Light path of a Newtonian (reflecting) telescope, which uses mirrors to bend and focus light*

*The VLT at the Paranal observing site in the Atacama Desert of Chile*

## A smooth surface

To produce sharp images and accurate measurements, the surface of the mirrors must be perfectly smooth. For the ELT, each individual segment will be polished to an accuracy of within

15 nanometres. This means that if one segment were the size of Europe, any remaining bumps on the surface would be the size of a ladybird.

As mirrors (single or segmented) get bigger, they start to sag under their

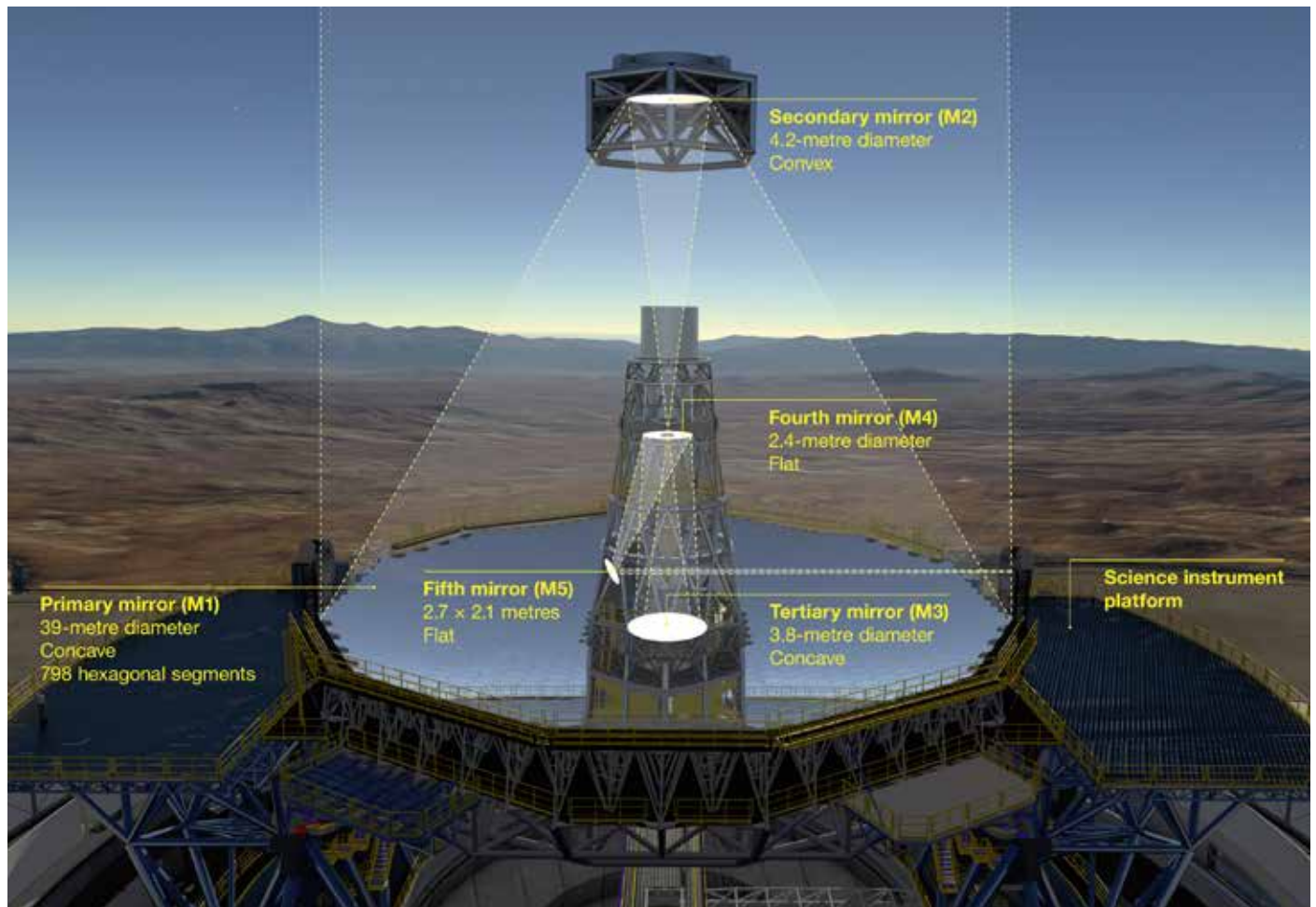
own weight due to the effects of gravity, thereby reducing their evenness.

To compensate, the VLT relies on a technique called active optics, which uses 150 actuators to adjust the mirror, making corrections roughly every 30 seconds. For the ELT, it's not just that the individual segments need to be extremely smooth: the segments must also be perfectly aligned with their neighbours to achieve the same effect as a single mirror. The ELT will have a total of 4524 sensors on the edges of the mirror segments; these will constantly report on their positions, allowing each segment to be precisely adjusted using 2394 actuators. This active optics system will make the overall surface of the primary mirror smooth to the accuracy of within about 50 nanometres – a thousandth of the thickness of a human hair.



ESO

A scale mock-up of the ELT primary mirror, using cardboard versions of the mirror segments



ESO

The ELT will consist of five mirrors, with the largest measuring 39 m in diameter.



Testing of the sensors and actuators underneath two segments of the giant primary mirrors of the ELT

**“The segments must also be perfectly aligned with their neighbours to achieve the same effect as a single mirror.”**

### Maintaining reflectivity

To ensure that the surface of the mirrors remains as reflective as possible, they must be protected from dust in high winds. When dust accumulates on the mirrors, it may reduce the reflectivity by only a few per cent, but every photon is valuable for producing high-quality images. Dust also scatters light and reduces the contrast in the images. During the day, the mirrors are kept covered, and at night the telescope is tilted before the dome is opened, so that anything on the roof (such as dust or bird poo) doesn't land on the surface of the mirrors.

Over time, the reflective coatings deteriorate, so the mirrors need to be

recoated on a regular basis. The primary mirrors of the VLT, for example, must be transported down from the observing platform to the base camp roughly every 18 months to be recoated. It is particularly challenging to deal with the most expensive and delicate part of the telescope, so the mirror is transported at a speed of just 5 km/h. The whole process (from removal to replacement) takes around one week.

For the ELT primary mirror, each of the 798 segments will also need recoating every 18 months. The most efficient way to do this will be to remove, recoat and replace two or three segments every single day. The telescope can still operate efficiently with a couple of segments missing, allowing for maximum operation time. By contrast, when any of the VLT mirrors are being recoated, that telescope is out of service.

### Exploring the Universe

Designing, building and operating such large-scale telescopes is no easy task. But the exciting prospects – discovering Earth-like planets, measuring the properties of the first stars and galaxies,

and probing the nature of dark matter and energy – are worth the hard work. In the coming decades, the world's most advanced telescopes have the potential to revolutionise our understanding of the Universe, much as Galileo's telescope did 400 years ago.

### Web reference

w1 ESO is the foremost inter-governmental 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](http://www.eso.org)

### Resources

Learn more about the VLT and ELT on the ESO website. See: [www.eso.org/public/teles-instr/paranal-observatory/vlt/](http://www.eso.org/public/teles-instr/paranal-observatory/vlt/) and [www.eso.org/public/teles-instr/elt/](http://www.eso.org/public/teles-instr/elt/)

For an infographic comparing the size of the ELT main mirror with that of other major ground-based telescopes, visit the ESO website. See: [www.eso.org/public/images/eso1617z/](http://www.eso.org/public/images/eso1617z/)

Find out more about the mirror production for the ELT by visiting the SCHOTT website. See: [http://microsites.schott.com/us-schott\\_and\\_e-elt/english/](http://microsites.schott.com/us-schott_and_e-elt/english/)

Learn what it's like to work at the VLT in the Atacama Desert in Chile. See:

Pierce D (2006) Running one of the world's largest telescopes. *Science in School* 1: 56–60. [www.scienceinschool.org/2006/issue1/telescope](http://www.scienceinschool.org/2006/issue1/telescope)

More information on the primary mirror of the ELT is available in ESO's quarterly journal, *The Messenger*. See: [www.eso.org/sci/publications/messenger/archive/no.171-mar18/messenger-no171-20-23.pdf](http://www.eso.org/sci/publications/messenger/archive/no.171-mar18/messenger-no171-20-23.pdf) or use the direct link <https://tinyurl.com/yb3gqgah>

Nicole Shearer is a science communicator with a master's degree in physics and a bachelor's degree in physics and astrophysics from Durham University, UK. At the time of writing, Nicole was undertaking a six-month science communication internship with ESO.

Tania Johnston has worked for over ten years in the field of astronomy communication, with a strong focus on providing support for teachers in using astronomy as a context for teaching science. Tania works for ESO as the ESO Supernova Coordinator.





# Bioinformatics: the new 'cabinet of curiosities'

The curation of 'big data' in molecular biology is changing the way scientists work.

By Oana Stroe

In the 16th century, a cabinet of curiosities (or *Wunderkammer*) was a popular way to show off a private collection of extraordinary objects. Animal specimens, skeletons, minerals, unusual handmade objects and intriguing antiquities from the New World could all be revealed with a flourish, arousing in visitors a keen sense of curiosity in that new age of wonder.

Over time, cabinets of curiosities made way for more modern museums. Like the cabinets, museums catered for two profoundly human tendencies: curiosity, and the desire to collect and preserve knowledge.

Today, these same tendencies, coupled with new technology and a tsunami of genetic data, are driving a major change in the life sciences: the democratisation of access. As well as cataloguing the visible world of biological species,



- ✓ Genetics
- ✓ Biodiversity
- ✓ Ages 16–19

REVIEW

This article illustrates an idea that is fundamental for many disciplines, from natural science to economics: the huge amount of data and knowledge we now possess needs to be professionally organised so that it can be accessed by researchers all around the world.

In biology teaching, the article could be used to introduce the role of big data and bioinformatics in molecular biology, and to highlight how new computing technologies can help scientists to compare and visualise DNA and protein sequences. This could encourage students to explore for themselves the multiple possibilities that communication technologies are opening up in science.

The article could also be used to encourage awareness of the amazing biodiversity that has not yet been discovered in the oceans and other unexplored natural habitats.

Jesús López Alonso, biology teacher, IES La Gándara High School, Spain



*The private collection of the Victorian naturalist Lionel Walter Rothschild, which is now a national museum in Tring, UK.*

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The European Bioinformatics Institute (EMBL-EBI) near Cambridge, UK



Data storage at EMBL-EBI: the data centre houses vast amounts of digital data, using hundreds of servers.

scientists can now sequence DNA from millions of species and enter the information into databases, along with other molecular biology data. The result is a new kind of menagerie: a constantly growing catalogue of biological information that can help scientists everywhere make sense of the living world. But all this data needs curating, and the discipline of bioinformatics – which combines biology with computer science – has been developed to deal with this.

## Opening up the cabinet

Research laboratories around the world produce a huge amount of data, which is then stored in specialised databases – such as those of the European Bioinformatics Institute (EMBL-EBI), located near Cambridge, UK<sup>w1</sup>. A key responsibility for EMBL-EBI is ensuring that the data it holds is publicly accessible, so the ‘collections’ are kept open to researchers everywhere.

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**“Like the cabinets, museums catered for two profoundly human tendencies: curiosity, and the desire to collect and preserve knowledge.”**

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“It’s only in the past few years that this kind of openness has become workable, due to improved communication channels, but now it is expected by users”, says Andy Yates, a team leader at EMBL-EBI. “Data accessibility is crucial for anybody doing science. With a traditional cabinet of curiosities, the collector was the ultimate authority. We’re making the contents – and ourselves – open to reanalysis and

review. It’s a necessary move if we want our resources to be truly useful”, he says.

## Organising the data

Traditional cabinets of curiosities organised items by type. The modern database organises biological data resources in a similar way – into categories. In the database, information and categories are interlinked, so the database is like a ‘smart’ or multidimensional cabinet of curiosities. Indexing is as central to public data resources today as it was to earlier collections, to make data sets easy to find among the petabytes of data. Without indexing, there is no way of knowing what is in a database or how it got there. And descriptions of data sets – called metadata – are needed too: “Without metadata, exploring a database is like wandering through the basement of the Louvre blindfolded, hoping you’ll find the Mona Lisa”, says Yates.

To make these hard-earned data sets reusable by other scientists, data curators carefully check data submissions to ensure they meet the necessary requirements. These requirements are set out in widely accepted guidelines known by their abbreviation, FAIR: findable, accessible, interoperable and re-usable. Research data sets must also be put into context and linked to the scientific publication that describes them.

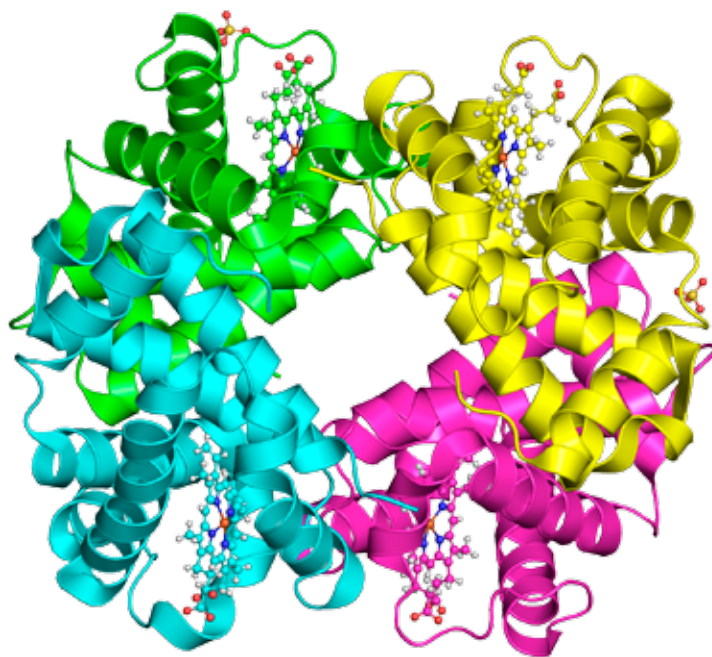
## Visualising the data

Along with organisation, ways to visualise the data are also important: being able to ‘see’ connections within the data inspires people to keep exploring. “The first obvious difference between a cabinet of curiosities and a database is the content”, explains Jee-Hyub Kim, a former data miner at EMBL-EBI. “On the one hand, a collection of physical objects makes you feel something straight away. Just imagine what it must have felt like for someone who may have never even seen the ocean, to see and touch a starfish or coral. It’s difficult to create this sort of rapport with something as intangible as data. That’s why you need a good interface and visualisation tools – to allow the user to explore and interact with a data set or a digital object.”

One example of a data visualisation tool is the Protein Data Bank in Europe (PDBe)<sup>w2</sup>, a resource for collecting, organising and disseminating data on macromolecular structures, such as proteins. Apart from being a central repository for scientists studying proteins, PDBe allows users to see and interact with digital, three-dimensional models of proteins. These visualisations can be accessed from any internet-connected device throughout the world, including phones and tablets.

## New methods, new insights

So how is the availability of so much data changing the way we do science? According to Chuck Cook, scientific services manager at EMBL-EBI, scientists are going to become more



PDBe

*The Protein Data Bank in Europe (PDBe) stores thousands of digital 3D models of proteins, including this image of the human haemoglobin molecule, showing the four subunits.*



Juan Sarasua/Flickr

*The research schooner Tara, which collected biological samples from the world’s oceans over more than a decade*



Specimen of the plankton *Histioneis elongata* collected by the Tara team in the South Pacific Ocean

entomology/flickr

dependent on big data – and those who don't use big data will be left behind professionally. "As we become more specialised, running isolated experiments is becoming more difficult. To delve deeper into research, we will need to collaborate with people from lots of different backgrounds."

"Biologists have to turn into programmers, to a certain extent", agrees Yates. "That's how the scientific questions are changing. The researcher will come up with a hypothesis and then prove or disprove it through data mining of large data resources. That requires some degree of programmatic knowledge."

As scientists begin to analyse these data sets on a massive scale, they are

revealing profound new insights. For example, the data from the Tara Oceans expeditions, in which a research ship has sailed more than 300 000 km worldwide since 2004, has led to the discovery of over 40 million new genes and is helping scientists to understand the invisible ecosystems that support the global food chain.

Scientists on the voyage systematically collected samples of plankton from all the world's oceans, then shipped them back to land for DNA sequencing and analysis. "Sequencing the samples from Tara lets us see some of the diversity of life in the oceans", says Rob Finn, a team leader in EMBL-EBI's metagenomics resource. "The first set of 40 million genes identified in Tara Oceans samples are mainly prokaryotes – bacterial species we haven't seen before. But in the second wave of data, we have identified over 117 million eukaryote genes so far, and there is still a long way to go", he says.

### The nitty-gritty details

In light of this ever-growing influx of data, what are the big challenges facing biology in the coming years? "Before open data, a scientist worked on one protein, gene or experimental system, possibly for their entire career", says senior scientist Janet Thornton, Director Emeritus of EMBL-EBI. "Seeing the bigger picture was practically impossible. Today, we can make genome-wide and species-wide observations", she says. But Thornton thinks that this shift also poses the biggest challenge: truly important discoveries in biology still lie within the nitty-gritty details.

"We will still need to look closely at these details to understand many fundamental questions, such as why do organisms age?", she says. "Initiatives like the Human Cell Atlas<sup>w3</sup> are very good examples of all the missing details we still need to understand before we begin to explain how things work. The next step will be to translate this knowledge into everyday areas, such as medicine, agriculture and biodiversity."

Much like the collectors who set up the first cabinets of curiosities, scientists are

still meticulously cataloguing everything they learn about the form and function of life, and linking it all up to help them make further discoveries.

### Acknowledgement

This article is based on one originally published in *EMBL etc.*, reproduced with kind permission.

### Web references

- w1 EMBL-EBI is the home of big data in biology. The institute hosts and shares data from life science experiments performed all over the world, and its scientists carry out basic research in computational biology. EMBL-EBI is one of the six sites of the European Molecular Biology Laboratory and is based just outside Cambridge, UK. See: [www.ebi.ac.uk](http://www.ebi.ac.uk)
- w2 PDBe is a database for three-dimensional structural data relating to large biological molecules, such as proteins and nucleic acids. The models are made freely available for scientists and students around the world. See: [www.ebi.ac.uk/pdbe/](http://www.ebi.ac.uk/pdbe/)
- w3 The Human Cell Atlas aims to map every single cell in the human body using single-cell sequencing technologies. This collaboration across the international scientific community brings together biologists, clinicians, geneticists, software engineers and others. See: [www.humancellatlas.org](http://www.humancellatlas.org)

### Resources

To read a *Science in School* article on the Tara expeditions, see:

Peyrot R (2015) Tara: an ocean odyssey. *Science in School* **33**: 6-11. [www.scienceinschool.org/content/tara-ocean-odyssey](http://www.scienceinschool.org/content/tara-ocean-odyssey)

Find out more about the Tara expeditions and ecological research on their website. See: <https://oceans.taraexpeditions.org/en/m/about-tara/>

Oana Stroe is a communications officer at the European Bioinformatics Institute (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.







ESA astronaut Paolo Nespoli in the Columbus module with Astro Pi Ed

# Run your coding experiment in space

The European Space Agency's Astro Pi Challenge gives students the chance to conduct their own science investigation on the International Space Station.

By Fatima Pinto, Elsa Sanchez and David Honess

Over 400 km from Earth, two 'crew members' on board the International Space Station (ISS) are working hard in the name of science. Affectionately known as Ed and Izzy, they are busy at all hours during their space flight, preparing and running scientific experiments using computer coding. But these are no ordinary crew: we're talking about two personified, space-hardened Astro Pi mini-computers, capable of sensing the environment, recording measurements and taking photos in space.

## Gadgets and gizmos

Developed by the Raspberry Pi Foundation in collaboration with the UK Space Agency and the European Space Agency<sup>1</sup> (ESA), an Astro Pi is a Raspberry Pi computer equipped with a set of sensors called Sense HAT. As well as detecting pressure, temperature and humidity, Sense HAT incorporates other gadgets including a gyroscope (for detecting variations in orientation), an accelerometer (for detecting changes

in motion) and a magnetometer (for measuring the strength and direction of a magnetic field). It contains an LED matrix to display information, and a little five-button joystick. The Astro Pi called Ed is also equipped with a visible light camera, and Izzy with an infrared camera.

As well as all these gadgets and gizmos, the really important thing about these two Astro Pi computers is that they allow school students to run their own code in space. Every year, teams of

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**“One of the main goals of the challenge is to inspire as many students as possible to participate in space science using code.”**

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students up to the age of 19 are invited to enter the European Astro Pi Challenge and design a scientific experiment that could be run using one of the Astro Pi computers on the ISS. As part of their design, students provide the necessary programming code. One of the main goals of the challenge is to inspire as many students as possible to participate in space science using code



*Teams receive an ESA Astro Pi kit to create and test their experiments.*

– in particular, the well-known and user-friendly programming language Python.

### Is anybody there?

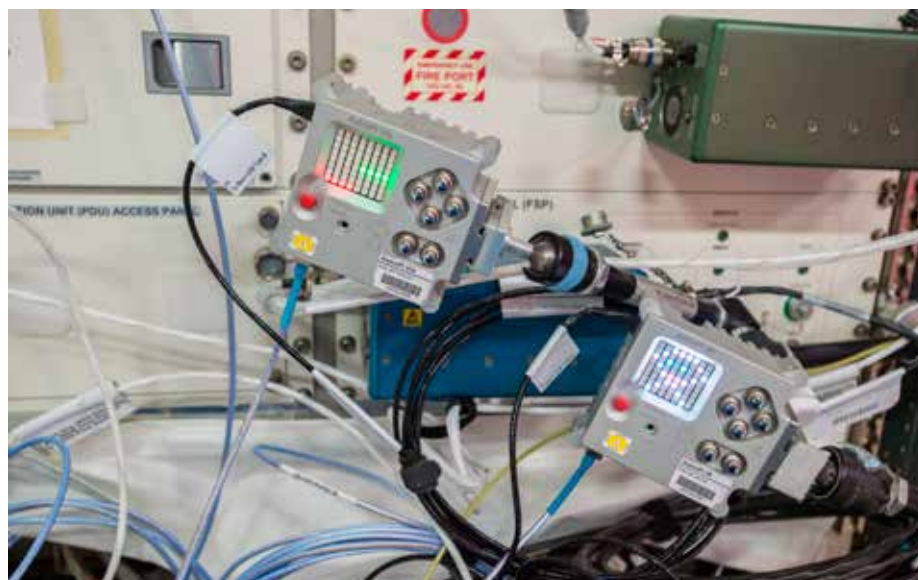
The challenge was first run by the UK Space Agency in 2015–16. One of the winning teams, which was made up of primary school pupils, devised a way to detect members of the crew on board the ISS by monitoring humidity levels. If a fluctuation was detected, the Astro Pi scrolled a message asking “Is anybody there?” before taking a picture with its camera. The team successfully managed to catch some of the crew.

In 2016, ESA welcomed entries from students across Europe for the first European Astro Pi Challenge. Since the crew-detection experiment proved to be such an interesting concept, this particular task became a mission for all participating teams. Students also had to come up with an additional experiment of their own. A popular idea used the Astro Pi to calculate the orbital period of the ISS, and one of the winning teams logged the position of the ISS alongside magnetometer readings to determine where the weakest point of Earth’s magnetic field is.

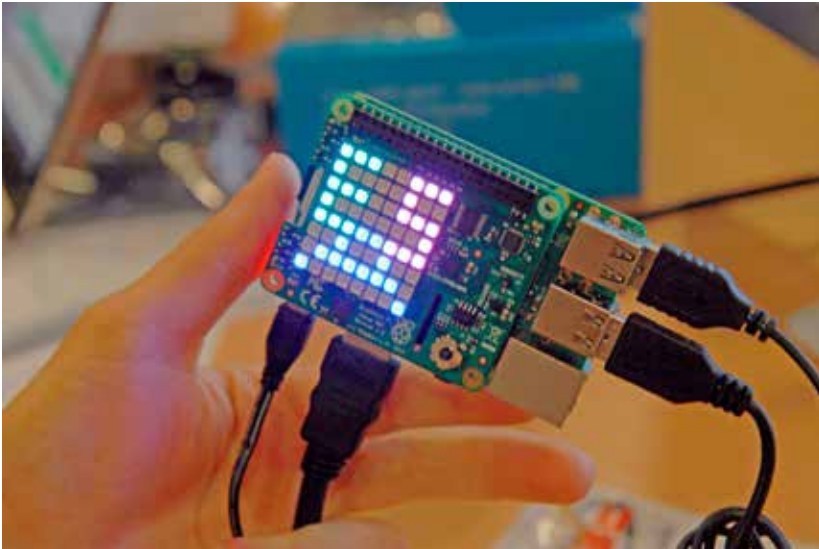
### Hello from planet Earth

For the current edition (2017–18), different challenges were issued to two different age groups: Mission Zero, a non-competitive task for students up to the age of 14; and Mission Space Lab, a competitive challenge for students up to the age of 19. In Mission Zero, students were asked to submit a simple computer program to display a greeting message on the Astro Pi LED matrix, in addition to reporting the current temperature inside the ISS. All 1700 teams that fulfilled the mission had their code run on the ISS<sup>w2</sup>, and students received a certificate showing the location of the ISS when their code was running.

In Mission Space Lab, students submitted proposals for scientific experiments related to one of two



*Ed and Izzy on board the ISS, running experiments for the Astro Pi Mission Zero challenge*



For the Mission Zero challenge, students submitted computer codes for displaying a message on the Astro Pi LED matrix, such as 'ESA' shown here.

themes: life on board the ISS, or life on Earth. Of the 334 teams that applied, 116 codes were selected and sent to run on the ISS. A popular idea among students was to monitor the health of our planet, for example by investigating light pollution, water pollution or deforestation using images of Earth taken from Izzy's near-infrared camera. After running their experiments, students analysed the data collected on the ISS and presented their results to the competition jury in the form of a scientific report – just like scientists would do. The winners of the Mission Space Lab challenge will be announced at the end of June 2018.

## Challenge your students to code

The European Astro Pi Challenge will return in September for the 2018–19 school year. Why not encourage your students to take part? You can stay informed about the next edition by visiting the ESA Education website<sup>w3</sup>. In the meantime, teachers can find online resources for exploring various science subjects using Astro Pi to combine technology and space in the classroom<sup>w4</sup>.

## Acknowledgements

Special thanks go to the Raspberry Pi Foundation for their collaboration on the European Astro Pi Challenge.

The authors would also like to thank Monica Talevi, Slawomir Zdybski, Alana Bartolini and Joshua Duncan for reviewing this article and providing constructive and valuable comments.

## Web references

- w1 ESA is Europe's gateway to space, with its headquarters in Paris, France. See: [www.esa.int](http://www.esa.int)
- w2 Watch a video showing a Mission Zero winner's code running on the ISS. See: [www.esa.int/spaceinvideos/Videos/2018/02/Astro\\_Pi\\_Mission\\_Zero\\_code\\_running\\_on\\_the\\_International\\_Space\\_Station](http://www.esa.int/spaceinvideos/Videos/2018/02/Astro_Pi_Mission_Zero_code_running_on_the_International_Space_Station) or use the direct link: <https://tinyurl.com/ycq8w4fm>
- w3 For updates on the European Astro Pi Challenge, visit the ESA Education website. See: [www.esa.int/Education](http://www.esa.int/Education)
- w4 For classroom resources related to Astro Pi, visit the ESA Education website. See: [www.esa.int/Education/AstroPI/Astro\\_Pi\\_classroom\\_resources](http://www.esa.int/Education/AstroPI/Astro_Pi_classroom_resources)

## Resources

Find some great projects to help students start writing code via the Raspberry Pi website See: <https://projects.raspberrypi.org/en/>

Fatima Pinto and Elsa Sanchez are STEM didactics experts, and David Honess coordinates educational operations on the ISS. They work at the ESA Education office, based at the European Space Research and Technology Centre (ESTEC) in Noordwijk, Netherlands.



Taslin Pollock/Twitter



Lesley D/Twitter



Brent Kelders/Twitter

Students proudly display their ESA certificates, which indicate the position of the ISS when their code was running in space.

Bananas are a useful model for learning about a variety of chemical processes in living organisms.

Hanna, photo/Shutterstock.com

# Go bananas for biochemistry

Learn about a variety of biochemical processes with these quick, simple experiments using one of the world's favourite fruits.

By Sacha Glardon and Thomas Scheuber

Bananas are one of the most popular fruits across the world – over 100 billion of them are eaten every year. They are not only a staple food for millions of people, but also an essential source of income and employment, especially in Latin America.

Along with plantains, bananas are part of the *Musa* genus, which includes around 70 species. Today, however, most sweet bananas come from a single variety called Cavendish. These bananas are cultivated using asexual reproduction so they are genetically identical. This loss of biodiversity, however, leaves them particularly vulnerable to parasitic attacks – as is currently happening in a global infection by the fungus *Fusarium*<sup>w1</sup>.

Perhaps surprisingly, bananas also provide a good way to understand biochemical processes. In this series of quick activities involving bananas, students can learn about sugar metabolism, starch storage, melanin production and the molecules responsible for the banana flavour. The activities are suitable for secondary school students and involve chemistry at several different levels.

## Activity 1: Measuring sugar content with a refractometer

Before starting, present your students with six bananas of differing ripeness (see bananas 1–6 in table 1, which are



- ✓ Cell metabolism
- ✓ Energy production
- ✓ Sugar metabolism
- ✓ Ages 14–19

This article describes a selection of simple but meaningful experiments using a common fruit (banana) to understand some basic metabolic processes. For example, the ripening process (and the consequent changes in colour and sweetness) is used to illustrate the conversion of starch into maltose and glucose. To get the full benefit of these activities, students should understand the difference between simple and complex sugars. Teachers can use the suggested questions to start a discussion, building on them to maximise the learning outcomes of the activities.

Monica Menesini, secondary school science teacher (retired), Italy

## REVIEW

	Banana ripeness	Sugar concentration (%)	Iodine staining
1		16.2	
2		19.3	
3		21.3	
4		20.7	
5		20.0	
6		19.3	

Table 1: Mean sugar content and images showing Lugol's iodine solution staining for starch content for bananas of varying ripeness

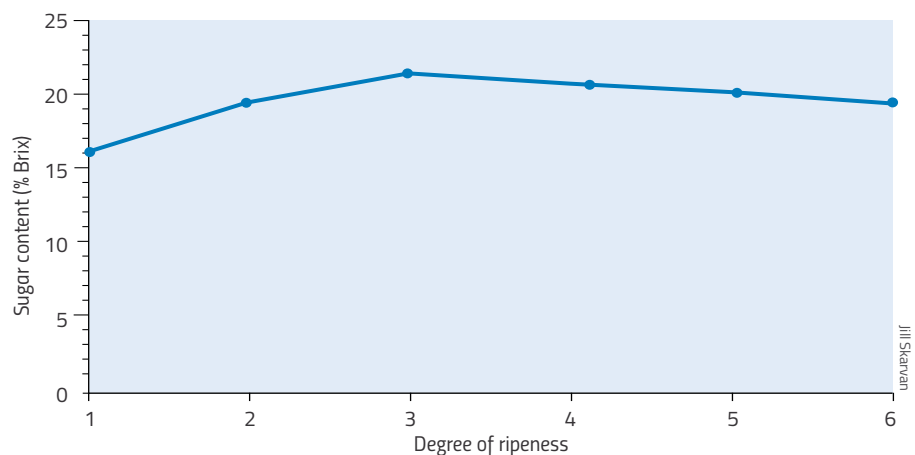


Figure 1: Mean sugar content in bananas of varying degrees of ripeness (1–6)

numbered in terms of increasing ripeness). Which banana do your students guess is the sweetest? Most students vote for the black banana, but is their assumption correct? Students can conduct a blind tasting test to judge which sample tastes sweetest. Do their taste buds identify the correct answer? To find out, students then measure the sugar content of various bananas using a refractometer. The activity will take around 20 minutes.

### Materials

- Bananas of varying ripeness (three bananas for each of the six degrees of ripeness, i.e. 18 bananas in total)
- Multiscale refractometer
- Fork
- Bowl
- Soft damp cloth

### Procedure

1. Peel the least-ripe banana (banana 1 in table 1) and break off a piece about 3 cm in length.
2. Using a fork, mash the banana in a bowl until you get a semi-fluid pulp.
3. Smear some pulp on top of the prism assembly of the refractometer. Close the daylight plate so the pulp spreads across the entire surface of the prism without any air bubbles or dry spots.
4. Hold the refractometer in the direction of a natural light source and look into the eyepiece. You will see a circular field with graduations

showing the % Brix – the number of grams of sucrose in 100 grams of sample (e.g. 1 g sucrose in 100 g sample = 1% Brix). You may have to focus the eyepiece to see the graduations clearly.

- Record the sugar content in % Brix.
- Clean the instrument (both the daylight plate and the top of the main prism assembly) using the cloth.
- Repeat these steps for at least three different bananas of the same ripeness and then calculate the mean sugar content (see table 1 and figure 1).
- Repeat the activity until you have recorded and calculated the sugar content for bananas 1–6.

## Activity 2: Analysing starch content with iodine

Here, students use Lugol's iodine solution to test for the presence of starch in different bananas, showing that the amount of starch declines during the ripening process. This activity takes approximately ten minutes.

### Materials

- Bananas of varying ripeness (three bananas for each of the six degrees of ripeness, i.e. 18 bananas in total)
- Lugol's iodine solution: 2% potassium iodide with 1% iodine in water ( $I_3K$ )
- Kitchen knife
- Brush

### Procedure

- Cut each banana in half lengthways.
- With a brush, cover the surface of the banana with Lugol's iodine solution.
- Wait one minute and compare the different results (see table 1).

### Discussion

During the ripening process, the enzyme amylase catalyses the breakdown of starch (a polysaccharide) to simple sugars – first to maltose (a

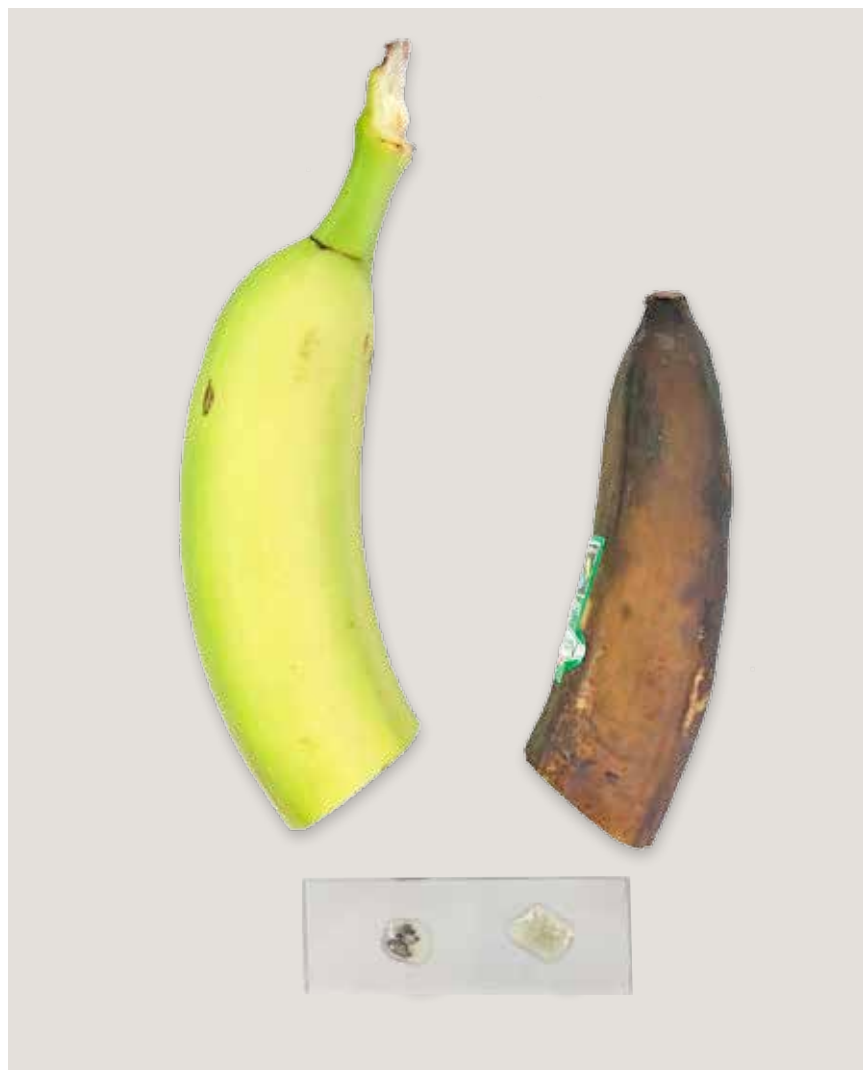


Figure 2: Two samples of banana pulp for viewing under the microscope

disaccharide) and then to glucose (a monosaccharide). In the activity, the banana with the highest sugar content (in the form of monosaccharides and disaccharides) is banana 3 in table 1. After this stage of ripening, the sugar content starts to decline because the majority of the starch has been converted into simple sugars and the banana continues to use glucose for cellular respiration.

This phenomenon is also demonstrated by the reaction with Lugol's iodine staining: unripe bananas have a higher starch content than ripe bananas, as shown by a darker staining with Lugol's iodine solution. With further ripening, the staining is considerably reduced due to the lower amount of starch.

In a blind tasting test, students might not choose the banana with the highest

sugar content as the sweetest. Other factors that can affect the taste include the softness of the banana and its water content. Moreover, since amylase is also present in our saliva, foods that contain lots of starch (but little sugar) start to taste sweet after chewing, as the amylase breaks down some of the starch into sugar.

Discuss some of the following questions with your students:

- Which banana is sweetest?
- Why does the sugar content increase at the start of the ripening process but decline towards the end?
- How does the starch content change during the ripening process?
- Is there more starch in bananas at the beginning of the ripening process compared to the end, or less starch? Can you explain why?

- Is sweetness purely connected to the amount of sugar present, or do other factors influence the sweetness?

### Activity 3: Locating the starch 'storage room'

In this activity, students prepare microscopic specimens using banana pulp from the most and least ripe bananas. Under the microscope, students can view the cellular organelles that store starch (amyloplasts) and understand why these organelles disappear during the ripening process. This activity takes approximately 15 minutes.

#### Materials

- Banana pulp from activity 1 (bananas 1 and 6 from table 1)
- Lugol's iodine solution
- Microscope
- Microscope slides
- Cover slips

#### Procedure

1. Smear a small amount of the banana pulp onto a microscope slide and add one drop of Lugol's iodine solution (figure 2).
2. Place the cover slip on top of the sample. Using the microscope at a magnification between 100x and 400x, try to locate the organelles that store starch in the banana.
3. Repeat steps 1 and 2 with the other sample of banana pulp.

#### Discussion

Amyloplasts are responsible for the synthesis and storage of starch granules through the polymerisation of glucose. In unripe bananas, staining with Lugol's iodine solution turns the starch and amyloplasts a deep purple colour (figure 3). In riper bananas, there is no reaction with the solution, because the amount of starch is reduced and the amyloplasts are no longer present in these samples (figure 4).

Discuss some of the following questions with your students:

- Why is iodine added to the banana sample?

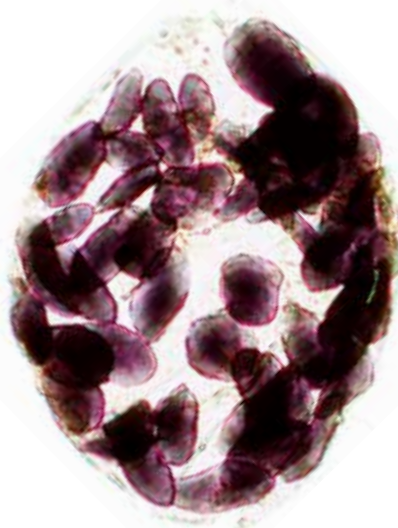


Figure 3: Iodine-stained amyloplasts in cells from an unripe banana, as viewed under a microscope

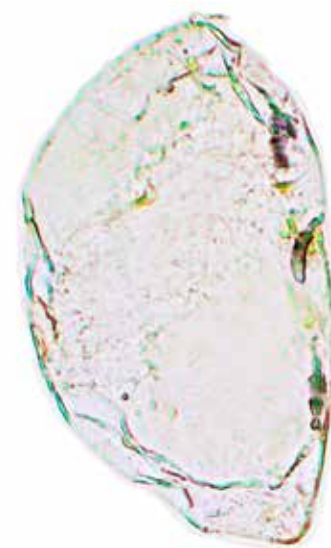


Figure 4: In cells from a ripe banana, all starch is converted into monosaccharides and disaccharides, so amyloplasts are no longer present.

Samuel Ginsburg

- What is the name of the organelle that stores starch in plants?
- What differences can you see between these organelles in the different banana samples and why?

### Activity 4: Turning bananas black

Students learn about the effect of melanin production and cell damage in bananas in this simple activity, in which a banana is submerged in hot water, causing the skin to turn black. The activity takes approximately five minutes.

#### Materials

- Yellow banana (e.g. banana 2 from table 1)
- 1 litre beaker containing boiled water

#### Procedure

1. Dip half of the banana into the hot water.
2. After one minute, the submerged half of the banana will turn black (figure 5).



Figure 5: After immersing half a banana in boiling water, the skin turns black due to the production of melanin.

Sachia Glardon

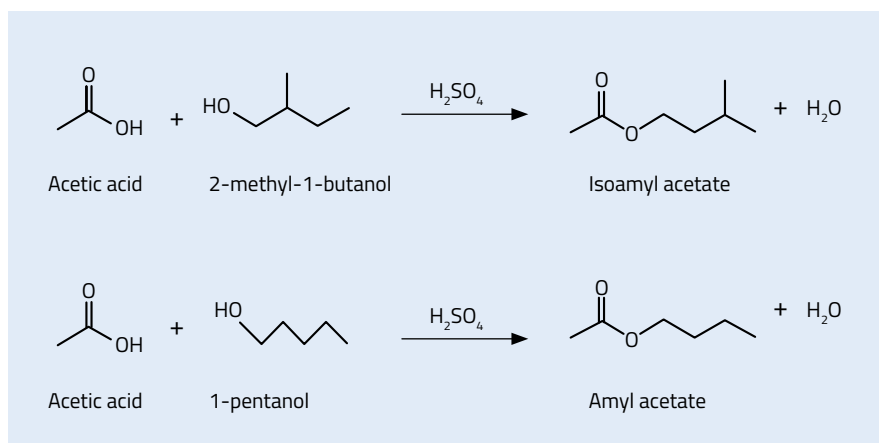


Figure 6: Esterification reactions producing isoamyl acetate (top) and amyl acetate (bottom)

## Discussion

When the banana is submerged in hot water, its cells are exposed to heat, causing cell damage. In response, the dark pigment melanin is produced, which results in the banana skin turning black. This pigment protects external cells (in both plants and animals) from ultraviolet damage and also counteracts the presence of free radicals due to its antioxidant properties. Melanin is produced from the oxidation of the amino acid tyrosine, which is catalysed by a copper-containing enzyme called tyrosinase. When the cells of the banana are damaged, tyrosinase is released. Melanin production does not affect the ripening process, but since riper bananas are older and have therefore suffered more cell damage, they are browner.

Discuss some of the following questions with your students:

- Why does the banana turn black?
- What causes this colour change?
- Does submerging the banana in hot water speed up the ripening process?
- What is the difference between a banana submerged in hot water and a naturally black banana?

## Activity 5: Making artificial banana flavouring

This activity is suitable for students aged 16–19 and involves synthesising artificial flavours. Using 2-methyl-1-butanol, students can produce the

organic compound isoamyl acetate (3-methylbutyl ethanoate), which has a scent similar to bananas and pears. Or, using 1-pentanol, students can produce the compound amyl acetate (pentyl ethanoate), which has a scent similar to bananas and apples. The activity will take approximately 15 minutes. You may wish to divide your class so that one half produces isoamyl acetate, and the other half produces amyl acetate. Groups can then compare scents.

## Materials

- Acetic acid (CH<sub>3</sub>COOH)
- 2-methyl-1-butanol (C<sub>5</sub>H<sub>12</sub>O) or 1-pentanol (C<sub>5</sub>H<sub>12</sub>O)
- Sulfuric acid (H<sub>2</sub>SO<sub>4</sub>)
- Boiling stones
- Bunsen burner
- Test tube
- 500 ml beaker

**Safety note:** This experiment involves the use of sulfuric acid. Students should wear safety glasses and gloves, and follow the usual safety rules for chemistry classes. As with any chemistry experiment, students should not taste the flavouring. Please also see the general safety note on the *Science in School* website and at the end of this print issue.

## Procedure

1. Pipette 2 ml of acetic acid into a test tube.
2. Add 2 ml of 2-methyl-1-butanol or 1-pentanol to the test tube.

3. Mix the educts and add one drop of sulfuric acid.
4. Heat the mixture over the Bunsen burner flame for approximately two minutes, without boiling. Adding boiling stones to the test tube will help avoid superheating. Take care to turn the opening of the test tube away from people.
5. Pour the content of the test tube into a 500 ml beaker to intensify the smell.

## Discussion

Isoamyl acetate and amyl acetate are the main components of banana flavouring, although flavour manufacturers usually keep their exact recipes a secret. Isoamyl acetate is produced by a condensation of 2-methyl-1-butanol with acetic acid, whereas amyl acetate is produced by a condensation of 1-pentanol with acetic acid. Both esterification reactions are catalysed by sulfuric acid (figure 6). As with all fruits, the natural flavour of banana is a mixture of several components<sup>w2</sup>, so it is difficult for artificial flavours to copy the flavour and smell exactly.

Discuss some of the following questions with your students:

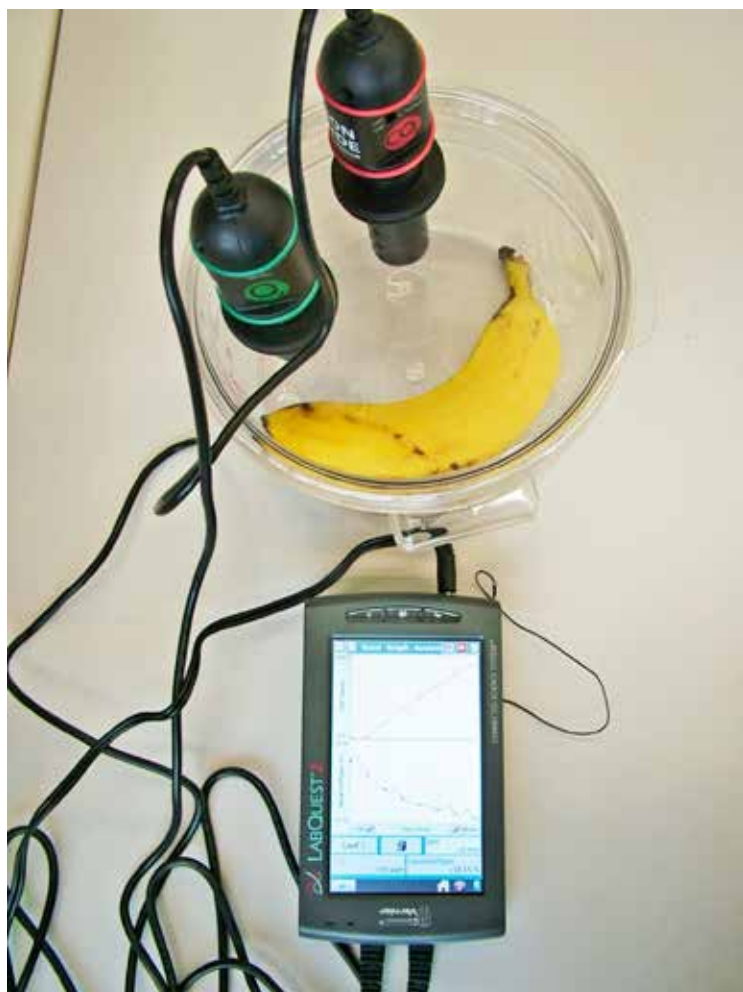
- What do the products of the reactions smell like?
- Which molecule is responsible for the typical banana flavour?
- What is the difference between an artificial and a natural flavour and why do they smell different?

## Extension activities: Uncovering more about bananas

There are a number of additional experiments you can carry out to learn more about the biology and chemistry of bananas, as well as to link to other interdisciplinary topics. For example, you could:

- Isolate banana DNA to understand that all living organisms (including bananas) contain DNA, which stores the genetic information that is passed from parent to offspring.





Sacha Glardon

Extension activity measuring the levels of oxygen and carbon dioxide to demonstrate cellular respiration

- Demonstrate cellular respiration by placing a banana in an airtight container and using CO<sub>2</sub> and O<sub>2</sub> sensors to measure the changing levels of these compounds.
- Understand more about the breakdown of starch, its effect on blood sugar levels and the storage of glycogen in the liver by measuring your blood sugar level every 15 minutes after consuming a banana (if permitted in your country).
- Investigate the importance of biodiversity in relation to disease outbreaks.
- Explore the historical, economical and ethical factors linked to the trade of bananas.

### Web references

- w1 One of the most destructive diseases currently affecting bananas is caused by the fungus *Fusarium*. Learn more by visiting the website of the United Nations' Food and Agriculture Organization. See: [www.fao.org/3/a-i5874e.pdf](http://www.fao.org/3/a-i5874e.pdf)
- w2 James Kennedy, a chemistry teacher from Australia, has created a fun graphic showing the list of ingredients in an 'all natural banana'. See: <https://jameskennedyonash.wordpress.com/2013/12/12/ingredients-of-an-all-natural-banana/>

### Resources

Read more about the production and trade of bananas by visiting the Banana Link website. See: [www.bananalink.org.uk/all-about-bananas](http://www.bananalink.org.uk/all-about-bananas)

Learn about the history of bananas in a video from *National Geographic*. See: [www.youtube.com/watch?v=SpAHPXNhAwk](http://www.youtube.com/watch?v=SpAHPXNhAwk)

Dr Sacha Glardon is a biology and chemistry teacher at the Gymnasium Bäumlhof, and Thomas Scheuber is a biology teacher at the Gymnasium Kirschgarten, both in Basel, Switzerland. They represented Switzerland at the Science on Stage festival in Debrecen, Hungary, in 2017 with their experiments using bananas.



# Look out! The physics of road safety

Use equations of motion to work out what happened in a car crash – and learn some valuable life lessons.

By Jennie Hargreaves

Living in a rural area in Scotland, many of our students learn to drive on their farms – and believe they have little to learn when they begin driving on public roads. As a result, there have been many road fatalities involving young people in our region. In response to these shocking events, we devised a school-based activity to make students who are approaching driving age more aware of the dangers involved in driving –

to themselves, other drivers and pedestrians. The activity also encourages students to apply the equations of motion they have learned in physics to a real-life situation relevant to their own lives.

In the activity, we mock up a crash scene based on an actual collision between a car and pedestrian that occurred locally, resulting in serious and life-changing injuries to the



pedestrian. The exact details of what happened during the crash are not known: the driver of the car ran from the crash scene, and witness statements were somewhat inconsistent. Students therefore try to reconstruct the incident, using measurements and other evidence from the crash scene, witness statements and calculations. The task is to find out the cause of the accident, who was responsible and if any traffic offences (such as speeding) were committed.

Although it is more engaging for the students to investigate the crash scene themselves, students could alternatively be provided with the key values to use in the equations (particularly the length of the skid marks after the pedestrian was hit), so the activity becomes a straightforward calculation exercise using equations of motion.

The activity is suitable for students aged around 13–17, depending on their maths skills. The version of the activity described here is based on UK roads with UK speed limits, but the details can

be adapted for roads in other countries. You could also invent different scenarios relevant to your region: perhaps ask local police if they can provide data from actual traffic incidents in your area.

### The scenario

We asked students to consider the following scenario, and also used it as a basis for building the crash scene:

A pedestrian was hit on a quiet urban road, lit by streetlights and with a 30 miles per hour (48 km/h), speed limit, near a pub at about 10.20 pm on a rainy night. The driver fled the scene. The pedestrian was left unconscious in the road. Although witnesses saw what occurred, parts of their reports were contradictory. One thought the pedestrian might have been drunk, while the other thought the driver was exceeding the speed limit.



Peter Monteith (Police Scotland)

Students examine the crash scene set-up in school.



- ✓ Linear motion
- ✓ Newton's laws of motion
- ✓ Ages 14–19

Unfortunately, traffic accidents seem to be a common occurrence in most countries. What better way to try and reduce the number of these incidents than by using science to educate our students to be more responsible drivers? This activity is relevant for a wide range of ages and can be easily adapted to every country's driving speed limit. Using a simulation of an actual car accident, students apply the laws of physics to solve some missing pieces of the puzzle and find out for themselves what really happened. This should lead to meaningful discussions about excessive speeding, and factors affecting the 'thinking' and 'braking' distances. Alcohol or drug consumption, tiredness, and being absent-minded can affect the thinking distance, while conditions of the road, weather and the condition of tyres can affect the braking distance. It is important that students realise that ignoring these facts while driving can have fatal results.

### REVIEW

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



Student measuring the tracks with a tape measure (left) and with a trundle wheel (right)

Optional extras:

- Police-style crime tape
- Masking tape, for road marking
- A pub sign and/or road signs, perhaps drawn on a sheet of paper
- Traffic lights and/or stop signs
- Vinyl flooring to act as road surface, to help define the incident space

Procedure

1. You will need to decide on a scale factor for your plan and scale all sizes accordingly. We suggest 1:3, as it is closest to life size while being compact enough for indoors. Smaller scales can be used if space is tight.
2. Lay out the scene to represent the distances shown in figure 1. The car's front tyres should be at the end of the where the tyre tracks will be marked, and the pedestrian should lie in the road at a distance equivalent to 9 m from the front of the car.
3. Make the tyre marks caused by the skid, which occurs only when the wheels lock up after braking hard (once the driver sees the pedestrian), not when braking first occurs. Use water-based paint to take a print of a tyre tread on paper, then photocopy this. Lay out the copies to make

Building the crash scene

Building a crash scene for students to investigate can take up to six hours.

Materials

- Model car (e.g. child's ride-on car, or a cardboard box made into a car)

- Doll to represent the pedestrian (around 60 cm tall is about the right size for a ride-on car)
- Tyre marks
- Witness statements<sup>w1</sup> (see downloadable documents, or create your own)
- Measuring tape, trundle wheel or metre rulers

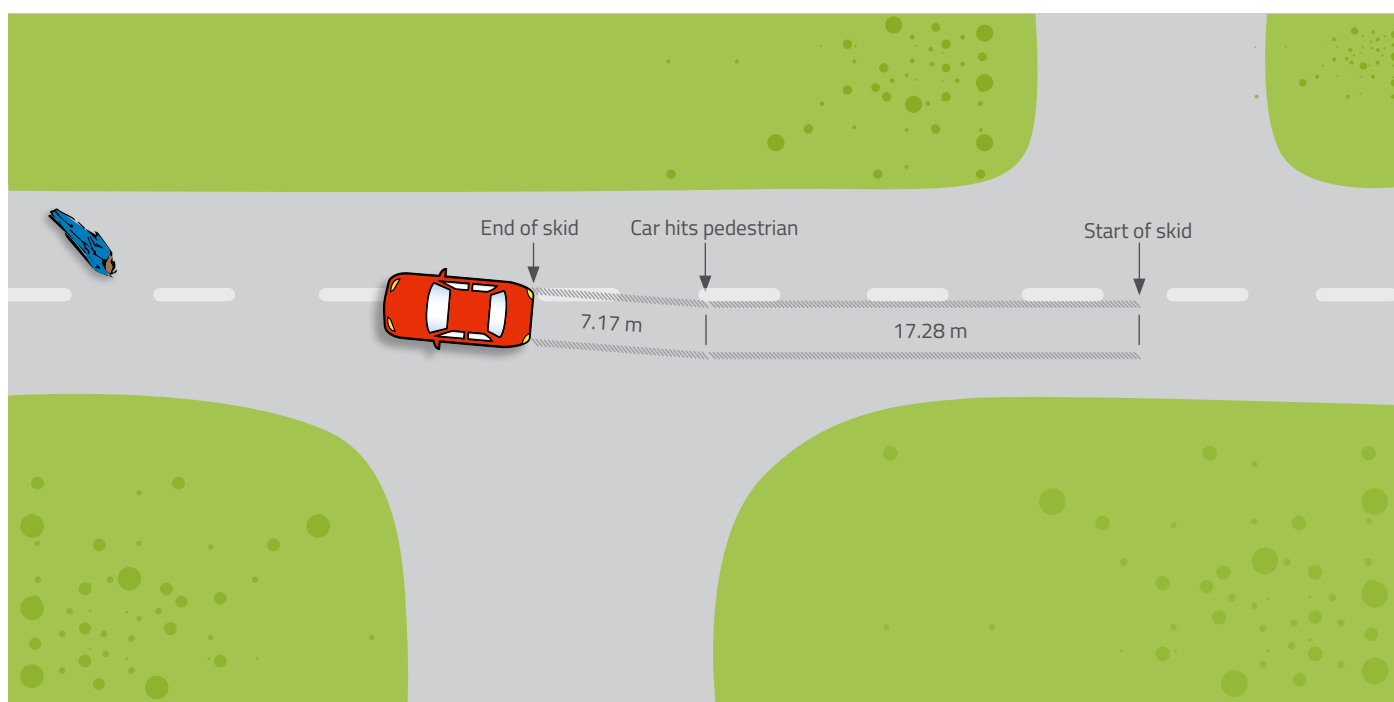


Figure 1: Plan of the crash scene, drawn to scale, showing the measurements obtained for the calculations. The total skid distance is the sum of the two measurements shown. The skid marks start when the wheels are locked after braking hard, and change direction slightly when the pedestrian is hit

two tracks, separated by the space between the car's tyres. At the point where the pedestrian is hit, the tyre marks should make a small deviation, similar to that shown in figure 1. The tracks should then continue, working backwards from the car, until the start of the skid, representing the dimensions in figure 1.

4. Make some street scenery to add to the authenticity of the scene. This can include road signs, road markings, traffic lights and a pub sign.

## What the students do

This part of the activity will take around two hours (or more, if the extension task is included).

1. Before the investigation starts, ask the students to work together to secure the crash scene (with police-style tape if available).
2. Ask the students to work out what happened by considering the scenario (see earlier). They should inspect the scene, writing down their initial observations and ideas about what they think occurred, and perhaps taking photographs.
3. Give the students three questions, which they will need to take measurements and carry out calculations to answer:
  - Question 1: What speed was the car travelling at when it started to skid?
  - Question 2: What speed was the car travelling at when it collided with the pedestrian?
  - Question 3: If the car had been travelling at the urban speed limit, would it still have collided with the pedestrian?

Ensure that the students also read the witness statements, which pose the question: was the driver exceeding the speed limit when the crash occurred?

4. Direct the students to take the following measurements at the scene:
  - The full length of the tyre tracks (to find the displacement of the vehicle as the brakes locked and the skid marks were made)
  - The distance from the car's front wheels to where the tyre tracks



UK speed limit sign, requiring drivers to slow down to 30 miles per hour (48 km/h) when entering a built-up area

deviate slightly, indicating where the collision took place (see figure 1).

For the calculations, students will also need a value for the deceleration of the car when the driver slammed on the brakes. To find this, a skid test would be performed by the police: they drive the crash car (or a near-identical one) along the same stretch of road in similar weather conditions and perform an emergency stop. An accelerometer on board the vehicle gives values for the acceleration, and the tests are continued until two results are obtained that are within 10% of each other. The lower result is used for any subsequent calculations of the driver's speed: this is in fairness to the driver, giving them the benefit of any uncertainty.

For this scenario, students can use the following results from the two deceleration tests:

- $-6.80 \text{ m s}^{-2}$
- $-7.01 \text{ m s}^{-2}$

## The calculations

The students now have all the information they need to answer the questions below. Here, we use the measurements obtained in our own

simulation, but yours can be based on your own data, ideally obtained from actual road incidents.

### Question 1: What speed was the car travelling at when it started to skid?

To calculate the velocity or speed of the car when it started to skid, we use the equation:

$$v^2 = u^2 + 2as$$

where:

$$v = \text{final velocity} = 0 \text{ m s}^{-1}$$

$$u = \text{initial velocity} = ?$$

$$a = \text{acceleration} = -6.80 \text{ m s}^{-2}$$

(lower result from police skid tests)

$s$  = displacement (total length of the skid mark, measured at 24.45 m)

Using the equation:

$$0 = u^2 + (2 \times -6.8 \times 24.45)$$

$$u^2 = 332.52$$

So  $u = 18.2 \text{ m s}^{-1}$ , or 65.6 km/h (approximately 41 miles per hour)

### Question 2: What speed was the car travelling at when it collided with the pedestrian?

To calculate the velocity or speed of the car when it collided with the pedestrian,



Peter Monteath (Police Scotland)

Wrecked car after a crash



ESB Professional/Shutterstock.com

Police investigating a real-life road crash

we use the same equation:

$$v^2 = u^2 + 2as$$

where:

$$v = \text{final velocity} = 0 \text{ m s}^{-1}$$

$$u = \text{initial velocity} = ?$$

$a = \text{acceleration} = -6.80 \text{ m s}^{-2}$  (lower result from police skid tests)

$s = \text{displacement}$  (length of skid mark after collision with pedestrian, measured at 7.17 m)

Using the equation:

$$0 = u^2 + (2 \times -6.80 \times 7.17)$$

$$u^2 = 97.512 \text{ m}^2 \text{ s}^{-2}$$

So  $u = 9.87 \text{ m s}^{-1}$ , or 35.5 km/h (approximately 22 miles per hour)

**Question 3:** If the car had been travelling at the urban speed limit, would the car still have collided with the pedestrian?

Again using the same equation:

$$v^2 = u^2 + 2as$$

$u = \text{initial velocity} = 13.41 \text{ m s}^{-1}$  (48.3 km/h, or 30 miles per hour)

$$0 = 13.41^2 + (2 \times -6.80 \times s)$$

$$13.41^2 = 13.60 s$$

$$\text{So } s = \frac{179.86}{13.60}$$

$$= 13.22 \text{ m}$$

Therefore, had the car been travelling at 30 miles per hour (the UK urban speed limit), it would have stopped approximately 4 m short of

the pedestrian's position, and would not have hit the pedestrian.

The situation is similar if the car had been travelling at 50 km/h - the urban speed limit in many European countries.

$$50 \text{ km/h} = 13.89 \text{ m s}^{-1}$$

$$0 = 13.89^2 + (2 \times -6.80 \times s)$$

$$13.89^2 = 13.60 s$$

$$\text{So } s = \frac{192.91}{13.60}$$

$$= 14.19 \text{ m}$$

Here, the car would have stopped approximately 3 m short of the pedestrian's position, and would not have hit them.

### Discussion

From the calculations, students should be able to conclude that the car was exceeding the legal speed limit given in the scenario, so the driver was at fault for speeding. In the real-life case, the driver was charged with dangerous driving. He was sent to jail for eight months and banned from driving for four years, for causing the collision and failing to stop at the crash scene.

**“The activity successfully engaged students who might otherwise think that physics is not for them.”**

We found that all students involved in the activity benefitted from the variety of skills involved – observing, hypothesising, recording, measuring, calculating, drawing conclusions and evaluating them – and it successfully engaged students who might otherwise think that physics is not for them. Were lessons also learned about why urban speed limits are set as they are? We think so.

## Extension activity: Pedestrian collisions

You can extend the activity by adding clues about what happened to the pedestrian when they were hit by the car. In creating the crash scene, use pieces of coloured tape (one colour matching the car, the other matching the pedestrian's clothes) so students can gather information on how the pedestrian was hit and thrown in the collision (see figure 2).

The downloadable document on pedestrian collisions<sup>w2</sup> provides additional information about what happens to pedestrians in car crashes – shocking details that should encourage students to think further about the risks involved in driving.

### Acknowledgements

The author would like to thank the following people and organisations for their help with this project:

- The Royal Society, for funding the project via the Partnership Grants Scheme
- Inspectors Neil Hewitson and Campbell Moffat and the team from Police Scotland Dumfries and Galloway Traffic Division, for explaining the physics of road crashes and providing scenarios for the students
- The Radcliffe Trust, for providing funding to take this work on tour
- Magnox, for additional funding for further road safety work.

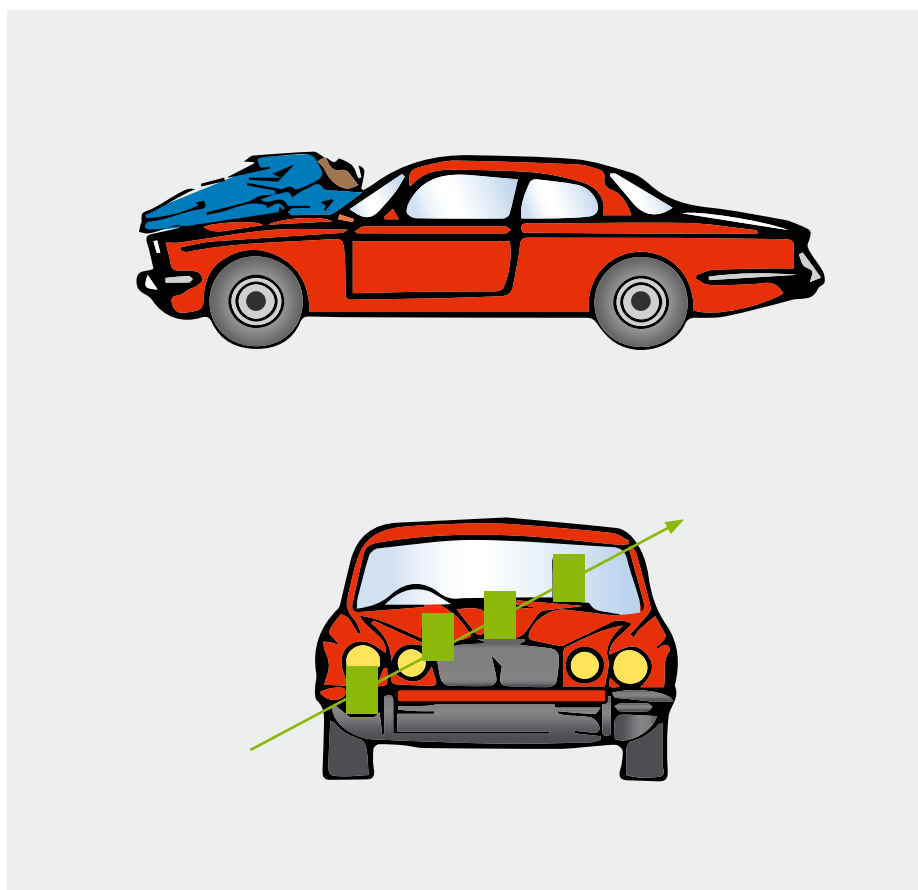
### Web references

- w1 Witness statements to use in this activity are available on the *Science in School* website. See: [www.scienceinschool.org/2018/issue44/roads](http://www.scienceinschool.org/2018/issue44/roads)
- w2 Information on what happens to pedestrians in collisions is available on the *Science in School* website. See: [www.scienceinschool.org/2018/issue44/roads](http://www.scienceinschool.org/2018/issue44/roads)

### Resource

How observant are you? Find out by watching this famous video: [www.youtube.com/watch?v=IGQmdoK\\_ZfY](https://www.youtube.com/watch?v=IGQmdoK_ZfY)

Jennie Hargreaves has taught physics in Scotland for nearly 30 years. She currently teaches at Lockerbie Academy in southwest Scotland, UK. She holds a degree in environmental physics and has an interest in raising the profile of physics and science to young people. In 2016, she won a Teacher of Physics Award from the Institute of Physics for her work in physics education. Her website ([www.mrsphysics.co.uk](http://www.mrsphysics.co.uk)) showcases much of her work in science education.



Peter Monteith (Police Scotland)

Figure 2: The contact points between the car and pedestrian (top image) can be represented in the activity using tape marks (lower image). The contact points indicate the direction in which the pedestrian was thrown.



# Perfumes with a pop: aroma chemistry with essential oils

Have fun with organic chemistry by extracting sweet-smelling essential oils from fragrant plants.

By Adrian Allan, Bob Worley and Mary Owen

For millennia, plants have been used for their medicinal benefits, flavours or smells. To determine which chemicals are responsible for certain properties in plants, scientists extract and analyse organic compounds in the laboratory. This can take many hours, so to enable students to try this

procedure in the classroom, we developed a method using an inexpensive microscale heater that extracts essential oils in a matter of minutes.

Using this heater, secondary school students can complete a number of distillation experiments to learn about the





chemical and physical properties of carbon compounds, including the effect of molecular polarity on solubility, and how to test for the presence of unsaturated carbon-carbon bonds.

### Preparation: building the microscale heater

Teachers should build the microscale heater prior to the lesson. It takes 20–30 minutes and requires materials that can be found in most school science departments. We recommend that students carry out the activities in groups of 2–4, so several heaters will be needed.

#### Materials

For one microscale heater (figure 1):

- 10 cm x 4 cm piece of copper metal foil
- Heavy-duty scissors
- 7 ml glass vial with bung and glass delivery tube
- Elastic band
- 3 m of 0.45 mm (26SWG) enamelled (insulated) copper wire
- Matches
- Sandpaper or wire wool
- Mineral wool
- 30 ml jar (such as a mini jam jar)

Number 14 11/ Shutterstock.com

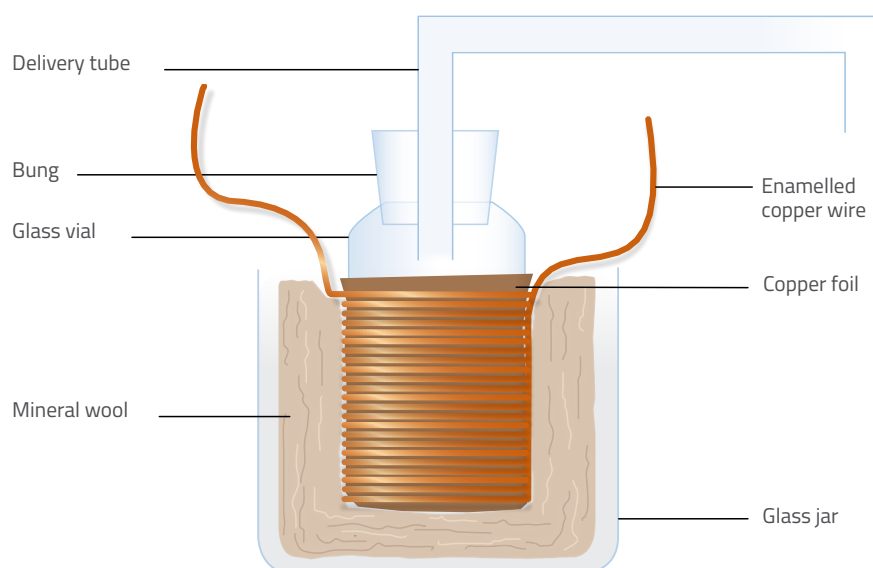


- ✓ Separation techniques
- ✓ Organic chemistry
- ✓ Aroma chemistry
- ✓ Ages 14–19

These hands-on experiments are ideal for introducing the topic of aroma chemistry and understanding how separation techniques are used to extract essential oils. The practical procedures are performed on a small scale, but are effective enough to illustrate large-scale industrial extractions that are usually carried out by steam or vacuum distillation. After distilling the essential oils, students can perform tests for unsaturation or reactivity, and discuss the theory behind them. A very interesting article!

Andrew Galea, chemistry teacher, Giovanni Curmi Higher Secondary School Naxxar, Malta

REVIEW



Adrian Allan/Nicola Graf

Figure 1: Diagram showing the elements of the microscale heater

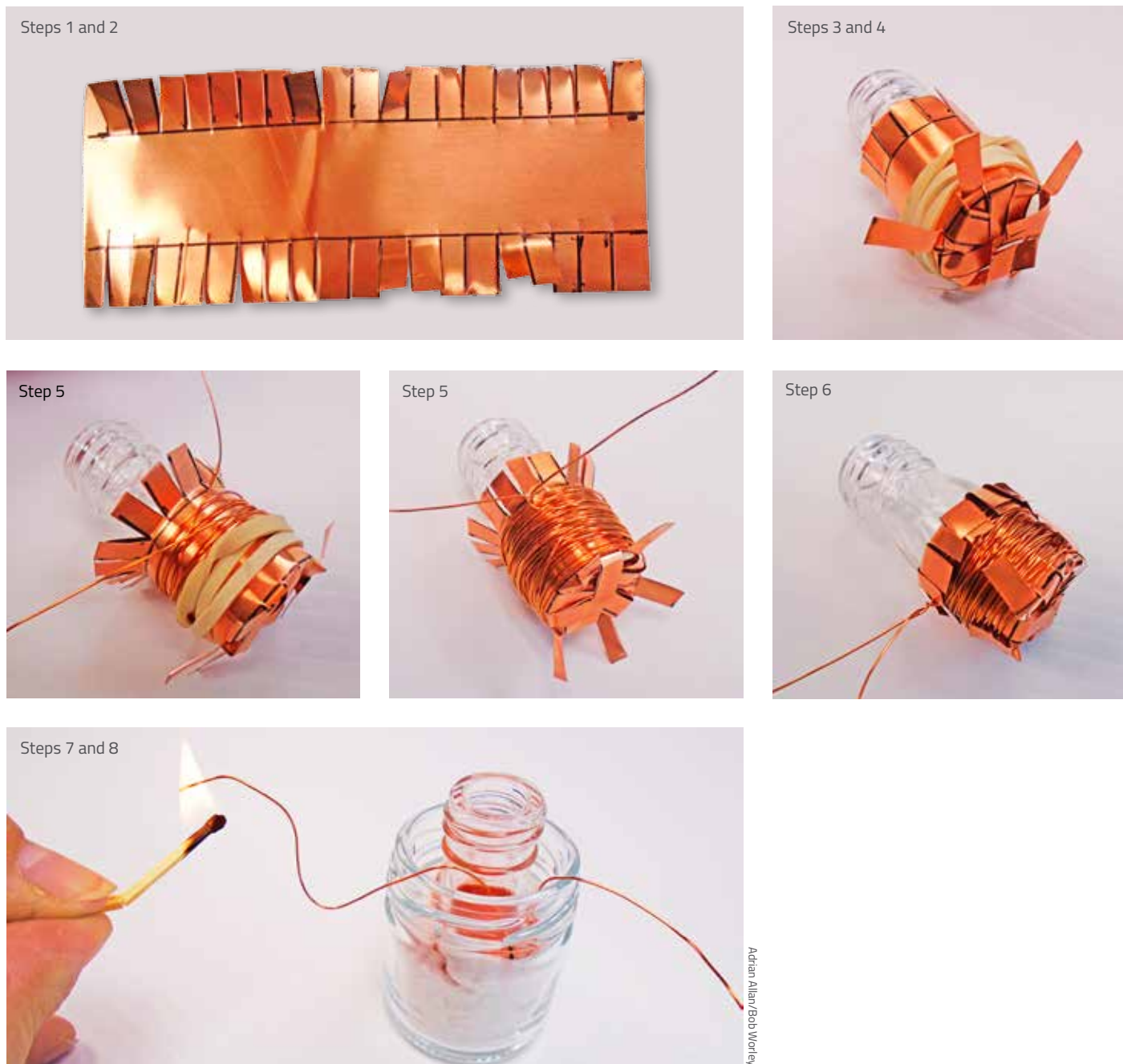


Figure 2: Steps for building a microscale heater

## Procedure

1. Cut out a 10 cm x 4 cm piece of copper foil. Draw horizontal lines 1 cm from each long edge (figure 2). Draw vertical lines in 0.5 cm intervals.
2. Cut along the small vertical lines with heavy-duty scissors as far as the horizontal lines.
3. Wrap the foil loosely around the glass vial. Hold it in place temporarily using an elastic band.
4. Fold some of the bottom flaps of foil under the base of the bottle to hold it in place. Leave three or four flaps unfolded.
5. Wrap 3 m of enamelled copper wire around the copper foil, leaving about 8 cm of wire free at each end. The copper coil is your heating element.
6. Fold over the upper foil flaps and the remaining lower flaps to keep the wire coil in place.
7. Wrap the heater in mineral wool and place it in the jar with the loose wire ends sticking out.
8. Using a match, burn the ends of the wire to remove some of the enamel insulation. Rub the ends with sandpaper or wire wool to allow electrical contact. Ensure that the exposed wires are not touching each other, or the copper foil.
9. The glass vial can now be removed from the copper foil in preparation for activity 1.

## Activity 1: Extracting essential oil using steam distillation

Essential oils are a mixture of volatile compounds that can be extracted from plants. They are composed mainly of a family of organic compounds called terpenes. In this activity, students use the microscale heater to extract essential oil distillates from orange peel, spearmint, lavender and cloves using steam distillation. The terpenes present in the oils are limonene, carvone, linalool and eugenol, respectively (figure 3). The activity takes about ten minutes. Each group of students will extract one type of essential oil.

### Materials

- Microscale heater
- 7 ml glass vial with bung and glass delivery tube
- Plant material e.g. orange peel, spearmint, lavender and cloves
- Spatula
- 1–2 ml of distilled water
- Glass bottle (to collect distillate)
- Low-voltage DC power supply (able to deliver a current up to 6 A)
- Ammeter
- 2 crocodile clips and 2 leads (4 mm)

### Procedure

1. Place two spatulas of plant material into the vial. This can be grated orange peel, dried leaves of lavender or spearmint, or a few dried cloves crushed with a pestle and mortar.
2. Add 1–2 ml of distilled water to the vial.
3. Insert the vial back into the copper wire coil of the heater, which is surrounded by mineral wool inside the jar.
4. Seal the vial by inserting the bung with a delivery tube. Place the other end of the delivery tube into a glass bottle to collect the distillate.
5. Using the crocodile clips, connect the ends of the copper wires to a low-voltage DC power supply (figure 4). A current of 4–5 A is required; an ammeter may be put in series to monitor this.

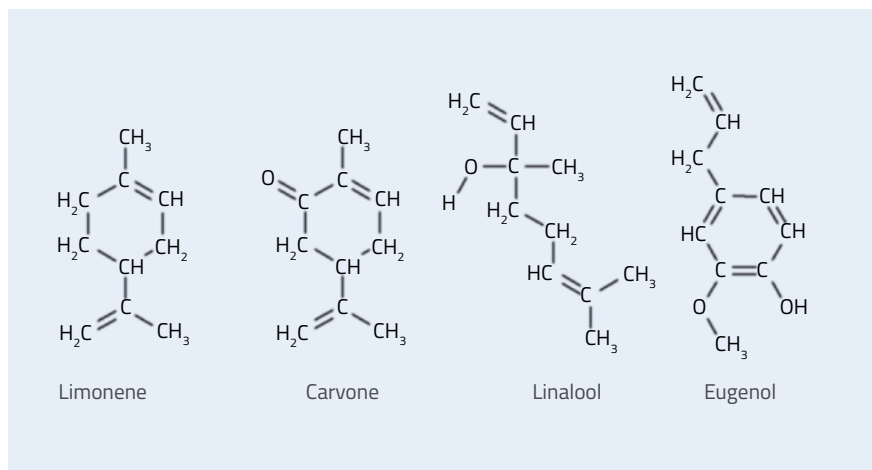


Figure 3: Example molecular structures of terpenes. From left to right, these chemicals are found in oranges, spearmint, lavender and cloves.

6. After 5–10 minutes, a colourless liquid will begin to drip into the bottle. Remove the first few drops of distillate from the bottle using a pipette for use in activity 2.
7. Continue heating the bottle until you have collected about 0.5 ml of liquid. This may take another 5–10 minutes.

- When terpene molecules evaporate, which forces are overcome: those between molecules or those within molecules?
- What compounds are present in the oil you have extracted?

### Discussion

To explore the chemistry behind essential oils, discuss the following questions with your students:

- What is distillation? How can it be used to separate mixtures of substances?

### Activity 2: Testing distillates for unsaturation

Terpenes – the primary component of essential oils – are unsaturated organic compounds, because they contain one or more carbon-carbon double bonds. This means they will react with bromine (in an addition reaction) or potassium



Figure 4: Experimental setup showing the microscale heater connected to the power supply

permanganate (in an oxidation reaction), resulting in the colour of the bromine solution changing from orange to colourless, and the potassium permanganate solution changing from pink to colourless. Limonene (the main terpene present in citrus fruits) can be used as an example (figure 5). This activity allows students to quickly demonstrate that unsaturated carbon-carbon bonds are present in essential oil extracts. The activity takes about five minutes.

### Materials

- Distillates from activity 1
- Potassium permanganate solution: 0.002 M potassium permanganate ( $\text{KMnO}_4$ ) in 0.1 M sulfuric acid ( $\text{H}_2\text{SO}_4$ )
- Aqueous bromine ( $\text{Br}_2$ ) solution: 0.002 M
- Dropping pipette
- Spotting tile or laminated worksheet<sup>w1</sup>
- Wooden splint cut to a point at one end, or cocktail stick

**Safety note:** Although the solutions are very dilute and used in small volumes, a lab coat and safety goggles are still recommended. If the solutions come into contact with skin, wash under the tap. Teachers should follow their local health and safety rules, in particular concerning the use of potassium permanganate and bromine and the disposal of the resulting solution. See also the general safety note on the *Science in School* website and at the end of this print issue.

### Procedure

1. Using a dropping pipette, add one drop of potassium permanganate solution to two separate wells of a spotting tile. Alternatively, you can use a laminated worksheet with pre-labelled circles, which is available to print from the *Science in School* website<sup>w1</sup> (figure 6). If using the worksheet, add the drops of solution to the two circles labelled 'potassium permanganate'.
2. Add one drop of bromine solution to two separate wells of the spotting tile, or the two worksheet circles labelled 'bromine solution'.
3. Add one drop of distillate (produced during activity 1) to one of the drops of potassium permanganate solution, and add another drop of distillate to one of the drops of bromine solution. Mix using a wooden splint. The distillate should decolourise the potassium permanganate and bromine solutions, showing that it contained unsaturated carbon-carbon bonds.

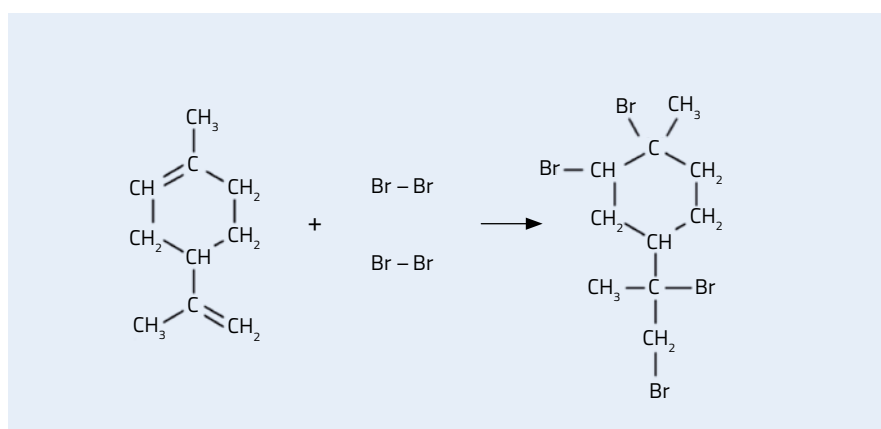


Figure 5: Molecular structures of the reaction of limonene with bromine

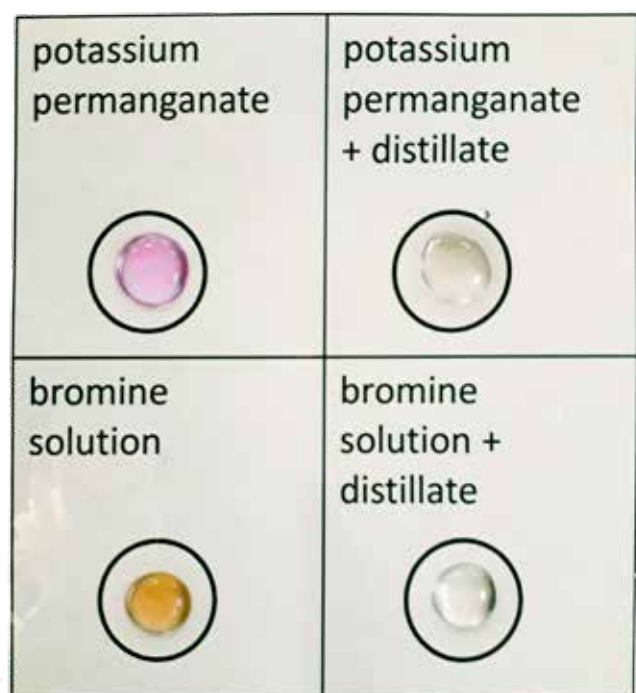


Figure 6: The essential oils decolourise potassium permanganate and bromine solutions, indicating the presence of unsaturated carbon-carbon bonds

### Discussion

To encourage students to think about the reactions taking place, discuss the following questions:

- What did you observe when the potassium permanganate or bromine solutions were added to the distillate?
- What does this tell you about the type of bonds that exist between the carbon atoms in the molecule?

### Activity 3: Popping a latex balloon

Polar substances tend to dissolve in polar solvents, and non-polar substances may dissolve in non-polar solvents. This activity shows that latex can be broken up using a non-polar solvent (e.g. essential oils) but not polar solvents (e.g. water). When orange oil comes into contact with the balloon, the non-polar limonene molecules in the oil disrupt the weak forces between the polymer chains in latex to rupture the balloon and make it pop. The activity takes about five minutes.

#### Materials

- Distillation apparatus from activity 1 using orange peel
- Latex balloon
- Dropping pipette
- Tripod

**Safety note:** Check if any students or staff involved in the activity have an identified allergy to latex. If this is the case, take steps to limit exposure or in serious cases, do not carry out the activity.

#### Procedure

1. Move the distillation apparatus on top of a tripod, or allow the delivery tube to hang over a lab bench.
2. Inflate the latex balloon fully so that the rubber is stretched tight, and place underneath the delivery tube.
3. Start the distillation using orange peel, as in activity 1. The suspense will build as each drop of distillate falls from the delivery tube onto the balloon, until the balloon bursts<sup>v2</sup> (figure 7).

#### Discussion

Encourage your students to think about the chemistry behind this fun trick by asking them the following questions:

- Why does limonene break up latex but water does not?
- Why is limonene used in many cleaning products?

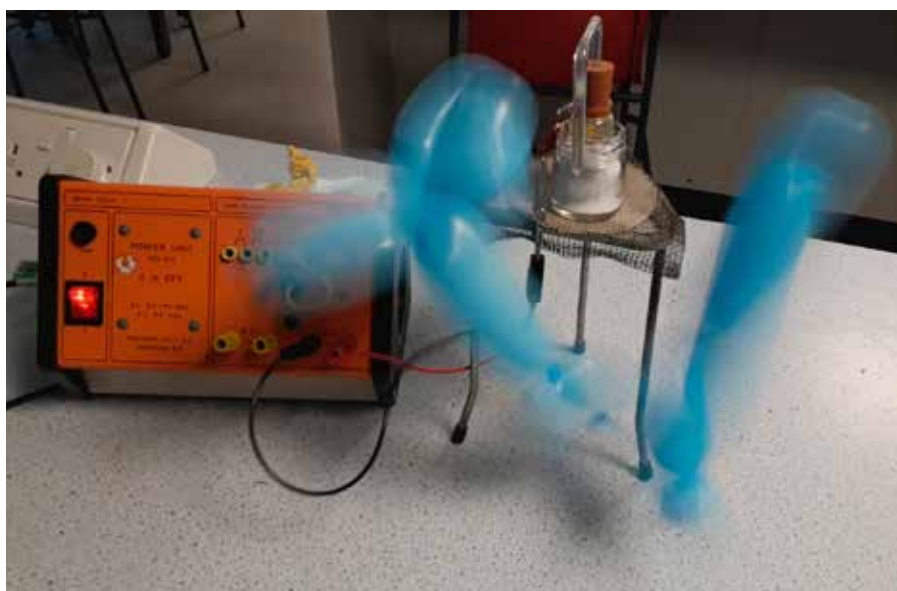
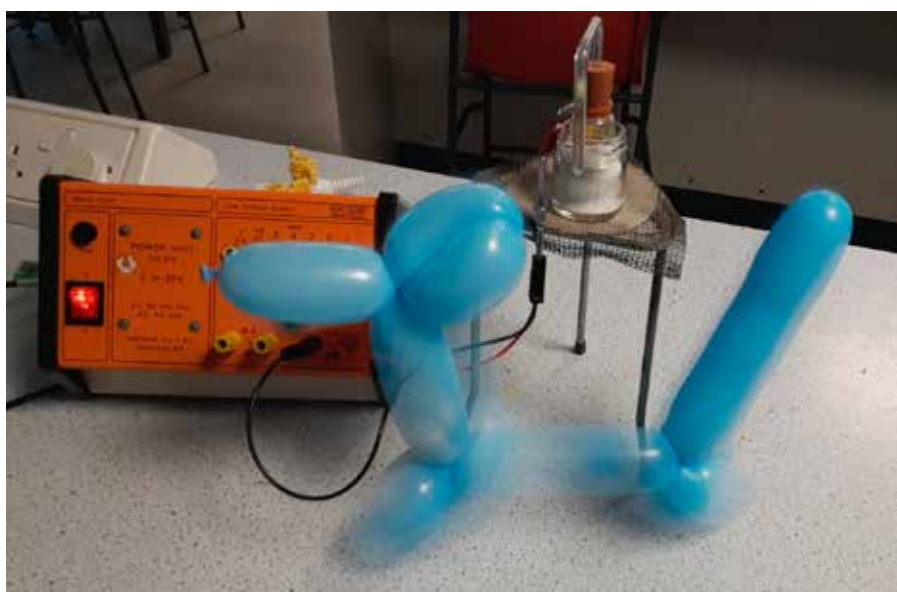
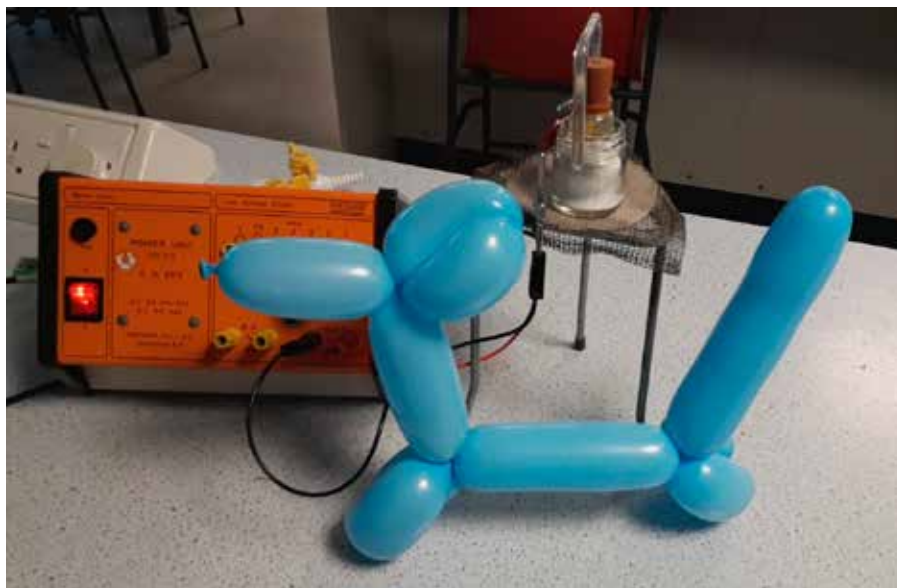


Figure 7: Limonene in orange oil dissolves the latex balloon, causing it to burst

## Activity 4: Purifying essential oils

Students aged 16–19 can purify the essential oil by extracting it from the distillate using hexane. Hexane is a non-polar substance so it dissolves essential oil. The mixture of oil and hexane is then separated by evaporating hexane. This purification takes 10–20 minutes. Each group of students will need access to the following materials:

### Materials

- Distillates from activity 1
- 3 glass Pasteur pipettes
- Test tube
- Small bottle of hexane (C<sub>6</sub>H<sub>14</sub>)
- Cotton wool
- Anhydrous sodium sulfate (Na<sub>2</sub>SO<sub>4</sub>)
- Wooden splint, cut in half lengthways
- Clamp and stand
- 7 ml glass vial
- Hot plate

### Procedure

1. Add several drops of distillate to a small test tube using a glass Pasteur pipette. Add an equal volume of hexane and mix by bubbling air into the solution using the pipette.
2. Remove the lower aqueous layer with the pipette and discard.
3. Insert a small piece of cotton wool (2–3 mm in diameter) to the wider open end of an unused Pasteur pipette. Using half of the wooden splint, push the cotton wool down until it reaches the point where the pipette starts to narrow, just before the tip.
4. Using the splint, spoon some anhydrous sodium sulfate into the top of the pipette, enough for a few millimetres to rest on top of the wool.
5. Attach the pipette to a stand using a clamp and place a glass vial below it.
6. Transfer the remaining upper layer (a mixture of hexane and oil) to the top of the pipette. Sodium sulfate absorbs water molecules to form hydrates (it is a drying agent), so as the mixture passes through, any remaining water

will be removed. The cotton wool plug stops any solid sodium sulfate passing through with the mixture. The liquid will eventually enter the glass vial below. This will take 1–2 minutes.

If blockage occurs, attach a rubber teat and squeeze it to increase the air pressure inside the pipette. If this does not work, repeat the procedure using less cotton wool and sodium sulfate.

7. Place the glass vial on a hot plate in a fume hood and gently heat for 4–5 minutes until the hexane evaporates. A pleasant smelling oily residue will remain.

### Discussion

During the extraction, discuss the following questions with your students:

- In the extraction, why was hexane added to the distillate?
- Why is the mixture of hexane and oil passed through anhydrous sodium sulfate?

As a follow-up activity, the extracted oil can be analysed using small-scale thin layer chromatography by following the procedure available on the *Science in School* website<sup>w1</sup>.

### Acknowledgements

The authors would like to thank Chris Lloyd for introducing them to using an electrical heater for distillation experiments in schools<sup>w3</sup>, and Steve Jones, the director of CLEAPSS, for encouraging them to discover new techniques in microscale chemistry and for giving permission to use the microscale heater procedure in this article. They would also like to acknowledge Howard Tolliday and Hamish McGill for their efforts in developing and testing the procedures at Dornoch Academy, Scotland, UK.

### Web references

- w1 The worksheet for activity 2 is available to download from the *Science in School* website, as is the procedure for analysing essential oils using thin-layer chromatography. See: [www.scienceinschool.org/2018/issue44/distillation](http://www.scienceinschool.org/2018/issue44/distillation)
- w2 A video showing the balloon demonstration is available on the *Science in School* website. See: [www.scienceinschool.org/2018/issue44/distillation](http://www.scienceinschool.org/2018/issue44/distillation)
- w3 Chris Lloyd from the Scottish Schools Education Research Centre (SSERC) developed his own method for building a microscale heater, which involved using plaster of Paris for insulation. Details can be found on the SSERC website. See: <http://info.sserc.org.uk/images/Chemistry/Chemistry%20Microscale/Making/HeatingMantle.docx>
- w4 Read about the Smells Like Teen Shampoo project in an article written by Adrian Allan's students, published in the *Young Scientists Journal*. See: <https://ysjournal.com/wp-content/uploads/2015/06/Smells-Like-Teen-Shampoo.pdf>

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