Summer 2017 | Issue 40

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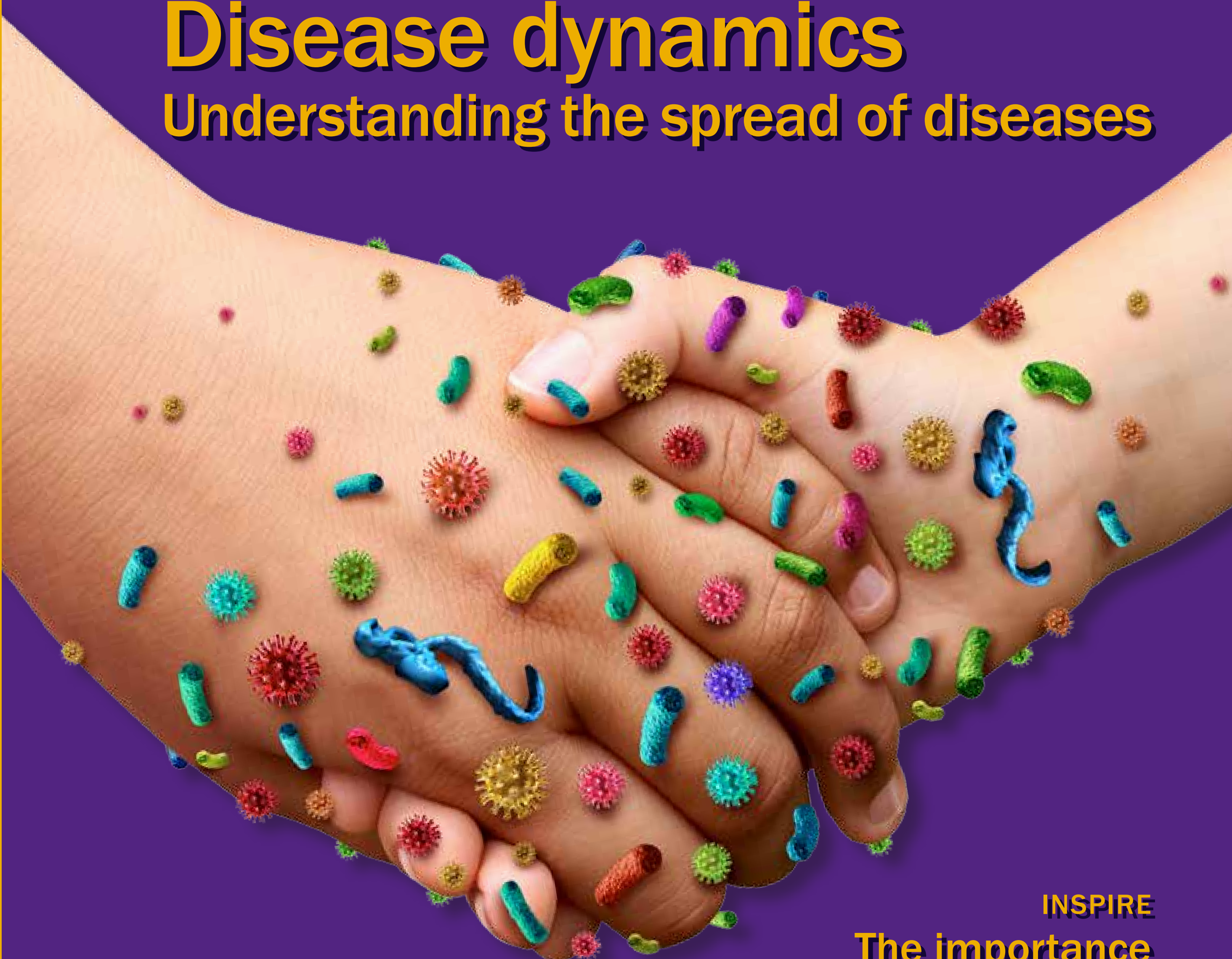
Science in School

The European journal for science teachers

Disease dynamics

Understanding the spread of diseases



INSPIRE

The importance of failure: interview with Paul Nurse

UNDERSTAND

More than meets the eye: the cold and the distant Universe

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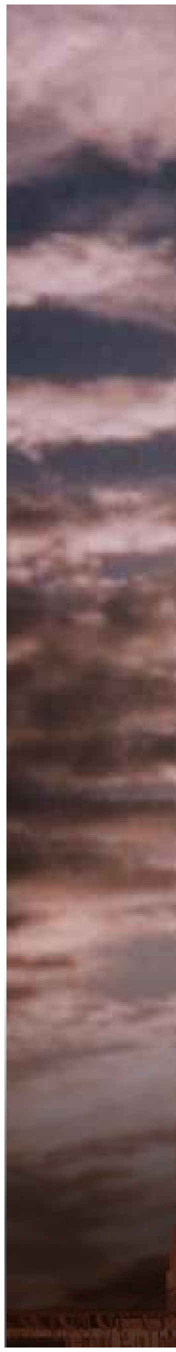


FUSION DRONES: ROBOT TECHNICIANS FOR NUCLEAR DEVICES 8

Repairing a fusion device can be challenging for humans. Drones may be the answer.

THE IMPORTANCE OF FAILURE: INTERVIEW WITH PAUL NURSE 31

Paul Nurse's failed experiment inspired a Nobel-prizewinning career.

Image courtesy of Maxim Maksutov / Shutterstock.com

HEROES AND VILLAINS: THE SCIENCE OF SUPERHEROES 57

Challenge your students to work out which exploits of comic-book heroes like Superman might actually be possible – given a miracle or two.

UNDERSTAND

INSPIRE

TEACH

Image courtesy of Eloy Celaya / © Eloy Celaya

EDITORIAL

Susan Watt
Editor
Science in School
editor@scienceinschool.org

At first glance, you might wonder if this is the horror issue of *Science in School*: with themes including murder, disease and excrement, plus a feature on failure, are we trying to give our readers a gloomy start to the summer holidays? Happily, no: while this may seem a grim selection of topics, all these articles have happy endings of sorts.

In the disease dynamics article (page 52), we look at how a mathematical understanding of the way diseases are spread can help with their control – and classrooms, of course, are a key factor in infection. Our fantasy murder mystery (page 46) gets students using the chemistry of spectra and the physics of sound to solve a crime. And poo (faeces) is now being used medically to beat life-threatening infections (page 23).

Elsewhere, we take another look at the amazing feat of detecting the gravitational waves reaching us from across the Universe (page 26), this time exploring how the necessary sensitivity has been achieved. Further into the fantastical realm, we look at how buildings of the future are being inspired by structures from nature (page 12), and how comic-book superheroes can be the inspiration for some in-depth science – if we allow them a few miracles (page 57).

Finally, what could be more inspiring than the story of a world-famous scientist, and how failing a language exam nearly cost him his career? Nobel prizewinner Sir Paul Nurse meditates on the value of failure on page 37.

This issue also represents a happy ending for me personally. As a long-standing freelance writer and editor for *Science in School*, I'm delighted to have now joined the staff team. And as a parent of a teenager, I'm impressed every day by how imaginative young people are – but also how they sometimes struggle with scientific concepts. So it's a privilege to be working on a publication for science teachers – people who are professionally dedicated to helping today's students to appreciate and succeed at science. After that, we all deserve a holiday.

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

Sentinel satellites, school ambassadors and synchrotron studies of dinosaurs

CERN
Exciting antimatter

Image courtesy of CERN

Jeffrey S Hangst, the current spokesperson for ALPHA from Aarhus University (Denmark), is pictured next to the ALPHA experiment.

ALPHA – a CERN experiment studying antimatter – has recently performed the first-ever measurement on the optical spectrum of an antimatter atom. Although producing antihydrogen atoms – the simplest anti-atom – is a routine job for most experiments at CERN's Antiproton Decelerator, it is no trivial matter to trap them and precisely study their physics behaviour. The high-precision measurement achieved by ALPHA is the result of over 20 years of work by the CERN antimatter community.

To observe the spectral line in an antihydrogen atom, the atoms were held in a specially designed magnetic trap. A laser was used to illuminate the trapped atoms at a precisely tuned frequency to trigger the energy transition inside the anti-atom. Subsequently, scientists measured the energy difference between the ground state and the first excited state of antihydrogen and compared it with that of hydrogen.

Within experimental limits – one part in ten billion (10^{10}) – the result shows no difference and confirms once again the expectations set by the Standard Model of particle physics.

For more details, read the full news article. See: www.cern.ch/about/udates or use the direct link: http://tinyurl.com/z9j2grc

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

EMBL
School ambassador programme

What does it mean to be a scientist? And how do you become one? Presumably, there are as many answers to these questions as there are scientists in the world.

The European Molecular Biology Laboratory (EMBL) school ambassador programme, which has just entered its fifth year, gives school students the chance to meet EMBL researchers and hear their personal science stories. Ambassadors visit schools, usually in their home country, and share their research and experience of working in a scientific environment.

In the past two years alone, the programme, led by EMBL's European Learning Laboratory for the Life Sciences (ELLS), engaged over 1000 students in countries as diverse as Italy, Belarus and Colombia. The ambassadors' profiles are a great tool to showcase career paths, break down stereotypes and highlight the international and interdisciplinary nature of scientific research.

To read the ambassadors' profiles and apply for a school visit, go to the ELLS website. See: http://emblog.embl.de

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

Image courtesy of Robert Slowley Photography

UK high-school students listen to a scientist discussing their research.

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.

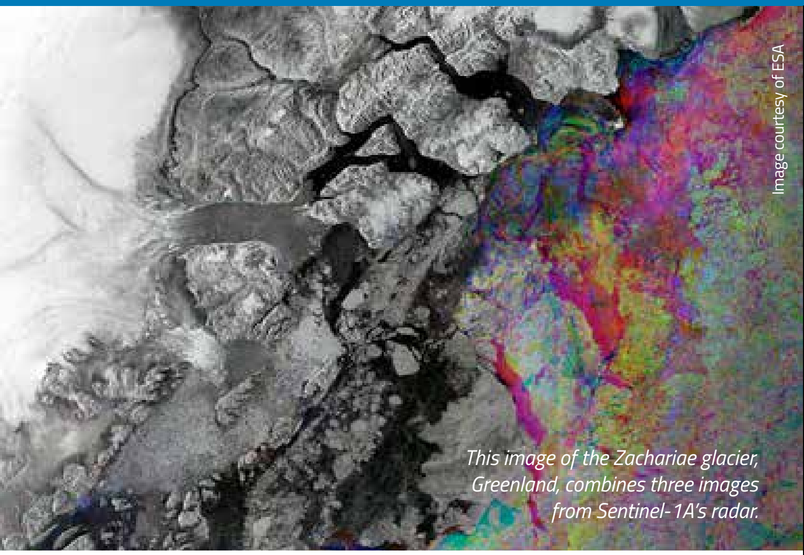


Image courtesy of ESA

This image of the Zachariae glacier, Greenland, combines three images from Sentinel-1A's radar.

ESA
Monitoring our changing world

The European Space Agency (ESA) is building a series of satellites, called the Sentinels, specifically for the European Union's Copernicus programme – the largest environmental monitoring programme in the world.

Using mainly satellite data, Copernicus offers arguably the most comprehensive view we have ever had of our changing world, and provides the information to decide how best to protect it and its citizens. The Sentinels will help provide accurate and timely data, which are central to this ambitious monitoring programme.

To date, five Copernicus Sentinel satellites have been launched. Sentinel-1A and Sentinel-1B carry radar so that they can still measure Earth's surface when it is dark or in bad weather. Sentinel-2A and Sentinel-2B carry high-resolution multispectral cameras to support agricultural improvements, monitor the world's forests, detect pollution in lakes and coastal waters, and contribute to disaster mapping. Sentinel-3A carries a suite of instruments to measure the height and temperature of the sea surface and to monitor seawater quality and pollution. Launched on 7 March 2017, Sentinel-2B is the most recent satellite put into orbit. Next up is Sentinel-5 Precursor, which lifts off in mid-2017 to monitor global air pollution.

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

ESO
Stars born in winds from supermassive black holes

Observations using the European Southern Observatory (ESO)'s Very Large Telescope (VLT) in Chile have revealed stars forming within powerful outflows of material blasted out of supermassive black holes at the cores of galaxies. These are the first confirmed observations of stars forming in this kind of extreme environment. The discovery has many consequences for understanding the properties and evolution of galaxies.

A UK-led group of European astronomers used the MUSE and X-shooter instruments on the VLT to study an ongoing collision between two galaxies, known collectively as IRAS F23128-5919, that lie around 600 million light years from Earth. The group observed the colossal winds of material — or outflows — that originate near the supermassive black hole at the heart of the pair's southern galaxy, and have found the first clear evidence that stars are being born within them.

Such galactic outflows are driven by the huge energy output from the active and turbulent centres of galaxies. Supermassive black holes lurk in the cores of most galaxies, and when they gobble up matter they also heat the surrounding gas and expel it from the host galaxy in powerful dense winds.

The discovery provides new and exciting information that could improve our understanding of some astrophysics, including how certain galaxies obtain their shapes, how intergalactic space becomes enriched with heavy elements and from where unexplained cosmic infrared background radiation may arise.

To read the full news story, visit the ESO website. See: www.eso.org/public/news/eso1710/

ESO is 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

Image courtesy of ESO

Artist's impression of stars born in winds from supermassive black holes

ESRF
How dinosaurs became giants

Thirty dinosaur eggs, one baby and a juvenile of the same species have travelled from their native Argentina to the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, to be studied with powerful X-rays. The goal: to understand more about the development and growth of prosauropod *Mussaurus patagonicus* – a primitive herbivorous dinosaur that lived about 200 million years ago – and find out how dinosaurs evolved to be so large.

It was vertebrate palaeontologist Diego Pol – a researcher at the Argentinian National Scientific and Technical Research Council (CONICET) – who brought the samples to ESRF. He believes that ESRF can provide many answers about the growth of *Mussaurus*, but also of dinosaurs in general. "There has never been such a range of fossils of the same species at different stages, so it is a really unique opportunity", he says.

"When the studies using synchrotron radiation started around a decade ago, it was eye-opening to see all the possibilities for finding out what is inside fossils without destroying them", Diego says. The experiments at ESRF are, for him, "exciting and very promising. It's like a second discovery." After examining all the data collected, scientists hope to unveil the secrets of *Mussaurus* and to explain the mystery of the evolutionary origins of dinosaurs' giant size.

For more details, read the full news article on the ESRF website. See: www.esrf.eu/news or use the direct link: http://tinyurl.com/m7ak8wc

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

Image courtesy of ESRF / C Argoud

The whole skeleton of a baby Mussaurus patagonicus, *roughly 1 month old*

Image courtesy of EUROfusion

Map showing the EUROfusion consortium members. The yellow dots indicate the headquarters of the EUROfusion beneficiaries who signed the grant agreement.

EUROfusion
Hello, Ukraine!

On 1 January 2017, EUROfusion welcomed Ukraine into its family. EUROfusion is the European consortium for the development of fusion energy, and it now has 30 members from 26 European Union countries plus Switzerland and Ukraine. The Ukrainian signatory is the Kharkov Institute for Physics and Technology.

The Ukrainian fusion infrastructure is currently equipped with two fusion devices known as stellarators; these are called Uragan-2M and Uragan-3M. Igor Garkusha, head of the Ukrainian research unit, says that by signing the EUROfusion agreement, Ukrainian researchers will have better participation in European fusion programmes. This includes access to the Joint European Torus (JET), EUROfusion's flagship device in Culham, UK, which is the largest tokamak in the world; and to Wendelstein 7-X, one of the most advanced stellarators, located in Germany.

Professor Garkusha also wants students to benefit from EUROfusion's education and training programmes. "Joining EUROfusion and establishing the Ukrainian research unit is an important milestone for our fusion community and we expect further fruitful work with EUROfusion", he says.

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

European XFEL
First laser light on its way

European XFEL, the world's biggest X-ray laser, is set to deliver its globally unique X-ray laser flashes. The facility, which started commissioning in October 2016, successfully tested its superconducting linear particle accelerator, which energises the electrons from which the X-ray laser flashes are generated. Scientists at European XFEL were able to detect the first X-ray laser light in Spring 2017, showing that the accelerator and undulators are in good working order and well on the way to providing users with the world's best X-ray laser flashes.

Since the beginning of the year, the 1.7 km long accelerator has been working at its operating temperature of 2 Kelvin (-271 °C). At this temperature, its main components – cavities made out of the element niobium – lose their electrical resistance and take on superconducting properties, allowing for highly efficient acceleration of the electrons. Manufacturing, testing, and installing the accelerator was a joint effort between 17 institutes across Europe, led by European XFEL's largest shareholder, DESY (*Deutsches Elektronen-Synchrotron*).

To generate the X-ray laser flashes, the electrons are directed through a special X-ray–generating section of the facility, known as an undulator. Within the 210 m long undulator, alternating magnetic fields make the electrons give up their energy in the form of X-ray flashes. The flashes are then distributed to instruments in the facility's experiment hall, where users perform their work.

Starting in autumn 2017, the flashes will be used by researchers from around the world to study the nature of matter. Until then, European XFEL and DESY scientists will work to ensure that the flashes are consistent and of the highest possible quality for the first users, who submitted their proposals for experiments in March.

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

Image courtesy of DESY

The European XFEL accelerator

ILL
50 years on and still in its prime

The Institut Laue-Langevin (ILL) celebrated its half-centenary on 19 January 2017, with festivities welcoming staff members and external guests, including many prominent personalities. The aim was to organise an event that, while looking back on past achievements, had its eyes firmly fixed on the future.

The institute presented itself in the best possible light, leaving everyone with the firm feeling that neutron science at ILL is in excellent hands and will remain so for many years to come. A special book has been produced to mark the event, retracing ILL's 50 years of service to science and society.

The electronic version of the book can be found on the ILL website. See: www.ill.eu/50yearsbook

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

ILL celebrates 50 years of scientific excellence.

Image courtesy of ILL

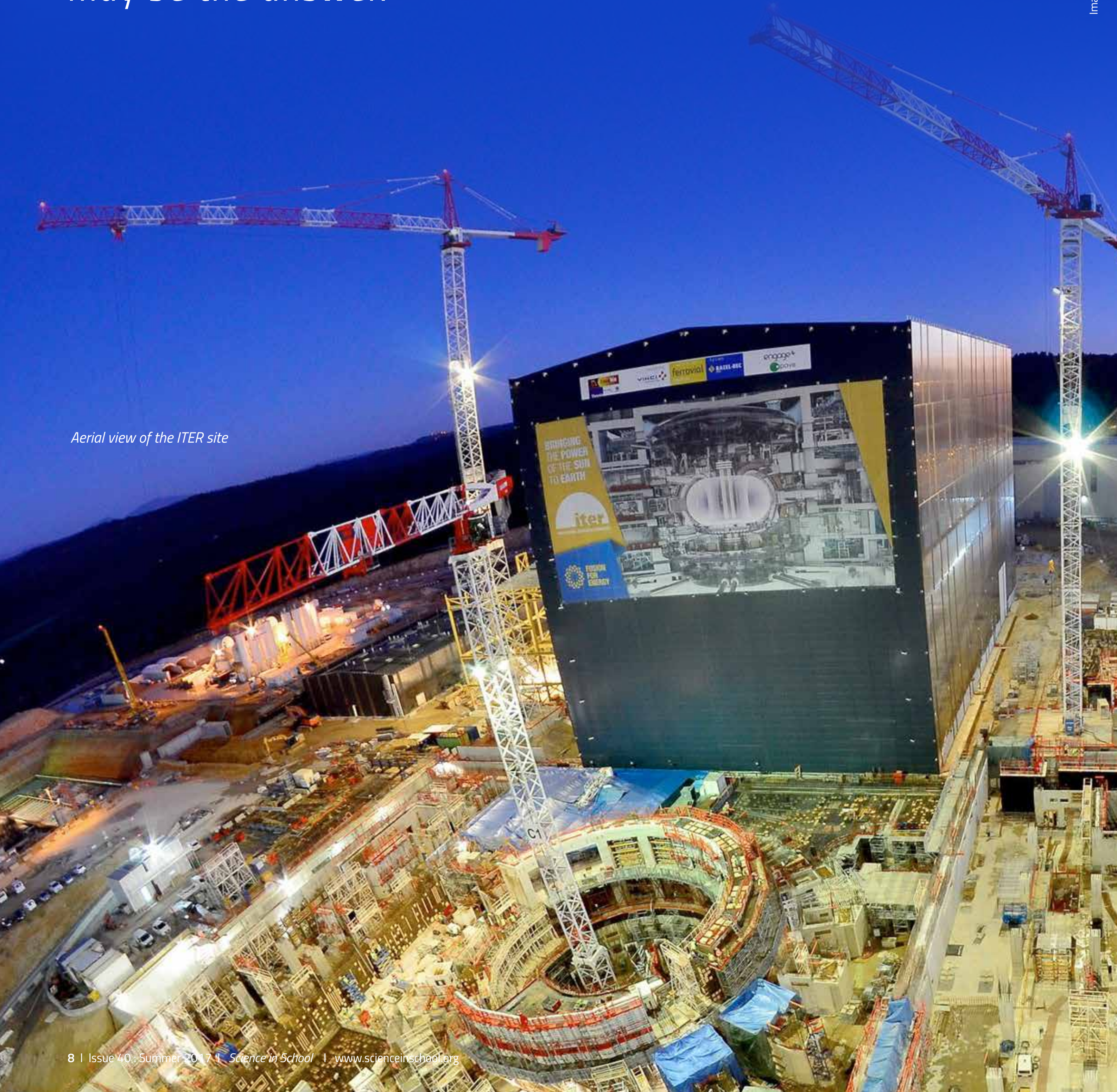
EIROforum combines the resources, facilities and expertise of its member organisations to support European science in reaching its full potential. To learn more, see: www.eiroforum.org

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

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

Fusion drones: technicians for nuclear devices

Repairing a fusion device can be challenging for humans. Drones may be the answer.



Aerial view of the ITER site

Image courtesy of ITER Organization

Public domain image; image source: Pixabay

An unmanned aerial vehicle, commonly known as a drone

By Misha Kidambi

Few places are too dangerous, dirty or difficult to access with unmanned aerial vehicles, known as drones. Resembling mini helicopters, drones were developed primarily for military use, but they soon found their way into civilian environments. Aerial photography, traffic surveillance and environmental monitoring are just a few examples of where drones are already in use, acting as our eyes and ears. Their potential applications are quickly expanding, and, by the looks of it, drones have a bright future in fusion research.

The physics of fusion

Nuclear fusion is the process that powers our Sun and stars. It occurs when atoms of lighter elements, such as hydrogen, fuse to form heavier elements, such as helium, releasing large amounts of energy in the process. Fusion researchers replicate the process here on Earth using fusion devices such as tokamaks and stellarators. The most efficient fusion fuel is a mixture of deuterium and tritium.

Because fusion relies on the nuclei of atoms colliding, the first requirement is to expose the nuclei by removing the atoms' outer layers, their electrons. This is done with heat and electric fields: the atoms get hot and shed their electrons, creating a plasma – a 'soup' of positively charged nuclei and negatively charged electrons. Similarly charged particles repel each other, but this can be overcome by colliding the nuclei at high speed, which is achieved by heating the plasma to more than 100 million degrees Celsius. As the plasma gets hotter, nuclei start to collide at high speeds and a small fraction of them stick together, releasing a large amount of energy.

REVIEW

- ✓ Physics
- ✓ Radioactivity
- ✓ Design technology
- ✓ Ages 14–19

This is an immediately engaging and well-structured article that sparks the imagination and gives a sense of 'anything is possible'. It inspires the reader and makes them consider the future of physics and engineering. The topic of fusion often has limited resources in a school setting, so this article is particularly useful and could be used as a comprehension exercise or within a discussion.

Key areas that could be considered include:

- Relate the conditions for fusion to the difficulty of making a practical and economic form of power station.
- Explain the precautions taken to ensure the safety of people exposed to radiation, including limiting their dose.
- Consider the social-science implications of robots performing large amounts of work currently carried out by humans – particularly the impact this could have on jobs. Students could look at the benefits and drawbacks of increasing autonomy to increase efficiency.
- Design a drone that needs special features to protect it from the high levels of radiation present inside a tokamak.

Seren Essex, Bodmin College, UK

Image courtesy of CCFE

A researcher uses remote handling to control a robotic arm inside the JET tokamak.

A helping hand

Once harnessed, fusion has the potential to provide abundant, carbon dioxide–free energy to the world. But fusion energy is not easy to achieve – fusion devices are complex machines requiring carefully controlled conditions and regular maintenance, with many corners being hard to reach.

The inside of a fusion device is extremely delicate, and the intricate geometry makes it difficult for humans to manoeuvre. Any damage to the device could mean millions of euros worth of repairs and loss of experimental time. For this reason, fusion research is no stranger to remote-controlled technology and robotic devices. The best-known technology in the fusion community is 'remote handling', used at EUROfusion's[w1] JET tokamak, currently the largest fusion device in the world. In remote handling, operators control robotic arms to carry out maintenance tasks inside areas of the tokamak that are difficult or impossible for humans to reach.

Robotic devices are also used outside the fusion reactors. At ITER, the biggest fusion experiment currently under construction in Cadarache, France, drones fitted with real-time 3D mapping technologies give fusion researchers detailed images of the reactors and allow for inspection on site – with the added bonus of taking some beautiful aerial photographs.

Robotic teammates

Antony Loving, head of JET's remote handling group, thinks there is certainly a place for drones in fusion research. "A fusion device has many spaces where access is restricted, either through the complexity of the plant or the environmental conditions", he

Image courtesy of EUROfusion

Interior view of the JET vacuum vessel with remote handling gripper

says. "I could imagine a day when a drone might carry small inspection and maintenance tools to a place of work well inside the fusion tokamak structures and autonomously undertake maintenance tasks."

In fact, a team at the Remote Applications in Challenging Environments Centre (RACE)[w2] at the Culham Centre for Fusion Energy, UK, is doing exactly that. "The primary use of a drone is to put your eyes in the right place – to collect the best possible visual (and other) data without having all the wires", says Rob Buckingham, director of RACE. "But, it's not great if we have to have one drone operator for every drone", he says. And that is why Rob's team is working on developing drones that can operate autonomously. "It seems likely that we will move from remote operations to remote oversight with increasing levels of autonomy being used to improve the efficiency of [future fusion] plants", he says.

Richard Kembleton, EUROfusion's socioeconomic studies coordinator, takes this idea even further. "Drones are only one potential technology for getting into these spaces. Robots that crawl or walk could also be useful." If drones and robots can work together inside a fusion device, we might well see a team of autonomous drone-robot inspectors and maintenance workers.

The grand challenge

The path to using drones inside fusion reactors is not without its challenges. "In normal operation, a power-producing fusion reactor would be too radioactive inside for complex electronics", says Richard. "The aftermath of the [fusion] reaction leaves a gamma-ray 'bath' which fairly rapidly degrades the electronics, such as the ones used in drones." The radioactivity inside a fusion reactor is much less than that of a fission reactor and almost never escapes the fusion vessel, but it is sufficient to destroy the drone inside the vessel. "Current drone technology relies heavily on on-board electronics, which would need to be hardened against radiation", says Antony.

Public domain image; image source: Pixabay

A typical drone used for aerial photography is about 35 cm across.

Image courtesy of ITER Organization / EJF Riche

Aerial view of the ITER site

At RACE, researchers are working on overcoming these obstacles. "One of the things we are doing is working with NIST [the US National Institute for Standards and Technology] on creating standardised tests for robotics. We now have three test environments, including one called 'aviary'. As you can imagine, this one is to test drones", says Rob. "We are expecting to first trial drones in this test area before moving onto the in-vessel test facility, and ultimately in JET itself", he says, but points out that the road to carrying out tests inside the vessel is still long.

"Of course, every drone researcher would love to be the first to fly a drone inside JET", says Rob. "And therein lies another beauty of fusion. Not only will fusion solve humanity's insatiable desire for energy, but we can rightfully claim to be one of the coolest places on the planet to work… robotics and fusion is a pretty exhilarating mix for us nerdy types!"

Web reference

w1 EUROfusion manages and funds European fusion research activities, with the aim to realise fusion electricity by 2050. The consortium comprises 30 members from 26 European Union countries as well as Switzerland and Ukraine. See: www.euro-fusion.org

w2 The Remote Applications in Challenging Environments Centre (RACE) is part of the UK Atomic Energy Authority, which manages the JET fusion project on behalf of the European Union. See: www.race.ukaea.uk

Resources

To learn more about drones and fusion reactors, see the BBC Future article 'The repair crew that can go where no human can'. See: www.bbc.com/future/ or use the direct link: http://tinyurl.com/loutvpf

For an example of two 6 m long robot arms replacing a tile inside a fusion reactor, watch a video from the EUROfusion website. See: www.euro-fusion.org/multimedia/video-gallery or use the direct link: http://tinyurl.com/k7c7fyh

Misha Kidambi is the communications officer for EUROfusion, the European Consortium for the Development of Fusion Energy, which manages and funds European fusion research activities. She completed her master's degree in science and technology journalism at Texas A&M University, USA, and has since worked in communication offices of research organisations. One aspect of her work at EUROfusion is to craft content on fusion research so that the topic is more accessible to non-specialist audiences.

Bionic structures: from stalks to skyscrapers

A blade of grass and a high tower both need to stand up against forces that threaten to level them. Are there design principles that they can exploit to achieve this?

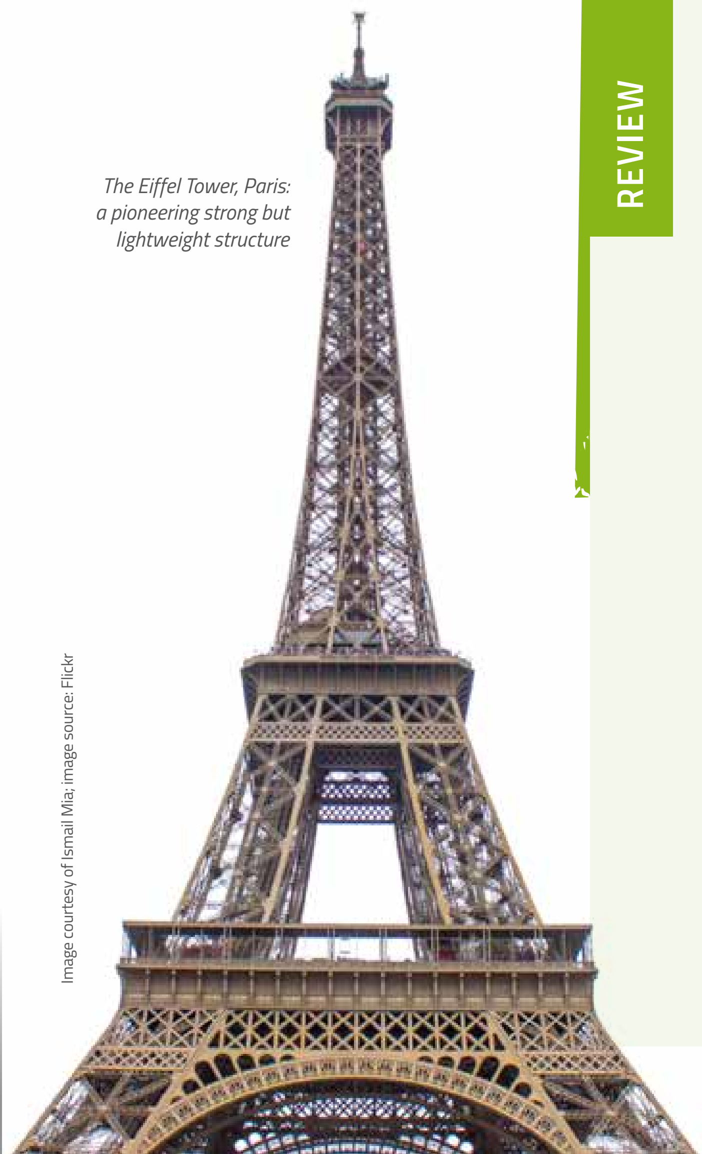
Image courtesy of Grimshaw architects

The proposed Sustainability Pavilion for the 2020 World Expo, Dubai. Inspired by plants in both form and function, the pavilion structure is designed to capture energy from sunlight and water from humid air.

By Claas Wegner, Lea Minnaert, Stephanie Ohlberger and Sabrina Pulka

What does the Eiffel Tower have in common with a stalk of wheat? Not their scale, obviously – but if we look closely at their inner structures, they have a lot in common. Gustave Eiffel's iconic structure, which heralded the new age of iron as a building material, succeeded because he was able to make a structure that was strong yet light. Like the tower, the wheat stalk needs to remain upright despite wind and weather, while using minimal materials. The design solution in each case is the same: the underlying structure is hollow and tubular rather than solid, retaining most of the strength without most of the weight.

Wheat stalks are not unique in providing a clever natural solution to an engineering problem. In fact, this is now an area of technical study with its own name: construction bionics.



The Eiffel Tower, Paris: a pioneering strong but lightweight structure

Image courtesy of Ismail Mia; image source: Flickr

What is construction bionics?

Construction bionics is a branch of the science of bionics. Its main function is to identify structures and processes in biological systems that can be usefully applied to engineering constructions. The aim is to reduce the amount of both materials and energy used, thus creating more sustainable design principles – a very 21st-century ambition.

In construction bionics, lightweight constructions in nature serve as an inspiration for technical solutions. Just as the Eiffel Tower was constructed using the principles of hollow tubes (as are some bones in the human body), biological structures can provide models for the development of new building materials and designs.

REVIEW

- ✓ Biology
- ✓ Physics
- ✓ Botany
- ✓ Engineering
- ✓ Ages: 11 and under, 11–14

What a great way to introduce some cross-curricular ideas and to enthuse students about plant biology and engineering. The idea that buildings of the future may well be inspired by knowledge and understanding of plant structure and function could help to raise the profiles of many science-related studies – from botany to architecture – in the minds of students.

Not only can the article be used for background reading and comprehension exercises, but also the two suggested classroom activities allow students to try out some of the ideas. Neither activity requires much in the way of specialised equipment, but they both give students the opportunity to investigate materials for themselves and practise some elementary construction. The activities could be extended to form longer projects, perhaps for a science fair or STEM (science, technology, engineering and mathematics) investigation.

Questions about the article could include:

- The article explains that construction bionics is a branch of the science of bionics. What other branches of bionics might there be?
- Two examples of the grass family are described in the article, wheat and bamboo.
  - a) Why are members of the grass family particularly useful in construction bionics?
  - b) How many other plants can you name that belong to the grass family?
  - c) Grasses are monocotyledons. What does 'monocotyledon' mean?
- The article suggests that winds could tear apart the materials of a stalk of wheat. What forces might be involved when wind acts on a stalk of wheat?

Dr Sue Howarth

Grass: strength through structure

The grass family (*Poaceae*, formerly *Graminaceae*) has a lot to offer construction bionics, with its long, thin stalks that combine high resistance to bending and breaking with minimal use of material. It's worth taking a closer look at how grasses achieve this.

Viewing a cross-section of a stalk of wheat (*Triticum* spp.) under a microscope reveals the explanation for the mechanical strength of this member of the grass family (Speck & Speck, 2006). An outer layer of hard, lignified (woody) tissue, called the sclerenchyma, is strengthened on the inside by pressure from other tissues, such as vascular tissue and parenchyma (figure 1). The whole structure forms a cylinder, with the strongest tissue on the outside.

But the plant has another secret source of strength: behind the stalk's outer wall is a fibre composite material. Lignified fibres are embedded into the softer, inner tissues, forming a material comparable in structure to reinforced concrete – a composite material made from a concrete matrix streaked with steel reinforcements.

However, this combination of different materials increases the risk that intense forces, such as strong wind, could tear the stalk apart, breaking one layer away from another as the stalk bends. This is why the inner stalk wall is constructed in the form of gradients, in which different properties, such cell size and cell wall thickness, change gradually and merge fluidly into each other, thus making the composite material more stable (figure 1).

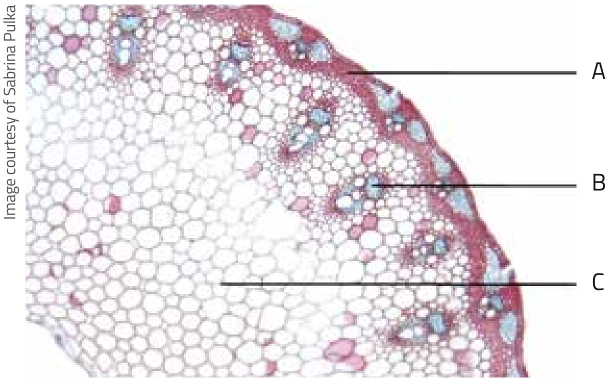


Figure 1: Microscopic image (magnification approx. x 100) of a cross-section of a wheat stalk. A: sclerenchyma; B: vascular tissue; C: parenchyma

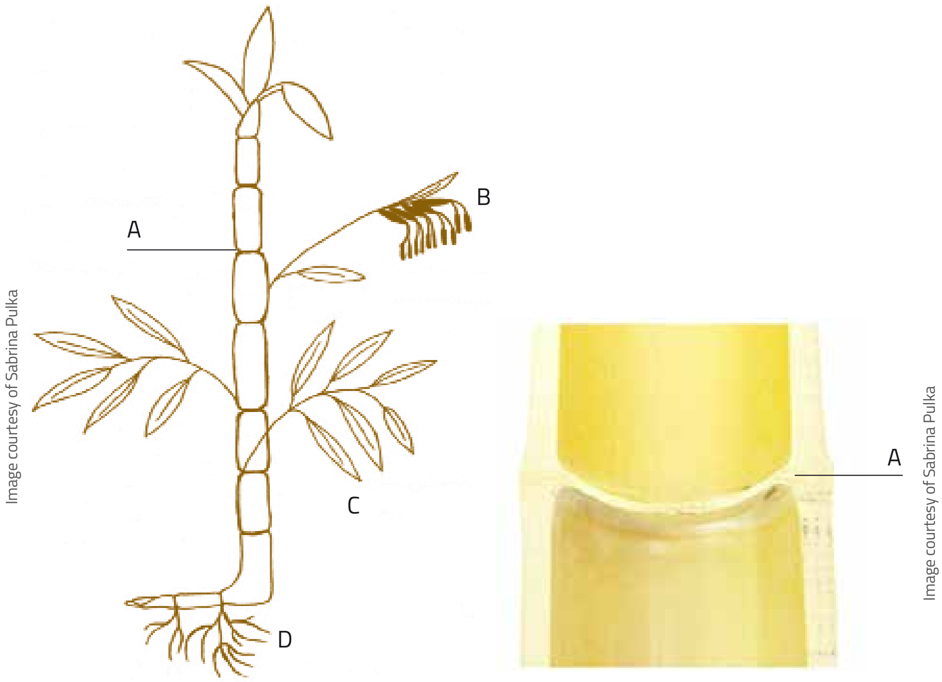


Figure 2: Structure of a bamboo plant (left); longitudinal section through a giant bamboo stalk (right). A: node; B: blossom; C: leaves; D: root

Rope-tied joints in traditional bamboo scaffolding

Bamboo: building with grass

Of course, the grass family member that we most readily think of as useful in construction is bamboo. In Asia, bamboo is often used as a building material or as scaffolding, even for some high-rise buildings, because of its excellent mechanical properties.

Although bamboo plants (*Bambusoideae* subfamily) are grasses, their size is exceptional. Some species, like the giant bamboo (*Dendrocalamus giganteus*), can reach a height of 30 m, growing up to 1 m a day. However, their structure is similar to that of many other plants: they have roots, a stalk, leaves and flowers.

Like other grass plants, bamboo has a hollow cylindrical stalk, with nodes (or knots) along its length (figure 2). The nodes, which divide the stem into segments, consist of thickened walls that extend across the interior of the stem. These strengthen the structure by preventing it from collapsing under a sideways force. If the stem were a completely hollow tube, any lateral pressure would cause it to first become oval-shaped and then to flatten completely; the flattened part could then bend and crease. The nodes provide support against the pressure of the applied force (Mattheck, 2004; Speck & Speck, 2006).

The Shanghai Bionic Tower

One futuristic architecture project that takes inspiration from nature to an extreme point is the proposed 'Bionic Tower' in Shanghai, China. If built, this visionary construction would be the tallest building in the world by far, at 1228 m tall and comprising some 300 floors. The design aims to copy structures found in nature – not only for the tower itself, but also for its foundations. A widespread network of anchorages, imitating tree roots, would replace conventional foundations, with the aim of providing better protection against earthquakes and transverse forces from high winds.

According to the architect Eloy Celaya, the extreme height of the building considers nature in another way: by providing living space for up to 100 000 inhabitants on a compact base area of just 166 m x 133 m, such towers could reduce the amount of land needed to accommodate an increasing world population, potentially allowing more of the world's natural areas to be preserved.

The proposed Bionic Tower in Shanghai, China– a bionic construction of the future?

Image courtesy of Eloy Celaya / © Eloy Celaya

Bionic construction in the classroom

We have devised some classroom activities on construction bionics, which are suitable for late primary-school to early secondary-school students. These experiments help students to discover for themselves the design principles discussed in this article. Worksheets and instructions for teachers can be downloaded from the *Science in School* website[w1].

In the first activity (Testing the stability of bamboo and wood), students compare the strength and rigidity of solid wood and bamboo by loading increasingly heavy weights onto sticks of each material and then measuring their deflection. Students will discover that a hollow bamboo stick deflects less than a solid wooden stick.

In the second activity (Ropes and cylinders), students investigate why bamboo is so strong and rigid by looking at a longitudinal section of a bamboo stick, showing the nodes and internodes. They then investigate how the nodes add strength to the whole stick by using paper strips taped across the inside of a cardboard tube.

These simple demonstrations can be followed up with further research or discussions on construction bionics, perhaps focusing on the fantasy-like Bionic Tower or other futuristic bionic architectural structures.

Image courtesy of Andrew Turner; image source: Flickr

Bamboo scaffolding in use in Hong Kong: combining old and new materials

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Web reference

w1 Download the supporting classroom activities from the *Science in School* website. See: www.scienceinschool.org/2017/issue40/bionics

Resources

Wired magazine has an accessible article on bionic construction. See: www.wired.com/2015/03/empzeal-eiffel-tower/

Take a look at the Bowooss bionics-inspired wooden shell structures built at Saarland University, Germany. See: www.arch2o.com

Find out more about the Shanghai Bionic Tower from the architect, Eloy Celaya. See: www.torrebionica.com

Watch a short video about the proposed Bionic Tower: www.youtube.com/watch?v=lIPfJQ-6iP8

Read about biomimetics – the application of principles in nature to engineering and technology. See:

Vincent J (2007) Is traditional engineering the right system with which to manipulate our world? *Science in School* **4**: 56-60. www.scienceinschool.org/2007/issue4/biomimetics

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For surveys of the history of bionics in architecture and engineering, see:

Nachtigall W, Wisser A (2015) *Bionics by examples: 250 Scenarios from Classical to Modern Times.* Heidelberg, Germany: Springer. ISBN: 9783319058580

Zakharchuk A (2012) Bionics in architecture. *Challenges of Modern Technology* **3**: 50-53.

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More than meets the eye: the cold and the distant Universe

The Orion A star-formation cloud seen by ESA's Herschel Space Observatory

Image courtesy of ESA / Herschel / Ph André, D Polychroni, A Roy, V Könyves, N Schneider for the Gould Belt survey Key Programme

In the fifth and final article in this series on astronomy and the electromagnetic spectrum, find out how scientists use the European Space Agency's missions to observe the sky in far-infrared, sub-millimetre and microwave light.

By Claudia Mignone and Rebecca Barnes

Five thousand light years from Earth lies the coldest object found in the Universe, the Boomerang Nebula – a dying star leaving behind a cloud of gas that is only one degree above 0 K – absolute zero. This cloud, like other cold objects in the Universe, is invisible to the naked eye.

The cooler an object is, the longer the wavelengths of light it emits[w1]. With temperatures of 50 K or less, cool portions of interstellar gas and cosmic dust emit light at far-infrared (25 to 350 μm) and sub-millimetre (350 μm to 1 mm) wavelengths, much longer than our eyes can see. So how do we know that these cold objects exist? To capture the radiation and 'see' the objects in wavelengths beyond the visible range, astronomers use dedicated far-infrared (FIR), sub-millimetre (sub-mm) and microwave telescopes.

This approach comes with challenges: light at these long wavelengths is absorbed by water vapour and other molecules in Earth's atmosphere, which makes observations from the ground extremely difficult and, at FIR wavelengths, simply impossible. For most infrared wavelengths, the atmosphere itself also emits light, adding an unwanted source of noise to the cosmic signals that astronomers are interested in.

To combat these problems, long-wavelength telescopes can be located in dry, high-altitude regions. The world's largest radio astronomy facility – the Atacama Large Millimeter/submillimeter Array (ALMA) – is in the Chilean Andes, for example. At an altitude of 5000 metres, ALMA is one of the highest observatory sites on Earth, studying light from some of the coldest objects in the Universe (as described in Mignone & Pierce-Price, 2010).

The European Space Agency[w2] (ESA) journeyed even higher on 14 May 2009 when they launched two new space observatories. Operating beyond Earth's atmosphere, the Herschel Space Observatory and the Planck satellite studied the cold and the distant Universe. In astronomical terms, looking at distant objects means looking back in time. When a telescope observes a galaxy 100 million light years away, we see the galaxy as it was 100 million years ago when the light was emitted. And because our Universe is expanding, the wavelength of light emitted by distant stars and galaxies

REVIEW

- ✓ Astronomy
- ✓ Physics
- ✓ Ages 14–19

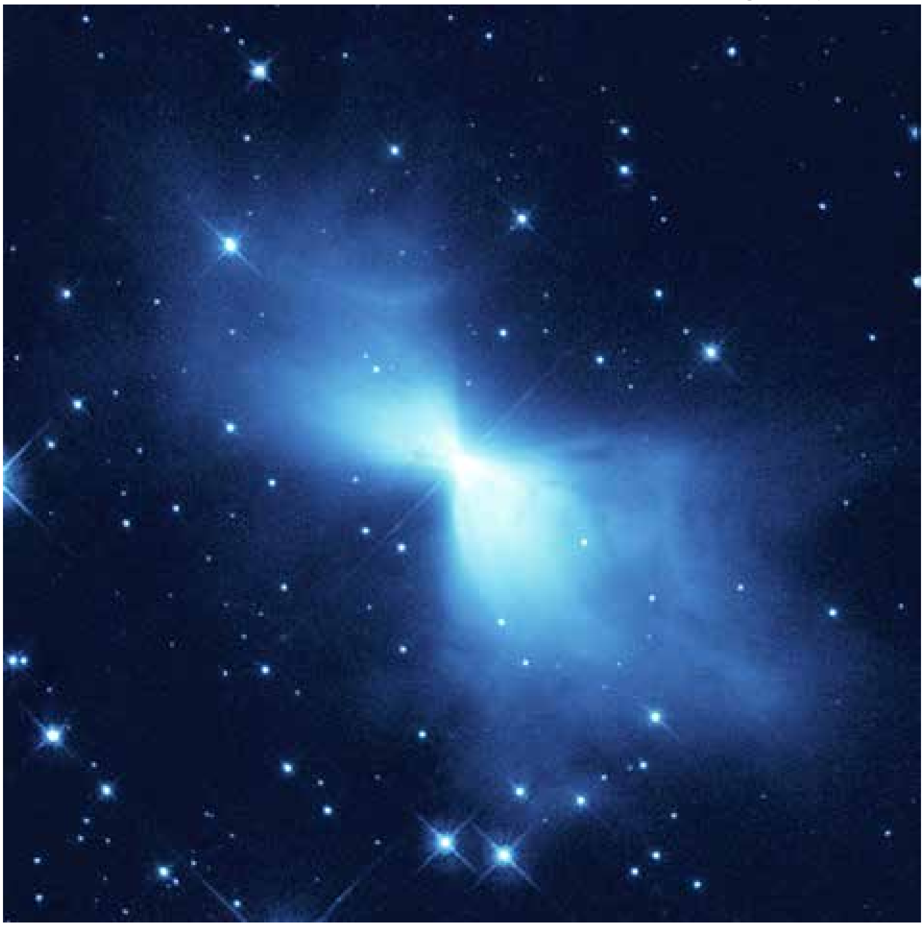
This article demonstrates how astronomers begin to answer the most probing of questions about the origins of the Universe and how stars formed in the early (and aged) Universe.

It could be used to develop discussions based on questions such as:

- How do astronomers use the electromagnetic spectrum?
- What can be gained from studying the cosmic microwave background (CMB)?
- Can the cost of scientific space missions be justified?

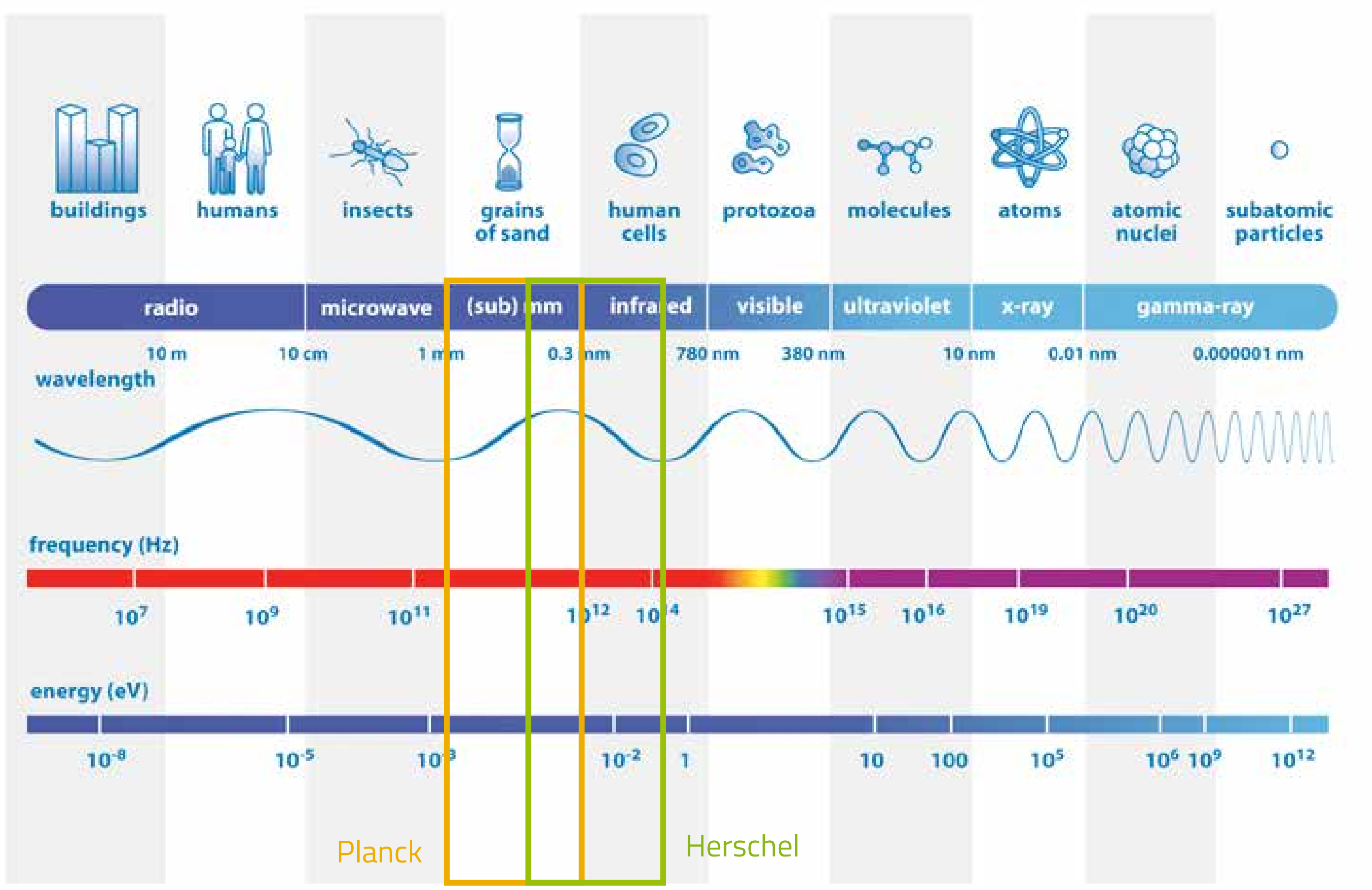
Robert Woodman, Ysgol Bro Gwaun, UK

Image courtesy of ESA / NASA



The Boomerang Nebula is a young planetary nebula and the coldest object found in the Universe so far.

Image courtesy of ESA / AOES Medialab



The electromagnetic spectrum, with an indication of wavelengths, frequencies and energies. The Planck satellite observed wavelengths from 0.3 mm to 1 cm and the Herschel Space Observatory observed wavelengths from 60 µm to 0.6 mm.

is stretched even longer by the time it reaches telescopes on or near Earth – a phenomenon known as redshift[w3].

The Herschel Space Observatory comprised a 3.5 m telescope for FIR and sub-mm observations, and its mission was to study the origin and evolution of stars and galaxies. The Planck satellite's goal, on the other hand, was to study the relic radiation from the Big Bang by surveying the entire sky in sub-mm and microwave wavelengths. Until 2013, when the two missions ended, their observations provided many missing clues for astronomers.

How stars are born

What stands out in observations from long-wave telescopes is the cold mixture of gas and dust that pervades galaxies. This interstellar medium is the raw material from which stars and planets are born: within the densest parts of molecular clouds, gravity causes the gas and dust to contract and fragment, eventually leading to stellar birth.

While fully fledged stars shine most brightly in ultraviolet, visible and near-infrared light (as described in Mignone & Barnes, 2014), the earliest stages in star formation are best revealed in other portions of the electromagnetic spectrum. In particular, individual proto-stars within the Milky Way and in nearby galaxies can be detected at FIR and sub-mm wavelengths.

Observations from the Herschel telescope revealed that the interstellar medium in our galaxy is threaded with filamentary structures of gas and dust on every scale. From nearby clouds hosting

Image courtesy of ESA / S Corvaja

Launch of Planck and Herschel on board an Ariane 5 rocket from Europe's Spaceport in French Guiana

Image courtesy of ESA / Herschel / SPIRE/PACS / D Arzoumanian (CEA Saclay) for the 'Gould Belt survey' Key Programme Consortium

The star-forming region IC 5146, threaded by interstellar filaments. Many pre-stellar cores and proto-stars are found in the densest filaments.

tangles of filaments a few light years long to gigantic structures stretching hundreds of light years across the Milky Way's spiral arms, these structures – only a few of which were known prior to the Herschel mission – appear to be everywhere.

Astronomers now believe that filaments are key to star formation: once the density of interstellar gas and dust in a filament exceeds a critical value, it can become gravitationally unstable, giving rise to denser concentrations of matter that might eventually form stars.

Scanning the entire sky, the Planck satellite detected thousands of cold and dense clumps where stars are born and showed that these clumps are not isolated but appear to be all linked to one other. They form huge filamentary structures across our Milky Way, resembling the smaller filaments detected by the Herschel Space Observatory.

The formation and evolution of galaxies

Observing star-forming regions of the Milky Way provides a window into the processes that give birth to stars closer to Earth now. However, the Herschel mission was also instrumental in investigating the evolution of star formation in galaxies throughout the history of the cosmos.

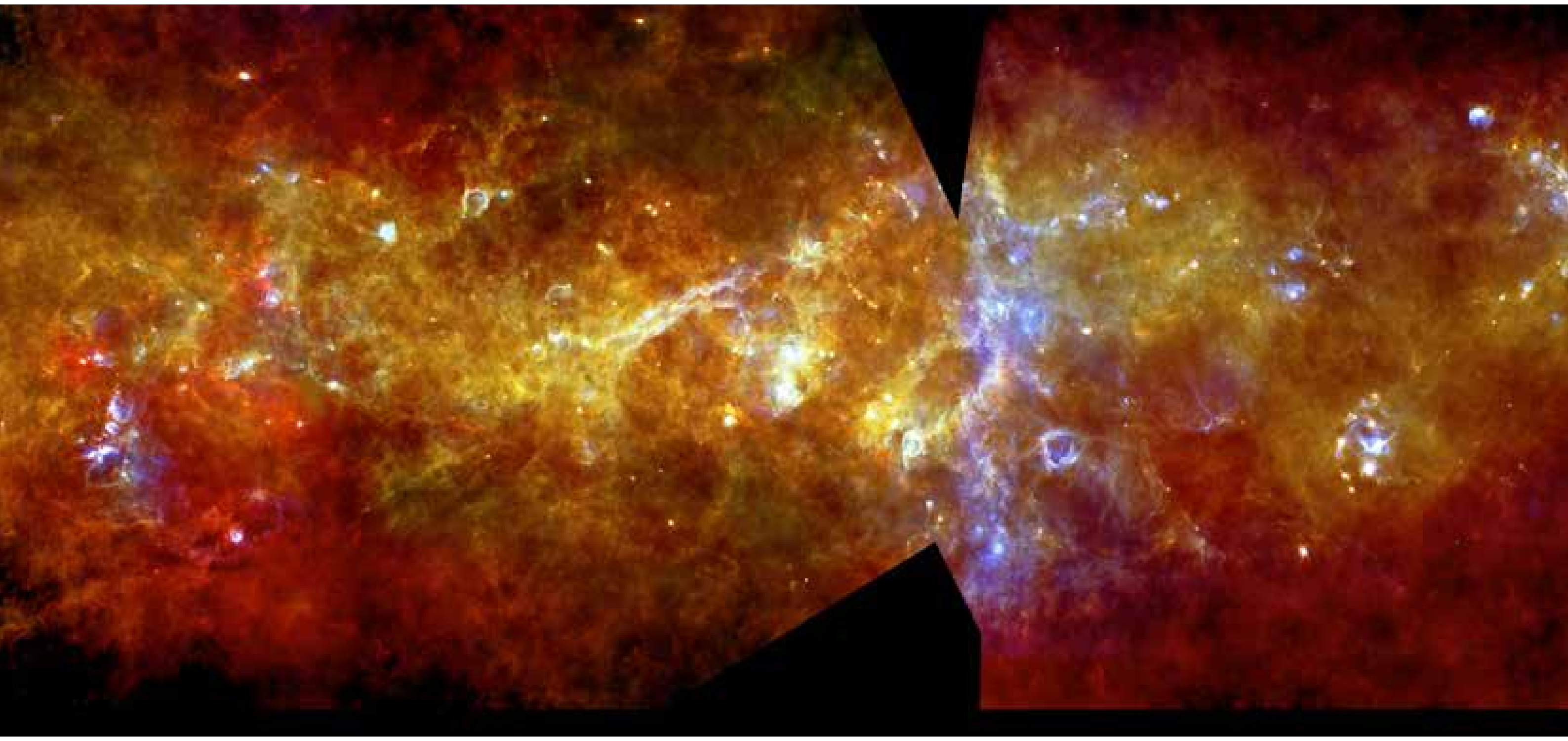
For example, studies based on Herschel observations have indicated that most stars in the history of the Universe have formed quietly in galaxies that are considered 'normal' for the epoch in which we see them, rather than through violent and tumultuous events such as the mergers of galaxies.

Mergers, although spectacular, are relatively rare and of short duration. They have not dominated the cosmic history of star formation for at least the past 10 billion (10^{10}) years. What is crucial for star formation is that galaxies have sufficient gas available to create stars, which could be provided by intergalactic streams of cold gas.

The early Universe

Ultimately, the oldest light in the history of our 13.8 billion-year-old Universe is the cosmic microwave background (CMB) – the remains of thermal radiation from the Big Bang. A fossil from the hot and dense state of the early

Image courtesy of ESA / PACS & SPIRE Consortium / S Molinari, Hi-GAL Project



The filamentary structure of the interstellar medium in the Galactic Plane, where most of the Milky Way's stars are born

Image courtesy of ESA-CNES-Arianespace / Optique Vidéo du CSG

The Herschel spacecraft in the clean room at Europe's Spaceport in Kourou, French Guiana, prior to launch in 2009

Image courtesy of ESA / Thales

The Planck spacecraft. A reflection of the Herschel spacecraft is visible in the telescope mirror.

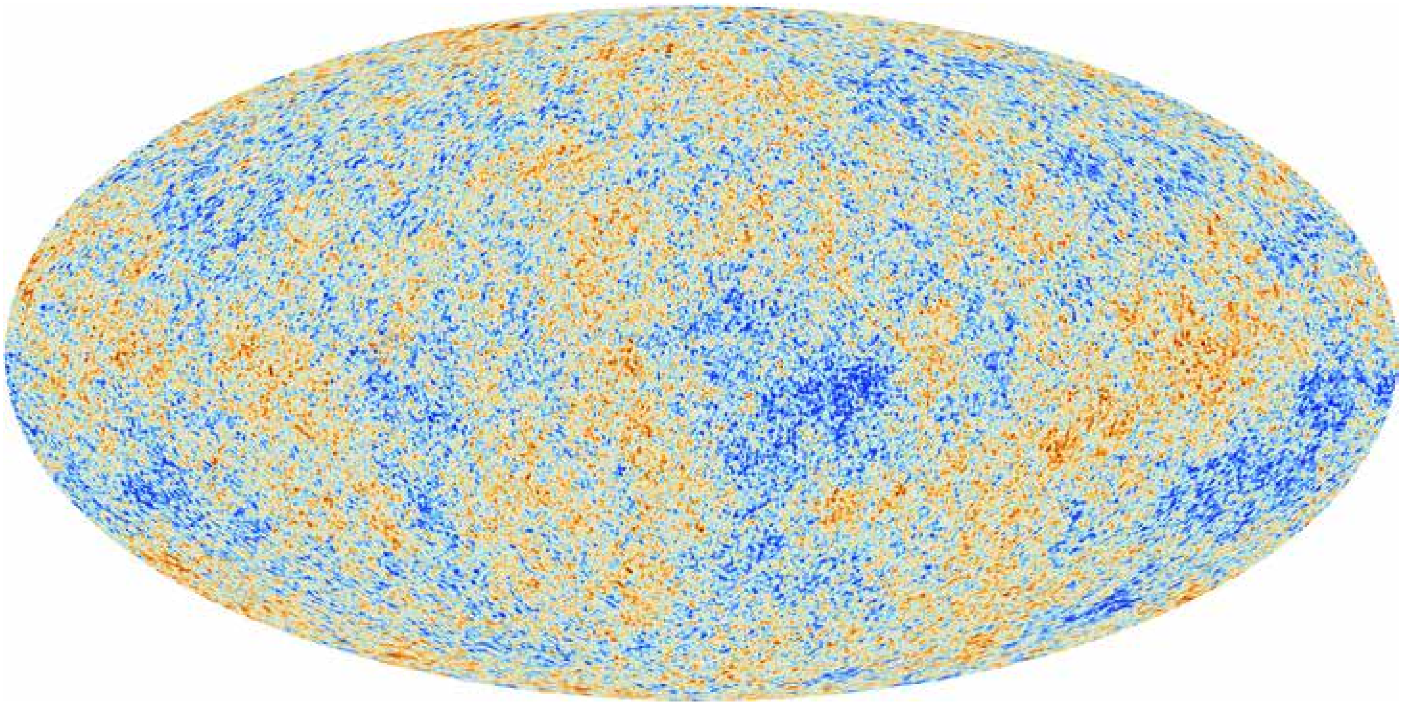
cosmos, the CMB was released only 380 000 years after the Big Bang and is the furthest back in time that we can explore using light. It contains a wealth of information about the formation and evolution of structure in the Universe and can be detected using microwaves.

Planck was the third space mission to survey this relic of the early Universe over the entire sky, after NASA's COBE and WMAP satellites. In unprecedented detail, the Planck satellite mapped the tiny differences in the temperature of the CMB – a mere 0.00001 K plus or minus the background temperature of 2.73 K[w4].

These minuscule fluctuations trace regions of slightly different density in the fluid that filled the early cosmos, before any stars or galaxies had formed. As such, they are the seeds around which all future cosmic structures, including the stars and galaxies of today, would later take shape.

Planck's map is the most precise picture of the early Universe so far, confirming the standard view of the cosmos and allowing astronomers to estimate its age, expansion rate and composition with even greater accuracy.

Image courtesy of ESA / Planck Collaboration



The Planck satellite mapped tiny differences in the temperature of the cosmic microwave background, which represent the seeds of today's stars and galaxies.

Web references

w1 Find out how the wavelength at which a celestial object emits most of its light is related to the object's temperature. See: www.esa.int or use the direct link: http://tinyurl.com/m9hoolq

w2 ESA is Europe's gateway to space, with its headquarters in Paris, France. See: www.esa.int

w3 Read more about redshift and its importance in astronomy. See: www.esa.int or use the direct link: http://tinyurl.com/kbwxhzd

w4 Learn more about the Planck satellite and the cosmic microwave background. See: www.esa.int or use the direct link: http://tinyurl.com/n7lgtno

Resources

To learn more about ESA's Planck and Herschel missions, watch episodes two and three of the Science@ESA vodcasts. See: www.esa.int or use the direct link: http://tinyurl.com/mft2me7

Herschel and Plank were equipped with state-of-the-art refrigeration systems to keep the detectors a few degrees above absolute zero. To read more, see: www.esa.int or use the direct link: http://tinyurl.com/ks5kcn3

Explore the Online Showcase of Herschel Images. See: http://oshi.esa.int/

For more freely available education materials produced by ESA, see: www.esa.int/educationmaterials

To read previous articles in the EM astronomy series, see:

Mignone C, Barnes R (2011) More than meets the eye: the electromagnetic spectrum. *Science in School* **20**: 51–59. www.scienceinschool.org/2011/issue20/em

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Mignone C, Pierce-Price D (2010) The ALMA Observatory: the sky is only one step away. *Science in School* **15**: 44–49. www.scienceinschool.org/2010/issue15/alma

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Manipulating the gut microbiome: the potential of poo

This medical treatment might sound repulsive, but don't pooh-pooh it just yet.

Image courtesy of Big Pants Production / shutterstock.com / Nicola Graf

By Hannah Voak

Faeces, stool, poo – whatever you call it, the thought of transferring someone else's into your own body certainly sounds disgusting. But for someone suffering from a *Clostridium difficile* infection, a potentially fatal bowel condition, a faecal transplant could save their life. So before you dismiss the idea, consider the reasoning behind this unusual medical treatment: stool contains one crucial component – beneficial bacteria. And the success rate for treating *C. difficile* infections with a faecal transplant is over 90%. What's more, scientists at the European Molecular Biology Laboratory[w1] (EMBL) now think that careful matching of donors to patients could make faecal transplants still more effective and widely applicable.

Bacteria and the gut microbiome

When your doctor prescribes antibiotics, you expect the drugs to treat the infection, not to cause a new illness. As well as killing the target bacteria, however, antibiotics (particularly broad-spectrum antibiotics) destroy beneficial bacteria, causing an imbalance in the complex community of micro-organisms in our intestines, known as the gut microbiome.

C. difficile is present in soil, water and air, and lives harmlessly in the guts of roughly one in every 30 healthy adults. But when the normal balance of gut microbes is skewed and there are fewer beneficial bacteria to keep the gut in check, *C. difficile* can quickly spread.

As it multiplies and grows in the gut, *C. difficile* produces toxins that cause diarrhoea. When the bacteria are passed

REVIEW

- ✓ Biology
- ✓ Physiology
- ✓ Medical sciences
- ✓ Microbiology
- ✓ Ecology
- ✓ Ages 16–19

Poo is an amusing subject for students to talk about with friends, and the 'disgusting' topic of faecal transplants is a good introduction to spark their interest in physiology and learn about different metabolic and physiological processes. Not only is this article relevant to medical sciences, but it could also be used to link to topics such as microbiology and ecology.

Bartolome Piza, CC. Pedro Poveda, Balearic Islands, Spain

An expanding colony of the spore-forming bacterium Clostridium difficile

out of the body, they can easily infect other people. This makes *C. difficile* a big problem in hospitals and a major healthcare-associated infection. Other common symptoms include abdominal pain and fever; in severe cases, *C. difficile* can cause dehydration, inflammation of the intestine, and even a ruptured colon.

For most patients, the infection can be treated with a course of antibiotics that specifically target *C. difficile*. But in about 20% of cases, the symptoms return, requiring further treatment. Treating recurrent *C. difficile* is becoming increasingly difficult, as new and resistant strains of the bacterium emerge. One final option for patients fighting the superbug is to undergo a faecal transplant.

Poo to patient

The screening process for potential stool samples is rigorous: only 3% of volunteers donating samples to the OpenBiome stool bank, for example, are accepted[w2]. A stool transplant carries the risk of passing on an infectious disease, and with growing evidence linking the microbiome to obesity, diabetes and allergies, it is possible that these conditions might also be transferred to the patient. In one case, a woman who was successfully treated for a *C. difficile* infection encountered a surprising side-effect after receiving a stool sample from an overweight donor: she rapidly gained weight herself (Alang & Kelly, 2015). Although the transplant may not have been the only cause, the case raises questions about the role of gut bacteria in metabolism and health.

If a stool sample is deemed suitable, it is liquidised and usually administered via a colonoscopy. The community of micro-organisms from the healthy donor, along with all their genes and metabolic functions, can then begin resetting the balance of the infected patient's microbiome.

Although the success rate for curing *C. difficile* infections with faecal transplants is over 90%, the use is still rare – probably due to its unusual nature and our aversion to it. Our faeces, just like blood or vomit, can contain disease-causing organisms, so it's no surprise that humans want to avoid it, let alone ingest it. Tighter rules on carrying out faecal transplants are also holding back its use, as is the treatment's invasiveness compared to antibiotics.

A personalised pill

To improve their appeal, faecal transplants are moving away from, more invasive delivery methods. Instead, patients can swallow something more aesthetically pleasing and manageable: a pill, dubbed a 'crapsule'. A recent study led by EMBL scientists, with collaborators at Wageningen University and the Academic Medical Centre, both in the Netherlands, and the University of Helsinki, Finland, has also highlighted the need for a tailored approach (Li et al., 2016).

Rather than looking at what species of bacteria inhabit a patient's gut, the key is to go one step further and see what strains of each species are present. The study found that new strains of bacteria from the donor were more likely to colonise a patient's gut if the patient

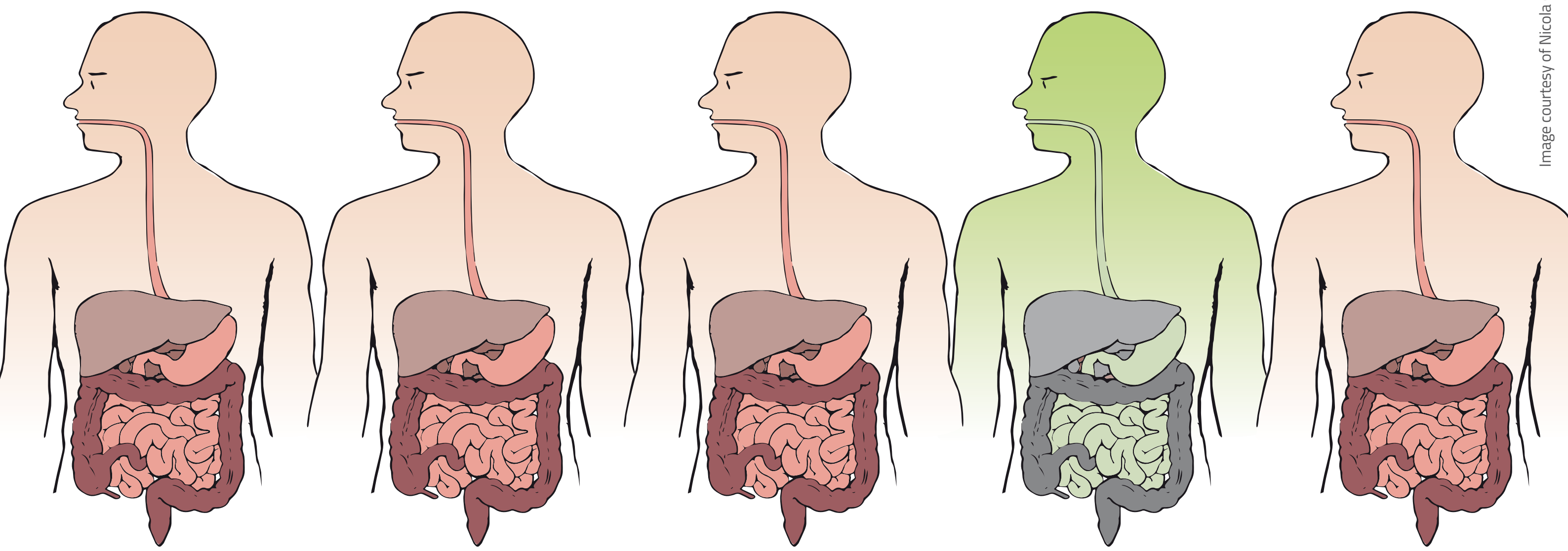
Image courtesy of Nicola Graf

One in every five patients with C. difficile *experiences a recurrence of the infection.*

already had that species. Simone Li, who carried out the work at EMBL, says the goal is to prescribe a "personalised bacterial cocktail, rather than a one-size-fits-all solution". Carefully matching donors to patients could improve the effectiveness of faecal transplants.

The demand for faecal transplants doesn't stop there. Scientists are trying to determine whether transplants could be used to treat other common conditions linked to a skewed microbiome, including allergies, obesity and type 2 diabetes (Bull & Plummer, 2014). And who knows? In the future, we could all be storing healthy poo for later use, and swallowing pills of frozen faecal matter from our personal stool banks.

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Web reference

w1 EMBL is Europe's leading laboratory for basic research in molecular biology, with its headquarters in Heidelberg, Germany. See: www.embl.org

w2 OpenBiome is a non-profit organisation dedicated to expanding safe access to faecal transplants. See: www.openbiome.org/impact/

Resources

Read more about the recent study on improving faecal transplants with a personalised approach on the EMBL news page. See: https://news.embl.de/science/1604-poo-transplants/

For more information on faecal transplantation, visit the Johns Hopkins Medicine website. See: www.hopkinsmedicine.org or use the direct link: http://tinyurl.com/kk9um5g

To learn more about faecal transplants, read the article 'Medicine's dirty secret' published in *Mosaic* magazine. See: www.mosaicscience.com/story/medicine's-dirty-secret

German scientist and best-selling author Guilia Enders reveals the latest science on our digestive system, including our gut bacteria, in her book *Gut*. See:

Enders G (2015) *Gut* 1st edition. Vancouver, Canada: Greystone Books. ISBN: 978-1771641494

To understand humans' dislike towards poo, read the article 'Why do humans hate poo so much?' from BBC Future. See: www.bbc.com/future or use the direct link: http://tinyurl.com/lpqrjxp

Hannah Voak is one of the editors of *Science in School*. With a bachelor's degree in biology and an enthusiasm for science communication, she moved to Germany in 2016 to join *Science in School* at the European Molecular Biology Laboratory.


Image courtesy of Ivaschenko Roman / shutterstock.com

Good vibrations: how to catch a gravitational wave

Artist's impression of two black holes as they spiral towards each other before merging, releasing gravitational waves

Image courtesy of ESA / C Carreau

Gravitational waves are among the most subtle messengers that reach us across the cosmos. But how can their infinitesimal effects be detected?

By Nicolas Arnaud

In 2015, the fantastically faint signals from gravitational waves crossing the cosmos were finally detected. Predicted a century ago by Albert Einstein, this first detection of gravitational waves marked the culmination of decades of experimental and theoretical work – and also the beginning of an exciting new era in cosmology.

So what are gravitational waves, and why was detecting them such a huge challenge? Gravitational waves are ripples in space-time caused when a mass accelerates. In effect, they are the gravitational equivalent of electromagnetic waves – and, like these, they travel at the speed of light.

The reason these elusive signals are so hard to detect is because their effects are so very, very slight: just a tiny distortion in space-time, even when the event producing them is as vast as the collision of two (distant) black holes, as was the case with the 2015 detections. This distortion means that the distance between two points on Earth will be stretched or squeezed by an absolutely tiny fraction when a gravitational wave passes by. And here, 'tiny' means by a

REVIEW

✓ Astronomy/space

✓ Physics

✓ Ages 16–19

This article describes the function of gravitational wave detectors – huge but very sensitive machines that students may find very interesting. The details of how these machines work, and the problems that had to be solved to achieve their high sensitivity, are described in a very understandable way by the author, who is a gravitational wave scientist.

Comprehension questions could include:

- What are gravitational waves?
- Why is it so difficult to detect gravitational waves?
- How do gravitational detectors work?
- Gravitational wave detectors are very sensitive sensors. Why are these machines so large?
- Building gravitational wave detectors is a real challenge. Describe the major difficulties and how they can be solved.

Gerd Vogt, Higher Secondary School for Environment and Economics, Austria factor of 10^{-21} (one thousand billion billionth) – roughly the diameter of an atom compared to the distance between Earth and the Sun: certainly quite a challenge to measure!

Since the early 1960s, physicists, engineers and technicians from all over the world have risen to this challenge, resulting in a handful of giant instruments dedicated to detecting gravitational waves, including LIGO[w1], Virgo[w2] and GEO600[w3]. In this article, we focus on the Virgo instrument (located in Italy), but the concepts apply equally to the other detectors – all of which are part of an international network that is much more powerful than any individual detector alone. In fact, the analysis of the 2015 data comprising the first detections was carried out jointly by LIGO and Virgo scientists, working in collaboration.

Image courtesy of Nicola Baldocchi / The Virgo Collaboration

Aerial view of the Virgo detector located near Pisa, Italy. Each 'arm' is 3 km long.

Measuring with light

Virgo's design is based on a device called a Michelson interferometer, which itself has a remarkable pedigree: it was first used in 1887 by physicists Albert Michelson and Edward Morley in a famous experiment to look for variations in the speed of light caused by the hypothetical ether (figure 1).

Here, light from a single source is split into two beams that travel out along perpendicular paths (or 'arms') and are then reflected back by mirrors so that they ultimately recombine. If there is a change in the length of one beam's path (as would be caused by a passing gravitational wave), this will very slightly change its travel time, and thus also cause a phase shift of one beam relative to the other. This phase shift affects how the two beams will interact when they meet on their return, which in turn affects the power measured at the detector output.

But even with this classic design combined with modern technology, the experimental challenges of detecting gravitational waves are very considerable.

Image courtesy of LIGO / T Pyle

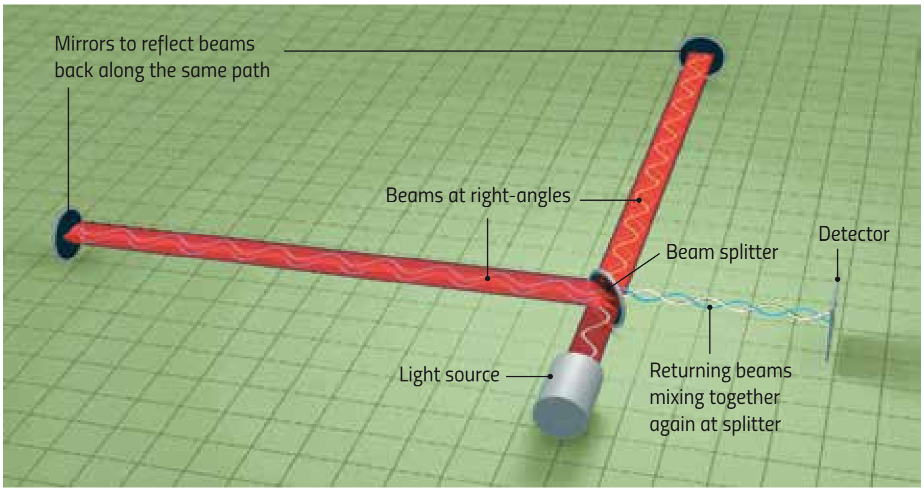


Figure 1: Michelson interferometer – the basic design of the Virgo detector

Virgo: overcoming the challenges

In Virgo, the basic design of the Michelson interferometer has been made much more complex – and bigger – because of the extreme stability and precision needed.

Long arms

Each arm of the Virgo detector is 3 km long. This large size is needed because the extremely small change in the beams' travel time, caused by a gravitational wave, increases with the arm length. Lengths beyond 3 km are not really feasible; one reason is that the Earth's curvature would then become a factor in building perfectly straight arms.

To prevent interactions between the beams' photons and gas molecules, the interior of the arms is evacuated to about one thousandth of a billionth (10^{-12}) of atmospheric pressure, similar to the pressure in space at the altitude of the International Space Station. This makes the Virgo tubes the largest ultrahigh-vacuum volume in Europe (see figure 2). At the end of each arm, the wall of the tube is cooled to cryogenic temperatures by liquid nitrogen to trap residual molecules (e.g. water).

Image courtesy of Cyril Fresillon / Virgo / CNRS Photothèque

Figure 2: Inside one of Virgo's arm tunnels, showing the vacuum tube

Mirrors, mirrors

The mirrors in Virgo are a key component of the detector. They are made with the utmost precision: their surfaces are polished to be perfectly flat (to the nearest nanometer), and special coatings optimise the way the mirrors reflect and transmit light, keeping losses from the beams to a minimum (around a few parts per million). The mirror arrangement is much more complicated than in a simple Michelson interferometer, with mirrors used to form additional 'optical cavities' through which the beam travels, or to 'clean' the laser beam (see figure 3).

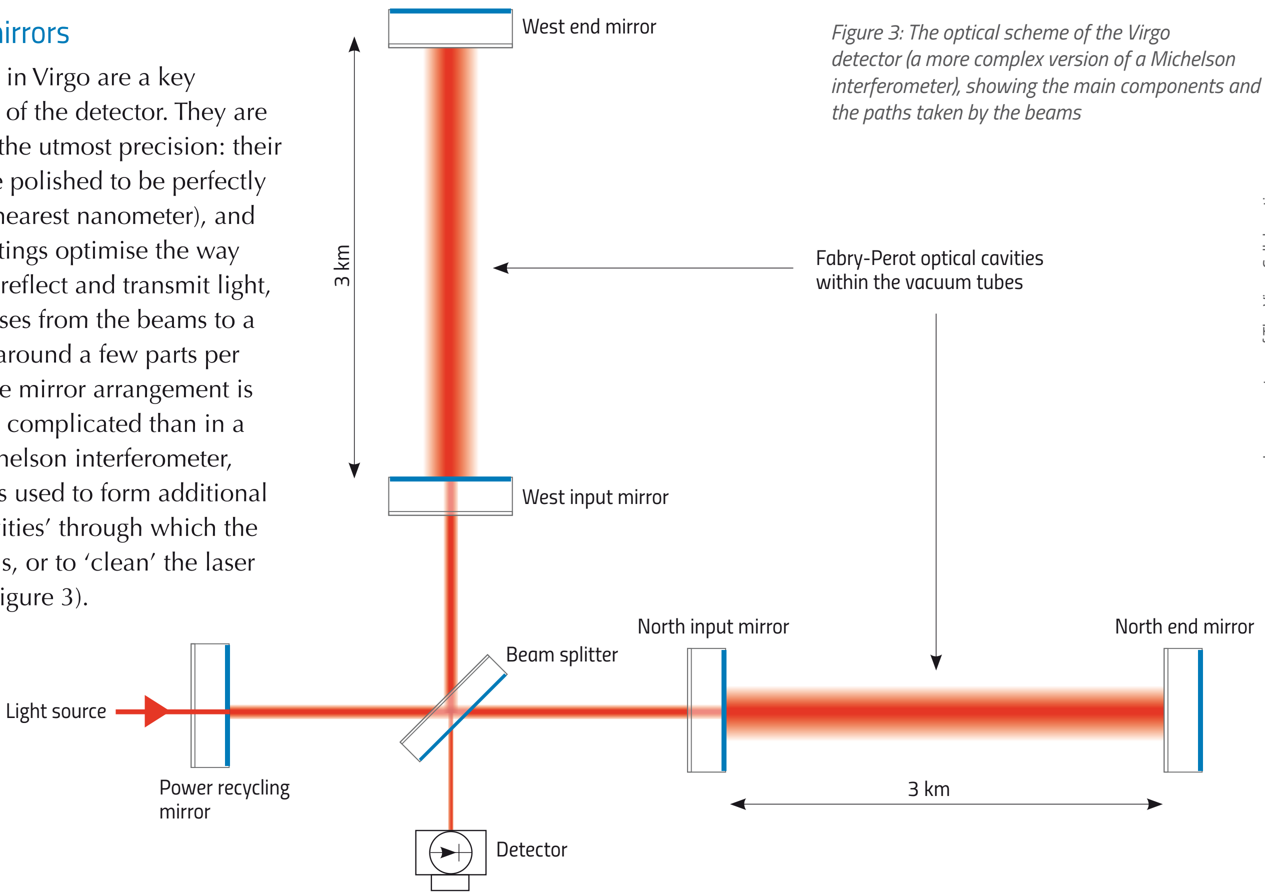


Figure 3: The optical scheme of the Virgo detector (a more complex version of a Michelson interferometer), showing the main components and the paths taken by the beams

Image courtesy of The Virgo Collaboration

Virgo's mirrors also play a trick to make the beam paths seem longer than they are: a device called a Fabry-Perot optical cavity installed in each arm increases the path length by a factor of around 300, increasing the beams' travel time – and thus the sensitivity of the whole detector – by a similar factor.

Vibration isolation

Virgo needs to be sensitive to the very small changes in the lengths of the beam paths induced by gravitational waves, so it needs to be isolated as much as possible from other disturbances in the environment – human activities, wind, storms, and so on. While the detector's design aims to shield it from such disturbances, one of the biggest problems is that the mirrors (which reflect the laser beams) are attached to the ground, which moves all the time – too slightly for us to feel, but by far more than the changes due to gravitational waves.

This means that the mirrors must be isolated from the ground – a feat achieved in Virgo by suspending each mirror at the end of a chain of pendulums called 'super-attenuators', which make its suspended mirrors some of the most motionless objects on the planet (see figure 4). But how does suspending an object isolate it from vibrations?

Every simple pendulum has its own natural or 'resonance' frequency – the frequency at which it will swing if just given a push. If we shake the top of the pendulum at a frequency lower than the resonance frequency, the end of the pendulum will move. But if the input motion is at a frequency higher than the resonance, the lower end will remain almost still. In Virgo, the pendulums supporting the mirrors have resonance frequencies that are as low as possible (a few hertz). This means that they are essentially undisturbed by movements at higher frequencies, allowing gravitational waves of frequencies above a few tens of hertz to be detected.

Maintaining precision

To be sensitive to gravitational waves whenever one might arrive, Virgo must be constantly maintained in a very precisely controlled working state. For example, the laser beam (an infrared laser with a wavelength of 1064 nm) must be kept ultra-stable to maintain a constant power level at the detector output. The laser's frequency must also be stabilised so that it varies less than one part in 10^{14}.

Probes located all along the Virgo apparatus continuously monitor its status and allow optical cavity lengths to be controlled at the femtometre (10^{-15} m) level, while mirror-angle misalignments are kept to within a few nanoradians (less than a millionth of a degree). In addition, thousands of probes constantly monitor Virgo's environment and status, providing data to be checked as soon as a potential gravitational wave signal is observed.

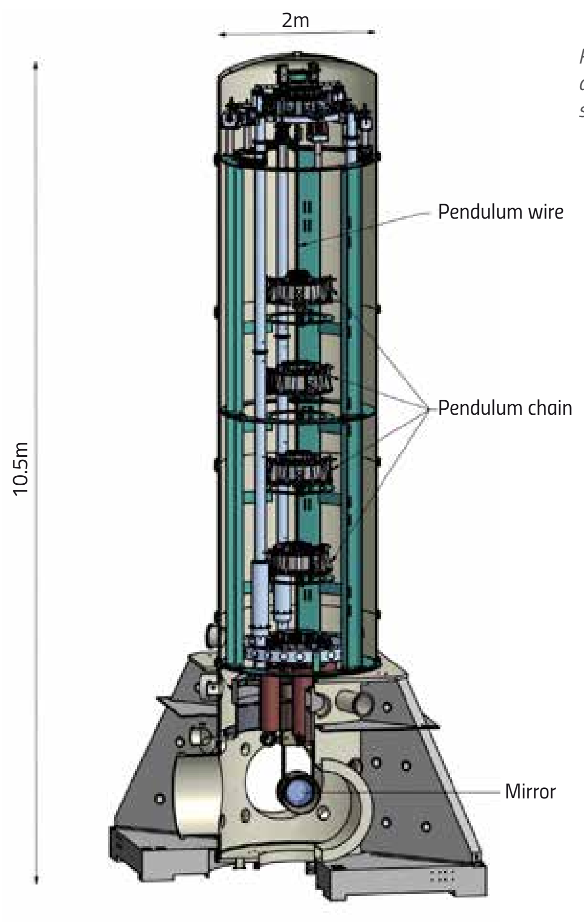


Figure 4: A Virgo 'super-attenuator': a cascade of pendulums for stabilising a mirror

Finding out more

There is much more to explain about the Virgo experiment – for example, how is the data analysed to find out if a gravitational wave has really been detected? If you would like to know more, please visit our website[w2] or read the recent article in *Science in School* that describes how gravitational waves were first detected (Kwon, 2017) – and the discoveries that this new ability could bring to astrophysics.

Acknowledgement

The author would like to thank Dan Hoak (European Gravitational Observatory) for his help in preparing this article.

Reference

For an earlier article in *Science in School* about detecting gravitational waves, see:
Kwon D (2017) *Turning on the cosmic microphone.* **39:** 8-11. www.scienceinschool.org/content/turning-cosmic-microphone

Web references

w1 The Laser Interferometer Gravitational-Wave Observatory (LIGO) is based in California, USA. See: www.ligo.caltech.edu

w2 Find out more information on Virgo from the website. See: http://public.virgo-gw.eu

w3 GEO600 is a ground-based interferometric gravitational wave detector located near Hannover, Germany. See: www.geo600.org

Resources

To find out how the Virgo detector works, watch this short animation: www.youtube.com/watch?v=6raomYIl9P4

Watch the press conference announcing the first gravitational wave detections: www.ligo.caltech.edu/detection

Learn more about LIGO Open Science Center, including data from the 2015 detections. See: https://losc.ligo.org/about

The LIGO-Virgo collaboration has its own YouTube channel featuring talks, lectures and explainer videos. See: www.youtube.com or use the direct link: https://tinyurl.com/kobzsbf

Find out more about gravitation and gravitational waves from an animation and comic in several languages, made by PhD Comics. See: www.phdcomics.com/comics.php?f=1853

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

The importance of failure: interview with Paul Nurse

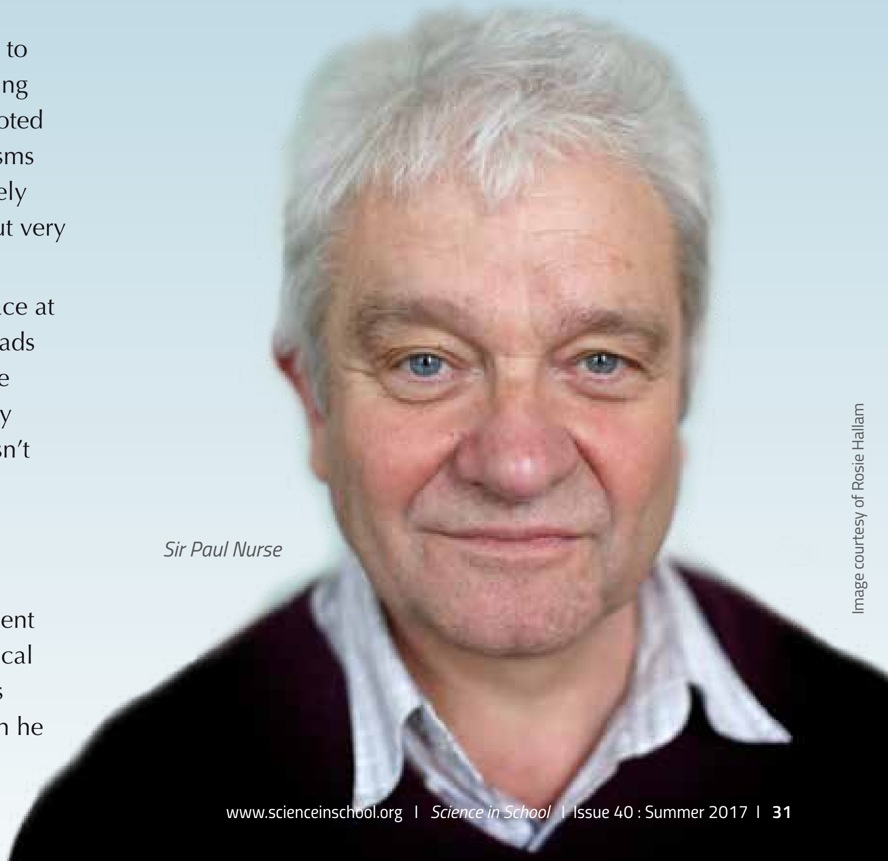
Image courtesy of Jirsak / Shutterstock.com

Paul Nurse's failed experiment inspired a Nobel-prizewinning career.

By Adam Gristwood

When Paul Nurse was a student in the 1960s, scientists knew that cells divide and make copies of themselves. Yet key questions remained a mystery: what drives cells to divide? What controls these divisions? How is the copying of DNA initiated? Gripped by these puzzles, Nurse devoted a large part of his career to identifying crucial mechanisms underlying the cell division process – work that ultimately won him a Nobel Prize. Yet things could have turned out very differently.

"I had very good grades in school and was offered a place at every university I applied for", says Nurse, who now heads the Francis Crick Institute in London, UK. "However, the offers were conditional on me passing a very elementary French exam, and I failed it six times – it's not like I wasn't trying, but I am completely incompetent at languages."



Sir Paul Nurse

Image courtesy of Rosie Hallam

Against the odds

Still struggling with his French, Nurse left school and spent time working as a technician in a laboratory run by a local Guinness brewery. Each week he quickly completed his work, leaving plenty of time for research projects, which he loved. But despite repeated attempts, he just could not pass the French exam. It took a chance encounter with genetics professor John Jinks to ignite Nurse's scientific career. Jinks recognised his potential and arranged for him to enrol as a biology student at Birmingham University, UK. "There was a sting in the tail because the university insisted I study French in my first year!" Nurse recalls.

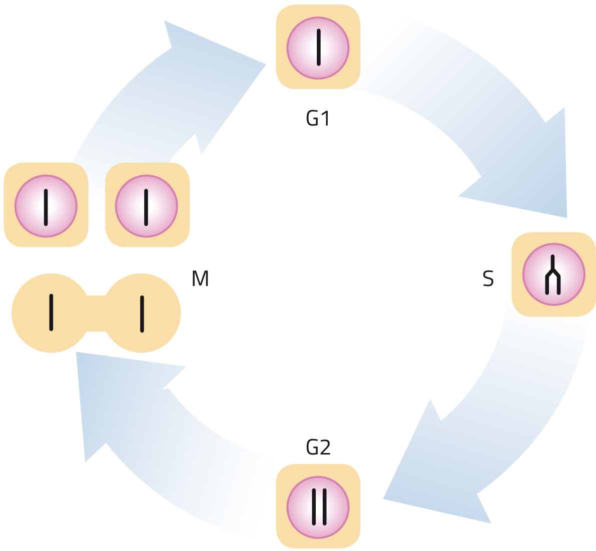
More hurdles followed. "I was initially interested in ecology, but a field trip collecting specimens in freezing waters taught me I was better suited to the warmer environment of the lab", Nurse says. It was there, under the guidance of an eccentric zoology lecturer, Jack Cohen, that he undertook a project measuring the respiration rate of dividing fish eggs.

"Cell division is the basis of all growth and development – I was immediately fascinated by it", Nurse recalls. Over the course of the following months, he carefully collected eggs from the university aquarium, placing samples in a sealed chamber. He then measured ambient oxygen levels, painstakingly observing the effects of different inhibitors. "I soon saw that the respiration rate oscillated every fifteen minutes or so, which is also roughly the time needed for the fish eggs to divide", he says. "Strangely this pattern persisted no matter what I did to the system – it seemed incredibly robust."

Yet a week before Nurse was due to hand in the work, a seemingly routine control test left him stunned. "I ran the experiment with no eggs in the chamber and I measured the same, perfect, oscillation", he says. "I repeated the experiment again and again, convinced there must be a mistake. But I eventually realised that rather than measuring the respiration rate of the eggs, all the time I had been monitoring the effects of a thermostat in my apparatus. It was a complete failure from beginning to end."

With his grades at stake and just one week to go before presenting the study, Nurse faced a big problem. "The only thing that I could think of to salvage

Image courtesy of Nicola Graf



Nurse, Hunt and Hartwell used genetic and molecular biology methods to discover the mechanisms that control the different phases of the cell cycle. G1 (gap 1 growth phase): the cell grows; S (synthesis phase): chromosomes are duplicated in DNA synthesis; G2 (gap 2 growth phase): cell prepares for division; M (mitotic phase): chromosomes are separated in mitosis and segregated to the daughter cells.

my degree was a piece of theatre", he recalls. "In my presentation I re-lived the whole study, from its exciting beginnings to its disastrous ending – and somehow the audience was impressed. One key message was: do controls early on in your study as soon as it becomes interesting!"

Keep going

"At my low points, I contemplated alternative careers," he says, "but I am very much an experimentalist at heart and I have been lucky over the course of my career to have had very supportive colleagues." Ultimately undeterred, Nurse successfully completed his degree and PhD. As a postdoc, he saw the cell cycle as a way to learn more about what fascinated him most: the nature of life. "The cell is the simplest thing that demonstrates life", he says. "Key to understanding that is knowing how information is managed in the cell to generate order in space and time."

Inspired by studies showing how genetics could be used to study the budding yeast cycle, Nurse returned to a research subject that he had first encountered when working in the Guinness laboratory: brewer's yeast. "I wanted a model organism that would be simple and effective", he recalls. He led work that treated yeast in a way that induced mutations randomly in genes throughout the yeast genome.

Nurse figured that the key to identifying genes controlling cell division in yeast would come from studying cells that divide particularly slowly (creating bigger cells) or particularly quickly (creating smaller cells). The second category was discovered by chance when Nurse observed some unusually small cells that divided more rapidly before they could grow. He identified a mutation in a gene called cdc2 that appeared to play a role in initiating key stages of the cell division cycle. "Sometimes nature provides the best leads", he says.

After discovering that a cdc2-like gene was also in another type of yeast, Nurse wondered if the gene might exist in all organisms – a question he began to tackle at the UK's Imperial Cancer Research Fund laboratories in 1984. "There were a few eyebrows raised as to what exactly a yeast researcher was doing at a cancer research centre", he says. His team took a human gene library and added it to yeast lacking the cdc2 gene. Incredibly, after one of the human genes was added to the yeast, the cells divided as normal. This observation enabled Nurse to draw the astounding conclusion that a fundamental engine driving the cell cycle was the same in all species, a mechanism that had traversed 1–1.5 billion years of evolution.

The work led to the discovery, with friend and colleague Tim Hunt, of cellular messenger molecules called cyclin-dependent protein kinases – cellular messengers that pass on signals – and other insights into the nature of the cell cycle, all crucial for understanding health and disease. In 2001, Nurse, Hunt and Leland H Hartwell were awarded the Nobel Prize in Physiology or Medicine for their discoveries of key regulators of the cell cycle[w1].

"It is important to know the real stories behind science and the failures and successes that are part and parcel of our work to inspire the next generation of scientists", Nurse adds. "There is still a lot we don't know about how cells organise in space and time, but I think we will make real progress in the coming half-century because of the methodologies that we have developed in the past five decades. And, of course – as I learned from my fruitless experiments on fish egg respiration – from the countless failures we have made along the way."

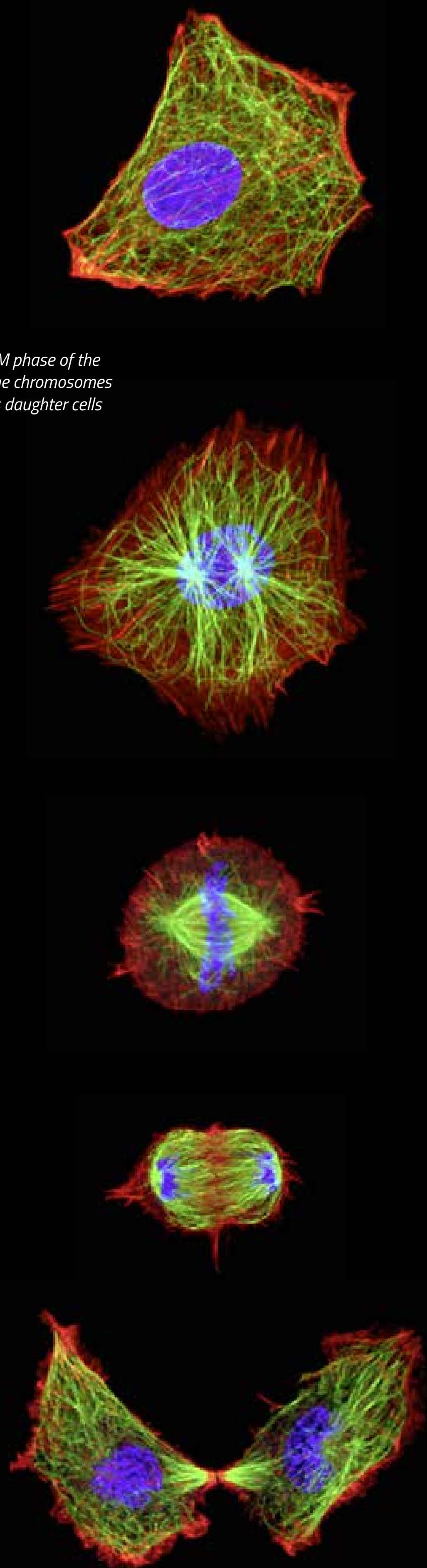


Image courtesy of Jan Ellenberg

During the M phase of the cell cycle, the chromosomes separate as daughter cells are formed.

Acknowledgement

The original version of this article was published in *EMBLetc*, the magazine of the European Molecular Biology Laboratory (EMBL)[w2].

Web references

w1 In 2001, the Nobel Prize in Physiology or Medicine was awarded jointly to Leland H Hartwell, Tim Hunt and Sir Paul M Nurse. Read more about Sir Paul Nurse on the Nobel Prize website. See www.nobelprize.org or use the direct link: www.tinyurl.com/msfny3j

w2 EMBL is one of the world's top research institutions, dedicated to basic research in the life sciences. EMBL is a member of EIROforum[w3], the publisher of *Science in School*. To find out more, visit: www.embl.org

w3 EIROforum is a collaboration between eight of Europe's largest inter-governmental scientific research organisations, which combine their resources, facilities and expertise to support European science in reaching its full potential. As part of its education and outreach activities, EIROforum publishes *Science in School*. See: www.eiroforum.org

Resource

For an interview with Paul Nurse's colleague Tim Hunt, see:

Gebhardt P (2007) Eyes on the horizon, feet on the ground: interview with Tim Hunt. *Science in School* **6**: 9-13. www.scienceinschool.org/2007/issue6/timhunt

Adam Gristwood is a journalist and editorial manager at the European Molecular Biology Laboratory (EMBL)[w2]. Reporting mainly on life sciences, he has also covered stories from the Atacama Desert, the Large Hadron Collider and a helicopter.

Science without borders: an astronomy-based school exchange

Typical school exchanges focus on language and culture – but you can also build a successful exchange programme around science.

Image courtesy of Ronald van der Graff; image source: Flickr

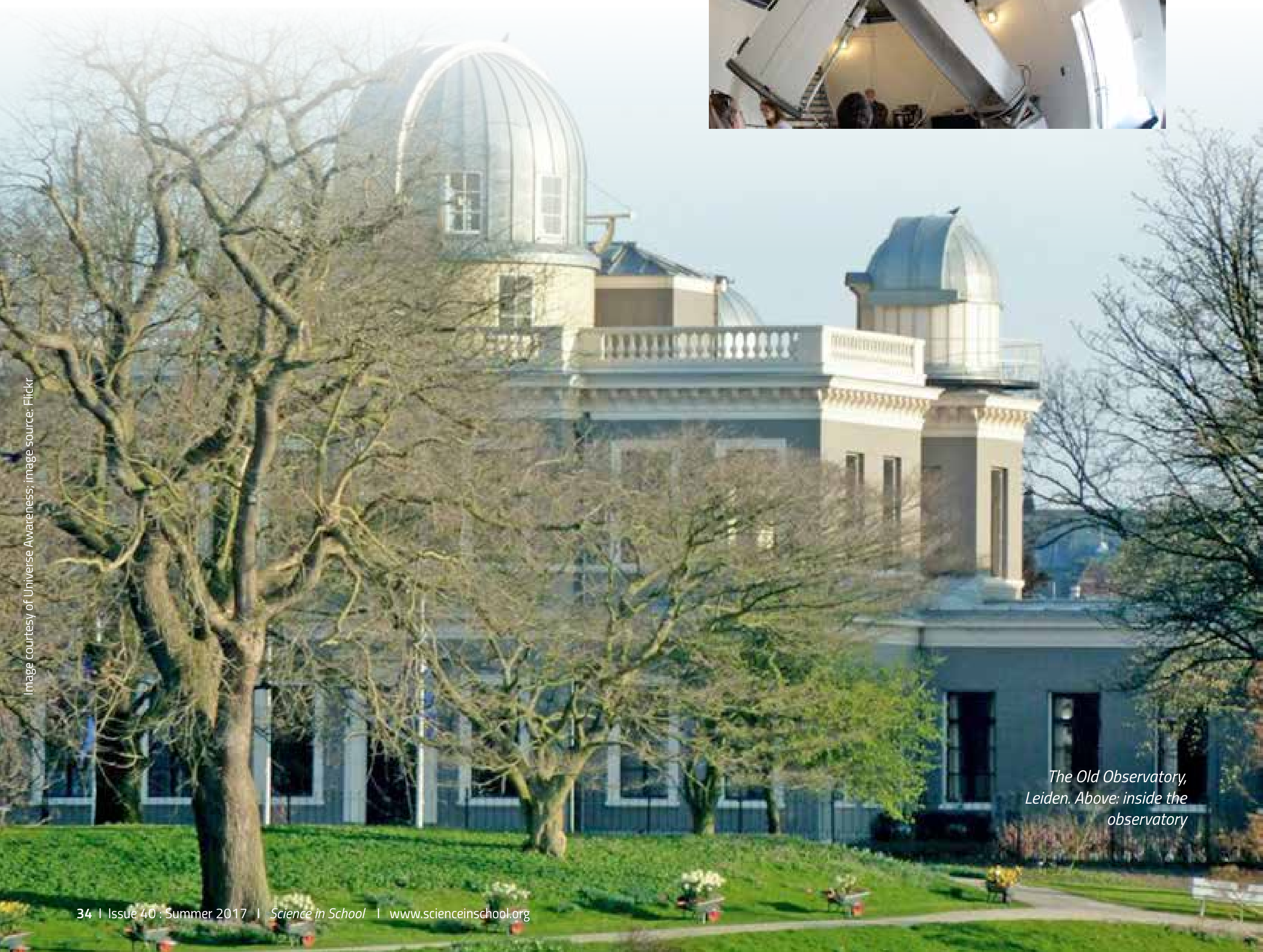


Image courtesy of Universe Awareness; image source: Flickr

The Old Observatory, Leiden. Above: inside the observatory

By Christina Diehl and Claudia Callies

The main aim of most school exchange programmes is to help students learn another language. Organised activities – often with social, cultural or historical aspects – are usually included to get students talking to each other. But why are there so few exchange programmes where students learn and talk about science? Science is truly international, and English – which is not the first language for most scientists – is the lingua franca of the international scientific community.

Five years ago, we – as science teachers – decided to devise an exchange programme based on science topics and conducted in English. Since then, our schools in Münster (Germany) and Leiden (the Netherlands) have worked together on a programme in which students aged 14–16 learn about astronomy. Twice a year (in Leiden in November and Münster in February), we introduce the students to methods, experiments and current research in astronomy – and, of course, have some fun with leisure-time activities.

Our students are enthusiastic about the programme, and we are proud that it has become a permanent fixture in our schools' calendars. Judging from the feedback we get from the students, we believe that the exchange helps students to develop or maintain a positive attitude towards natural sciences. During the exchange, the students gain an insight into real research and have the opportunity to practice their English skills within a scientific field. In the future, this experience might encourage them to take a STEM subject at school or university, or give them the confidence to go abroad for their studies.

In this article, we describe how we organise these exchanges and what we have learned along the way. Perhaps our experiences can inspire others to set up a scientific exchange at their school?

REVIEW

- ✓ Astronomy/space
- ✓ General science
- ✓ Physics
- ✓ Ages 14–16

This article describes a novel and innovative way of teaching science by exchanging ideas between students, teachers and scientists from different countries.

Two ambitious teachers introduce their students to science, astronomy and to each other through an exchange programme. Via various activities, students from two countries obtain new experiences, exchange ideas, learn a new language and overcome obstacles with a common aim: to learn about science through experience within a multicultural environment.

Teachers will be able to adapt the ideas in the article to create similar activities in their own schools. Those from different subjects could work together to create an interdisciplinary approach. If schools can find a university department to co-operate with, this could also give the students their first taste of university life.

Christina Aristodimou, St Peter and Paul Lyceum, Cyprus

How to set up a scientific school exchange

If you wish to initiate a scientific school exchange programme of your own, the following steps might serve as a guideline.

1. Choose a topic

Find a suitable topic and one or more local co-operation partners who can provide expertise and opportunities for visits (e.g. a university with facilities for schools, a museum or observatory, or even a company).

For the school in Leiden, astronomy was a natural choice: the town has an old observatory that offers guided tours, the European Space and Technology Centre (ESTEC) is close by, and the University of Leiden has an astronomy department. Another advantage is that astronomy is not part of the national school curriculum, so the students would all start at the same level.

2. Find a partner school

Decide on how much time and money you can afford to spend on the exchange programme. Then find a country, a town and a twin school that suit your ideas.

Since the students stay with host families, the largest part of the exchange cost is travel. In the Leiden school, we decided that the twin school should not be too far away. We also wanted the students to experience communicating about science in English with other non-native speakers, so we chose a non-English speaking country. The duration, as for other exchanges the school offers, was four days. We found out where in Germany astronomy could be studied at a university and chose two cities not too far from Leiden: Bonn and Münster. We then read the websites of the high schools in those cities to see if they might be interested in a scientific exchange programme. We contacted eight schools, and two of them responded positively. The final decision was made after we investigated which German school might be best suited in terms of the school calendar, enthusiasm of the teachers, and support from the school administration.

In Münster, the exchange started with the email from Leiden asking if their school might be interested in the programme, which we named Science in Space.

3. Agree on the details

Arrange a meeting with the partner school to agree on the main organisational details at both schools, e.g. age and number of students, duration and date of the exchange, application deadlines, costs for students and teachers, and accommodation.

We wanted the students to have enough knowledge of algebra to do interesting calculations, but not to be too close to their final exams, so we decided on students aged around 15. Since we planned activities requiring all the students from both schools to fit into a classroom or to go on a guided tour, we offered a maximum of 16 places for each school.

4. Devise the programme

Prepare the schedule and the scientific part of the programme for the home visit by the partner school.

Each team is responsible mainly for their home part of the programme. We now have an established pattern for the programme, comprising a mixture of social and astronomy-related activities. The arrival half-day is used for students and staff to get to know each other and the town. This is followed by a day at school, then a day at university, and a half-day at school again. You could also (or instead) include a visit to an external facility – somewhere like the Old Observatory in Leiden, which is still in operation, or the planetarium in Münster.

5. Publicise your exchange

Advertise the exchange at your school and select participants.

Each year, we produce a flyer and put a notice on the schools' websites to inform students and parents about the exchange. Students who participated in the previous year's exchange visit classes to explain why it's great to get involved.
To compete for places, the students write letters of application. We use these letters, the students' grades and the aim of gender parity as the selection criteria.

6. Organise the social side

The student participants organise the social and cultural activities for the home visit.

At each school, we usually have the first meeting with the students in mid-September. We tell them about the programme schedule and ask them to plan the group activities themselves. For example, we always have a city tour and dinner together on the first day, but the students organise the details. They might plan a trail-based quiz to get to know the town, and book a restaurant likely to appeal to other students.

7. Refine your plan

Check the programme from both sides, and take the time to fine-tune as needed.

Although most of the activities are organised by the home school in each location, we always review both sides of the programme between us before the exchange, to ensure they form a coherent whole.

As well as balancing the social and scientific aspects, the programme should be arranged so that the second visit builds on the ideas from the first visit.

8. Evaluate your exchange

Evaluate the programme after both sides of the exchange have taken place.

We ask the students for feedback after each trip, but we also have an evaluation session with the teachers every year to discuss possible improvements.

Pitfalls and problems

Our school exchange is now in its fifth year. While this means that much has gone right, it does not mean that nothing has ever gone wrong. We mention here two problems that we have had to resolve, in the hope that our experiences will help others to avoid these pitfalls.

Workload

Be realistic about what students can achieve during a short exchange.

In the first year, we devised a very ambitious programme with many different assignments for every student to complete. It turned out that the students had to work so fast that they often did not understand the assignments well. We found that it was better to allocate the assignments to different groups of students (and omit some). This led to students understanding the material for their own topics better, and making more interesting presentations about them, which the other students were then more able to follow.

Communication

Evaluate the programme every year, not only with the students but also with the teachers.

In the fourth year of the exchange, we experienced some tension between the two teacher teams. What had happened? It turned out that we had

Image courtesy of Christina Diehl

At the student laboratory at Leiden University, the school students simulate the discovery of exoplanets by transit photometry.

Image courtesy of Christina Diehl

Students build their own spectroscope ...

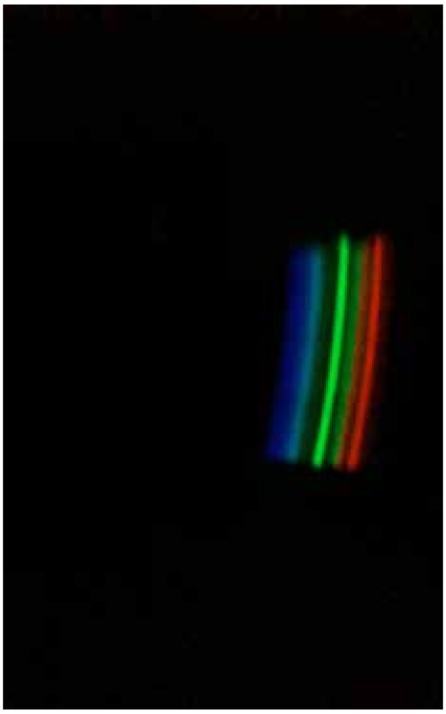
Image courtesy of Christina Diehl

... and test it on a natural light source.

Image courtesy of Christina Diehl

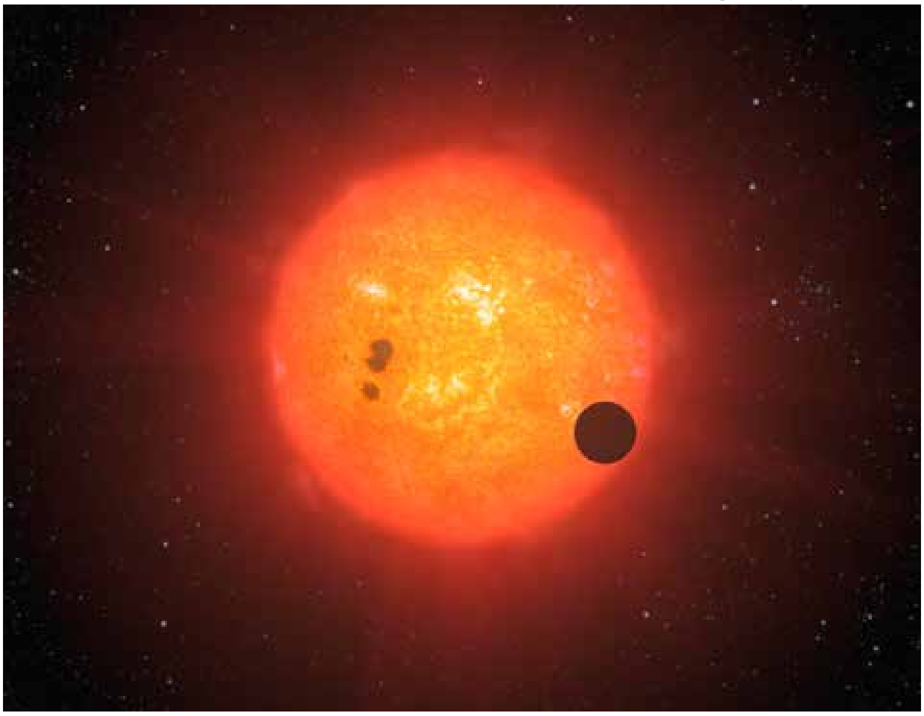
After work, a group of students have fun at a Leiden bowling centre.

Image courtesy of Claudia Callies



Spectroscopic image of a fluorescent ceiling light, taken with the student spectroscope and a smartphone

Image courtesy of ESO / L Calçada



Artist's impression of an exoplanet seen transiting a star. The slight dimming caused by such transits has led to exoplanet discoveries.

not talked enough about the different circumstances and practicalities at the two schools. We arranged a telephone conference, stated the problems as we saw them, discussed the limitations and possible options at the two schools, and then went on to establish some written guidelines that both teams felt they could follow comfortably.

Because the exchange programme had gone so well for the students, we had not established a feedback culture among ourselves. Now, we not only ask the students for feedback, but also take the time to look back at how things went for the teachers and how we feel about it.

The towns of Leiden (left) and Münster (right)

Image courtesy of Canadian Pacific; image source: Flickr

Creating your own programme

If you would like to set up your own science exchange programme, the topic doesn't need to be astronomy and you don't need to be close to a university. If you have a chemical company nearby, find out if you can work together. Perhaps the company has a branch abroad and you can find a school near there? There are also other ways to set up a programme: for example, you can start searching the eTwinning site of the Erasmus+ programme[w1, w2].

Each programme must be designed to suit its schools' individual circumstances. Whatever you decide to do, be creative: this will help you to set up a programme that will be enjoyed by your students now, and perhaps many others in years to come.

Finally, if you are interested in establishing an astronomical exchange programme at your school, we would be happy to send you our complete materials (Word and PDF files, including the workbooks we use in Leiden and Münster). Please send us an e-mail (christina.diehl@gmx.de, c.callies@gymnasiumleiden.nl).

Acknowledgement

This article is based on a presentation at the German national Science on Stage festival in 2016. Science on Stage[w3] is the network for European science, technology, engineering and mathematics (STEM) teachers, which was initially launched in 1999 by EIROforum, the publisher of *Science in School*. The non-profit association Science on Stage brings together science teachers from across Europe to exchange teaching ideas and best practice with enthusiastic colleagues from 25 countries.

Web references

w1 The Erasmus+ programme supports education, training, youth and sport in Europe. See: http://ec.europa.eu/programmes/erasmus-plus

w2 The Erasmus+ programme eTwinning promotes school collaboration in Europe. For more information, see: www.etwinning.net

w3 Visit the Science on Stage website. See: www.science-on-stage.eu

Image courtesy of Foto Fitti; image source: Wikimedia Commons

Resources

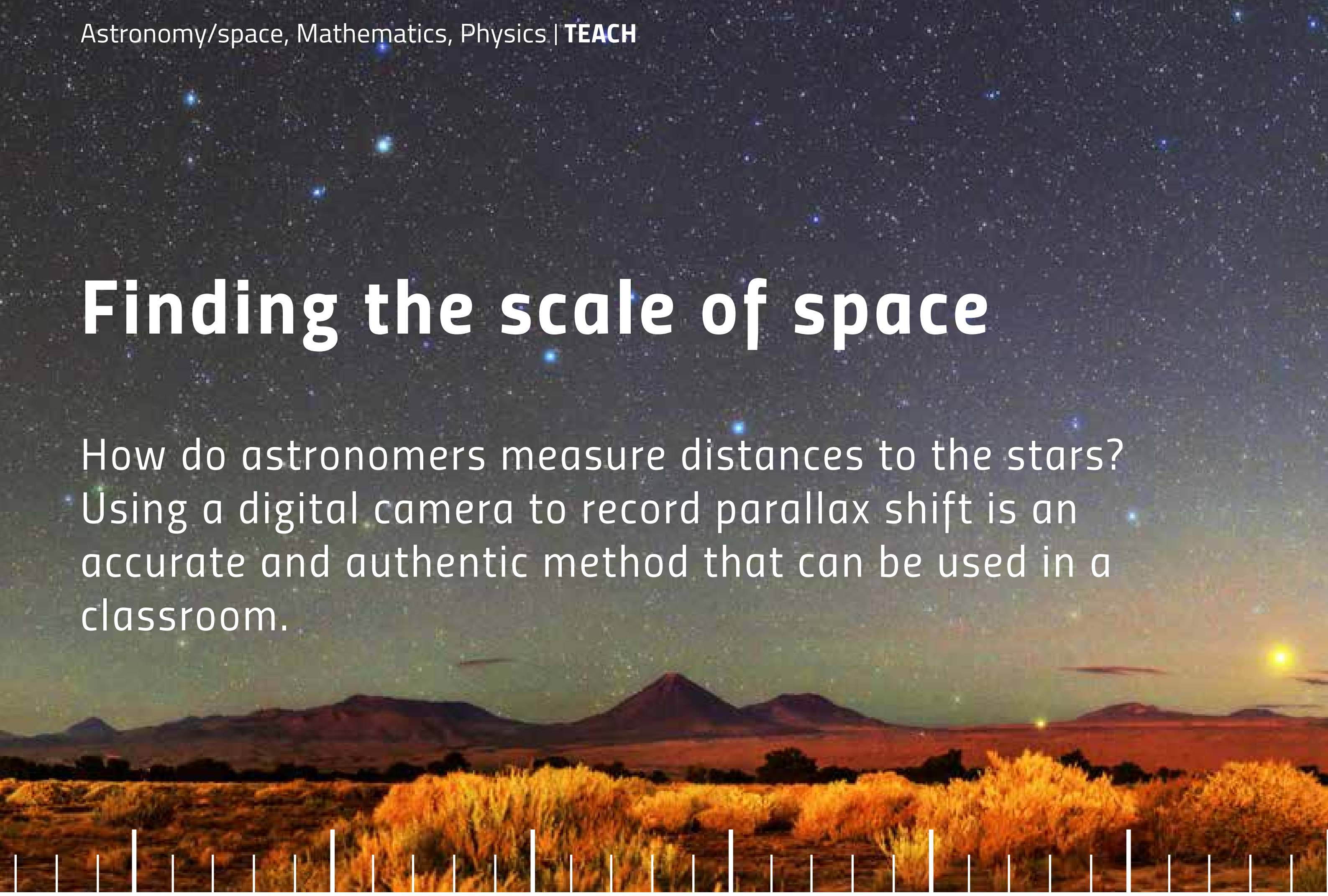
For our astronomical programme, we found the following resources very useful:

- ESA (the European Space Agency) provides a lot of educational material – for example, the ESA/ESO Exercise series booklets. See: www.eso.org/public/products/education
- NASA has a website, Astronomy Picture of the Day, which we used for an assignment. See: https://apod.nasa.gov/apod/astropix.html
- The House of Astronomy in Heidelberg, Germany, provides useful teaching material. For our exchange, we use their infrared box, which comes complete with a set of 15 experiments and a handbook (in German). See: www.haus-der-astronomie.de/de/was-wir-tun/materialien/infrarotkoffer or use the direct link: https://tinyurl.com/lefvzk8
- The German project, Wissenschaft in die Schulen (Science in Schools), also provides useful teaching material, part of which we translated into English for our exchange programme. See: www.wissenschaft-schulen.de

Christina Diehl teaches mathematics, physics and English at the Gymnasium Paulinum in Münster. She enjoyed astronomy as a student and is enthusiastic about introducing young people to the subject.

Claudia Callies teaches physics at the Stedelijk Gymnasium, Leiden. Since becoming a teacher in 2001, she has been involved in a variety of student-focused programmes.

In 2017, Christina and Claudia will present their exchange programme at the international Science on Stage festival in Debrecen, Hungary.



Finding the scale of space

How do astronomers measure distances to the stars? Using a digital camera to record parallax shift is an accurate and authentic method that can be used in a classroom.

By Markus Pössel

Astronomers are remote observers, separated by great distances from the objects they study. Knowing the distance of celestial objects is crucial: it provides a key factor in distinguishing a very luminous, distant object from one that is much closer but inherently less bright – and thus in working out what the object is. Even single stars and whole galaxies can look similar – until we know that one is a billion times further away than the other, and thus in reality trillions of times brighter.

The most important astronomical method for determining distances from Earth to the stars is parallax – the apparent shift in position of a viewed object when the observer changes position. We notice the parallax effect when we look out a train window: nearby objects seem to move past much faster than distant ones. Using this effect, we can work out the distance of an object by measuring the apparent change in its position when our position as observers changes.

The challenge, of course, is accuracy. How can we make distance measurements based on parallax as accurate as possible? In this second article on measuring distances using parallax, we use an authentic method very similar to that used by astronomers, which has been adapted for use in a classroom (for the previous article, see Pössel, 2017). Instead of using angle-measuring devices (as in the previous article, based on theodolite measurements) to work out the distance

REVIEW

- ✓ Astronomy/space
- ✓ Mathematics
- ✓ Physics
- ✓ Ages 16–19

This article describes an innovative way to find the distances to celestial bodies using the parallax method. It is very suitable for students and teachers who have a keen interest in both photography and astronomy. It presents the necessary detail to be able to calculate the distance to a 'star' to a good degree of accuracy, illustrated with an example.

The activity is ideal to use with a group of students or in a workshop on astronomy or photography for advanced students.

Stephanie Maggi-Pulis, Secretariat for Catholic Education, Malta

When we look at the sky at night, bright stars far away look similar to duller, nearer stars. Parallax measurements allow us to tell these apart.

Image courtesy of ESO / B Tafreshi

Image courtesy of HdA / M Pössel

Figure 1: Camera mounted on optical bench for easy sideways shifting

to a 'star', here we take photographs from different positions and use these to provide the measurements we need to calculate our star's distance.

A variation of this photographic method, described later in this article, is even more authentic and accurate, although slightly more complicated. It involves using a fixed reference point outside the classroom – just as astronomers use very distant background objects (e.g. active galaxies called quasars) as fixed reference points when measuring stellar parallax, rather than relying on their telescopes pointing in the same direction for each observation.

For these activities, you will need a digital camera, mounted (if possible) on an optical bench (see figure 1). The activities can be carried out by groups of students. Allow around 30 minutes for setting up and taking measurements, and an additional 30 minutes for the analysis and calculations.

Materials

- Digital camera with lens of known focal length (at least 50 mm)
- Optical bench (or similar setup for moving the camera sideways and measuring the shift, such as a flat table top and a long ruler)
- Model star (a small sphere no more than 1 cm in diameter or an LED, mounted on a stick)
- Object of known length with clear markings (e.g. a metre rule), as a calibration object
- Tape measure
- Image processing programme, e.g. Adobe Photoshop, GIMP

Procedure

1. Mount the camera on the optical bench so that you can shift the camera sideways by a known distance. The camera should be pointing at right angles to the length of the bench (figure 1). If you don't have an optical bench, tape a long ruler to the surface of a table so that you can move the camera along the ruler and measure the shift distance.
2. Mount the model star so that it is at eye level with the camera and a few metres away from the camera bench.
3. Slide the camera to one end of bench, making sure that the star is visible through the camera. Take a photo of the star from this position.
4. Then, shift the camera along the optical bench so that the star is still visible through the lens. Record the distance moved, and then take another photo from this position.
5. Move the camera back to a central position. Now place the calibration object (e.g. a metre rule) at a right angle to the camera's direction of view and take a photo of it. This image will be used to calibrate your measurements.
6. Using a tape measure, find and record the distance from the camera to the metre rule.

Calculating the star distance

The experimental situation is shown in figure 2. Here, *b* represents the shift distance along the camera baseline (the optical bench or table) between the first and second positions (A and B), while C is the position of the model star, and *d* is the distance from the camera baseline to the star – that is, the distance we are trying to calculate.

The steps for calculating the distance *d* are set out below.

1. If we a draw a line that is parallel to the baseline and at the same distance *d* as the star, the camera's line of sight from position A will intersect the new line at OA, and from position B at OB. The angles between the camera's lines of sight and the direction to the star at camera positions A and B are *α* and *ß*, respectively.

   Unlike theodolites, cameras do not allow us to measure angles directly. We thus need to relate the location of the images of the star on the camera's image detector screen to the angle of the light rays from the star when the camera is in different positions.
2. To do this, we need to think of the situation in a slightly simplified and fictionalised way. First, we treat the lens in the camera as a pinhole – as shown in figure 3, where P is the position of the lens. So a light ray from the star travels in a straight line through the camera lens and hits the photographic detector on the imaging screen at a distance *f* (the focal length of the lens) behind the front of the camera.
3. Starting with figure 2, we then think about the situation from the point of view of the camera as it is moved from A to B – as if we were an observer sitting on the camera throughout. We can achieve this by, in effect, shifting the position of the camera position A (and the line AC) to the right by the distance *b* that the camera was moved, so that the two camera positions now coincide.

   The viewpoint of the camera is shown in figure 3. The star's apparent location will be at location C_A when the camera is at the first position (A), and its image will be located at D_A on the detector screen. Similarly, after moving the camera to B, the star's apparent

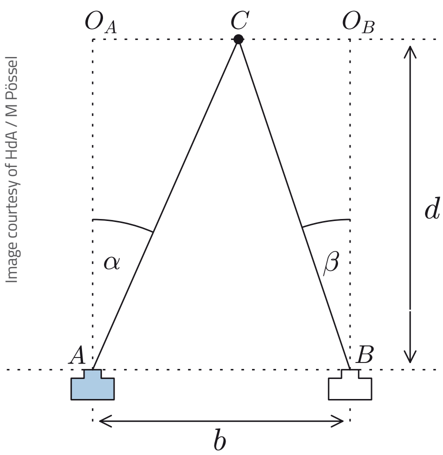


Image courtesy of HdA / M Pössel

Figure 2: The model star, at position C, photographed from two different camera positions, A and B, separated by a shift of distance b

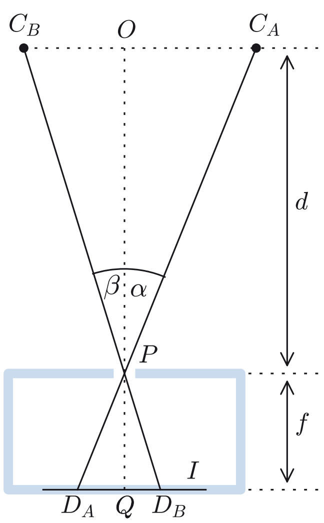


Image courtesy of HdA / M Pössel

Figure 3: Simplified model of the parallax setup

location will be at C_B and its image at D_B. (Here, the line segment OQ represents the distance between the camera's image plane and the parallel plane that contains the star.) The length C_BC_A is the distance *b* in figure 2, while the angles α and ß remain the same.

4. Looking at the geometry, we can see some similar triangles. Using these triangles yields a formula linking the distance *d* to the other known lengths *b* and *f*, allowing us to calculate its value. You can find out how to derive this formula on the *Science in School* website[w1].

   The formula is:

   $$d = \frac{p_L \times d_L \times b}{L \times p}$$

   where:

   d = distance to star

   L = actual length of the calibration object

   b = actual distance the camera was moved (which corresponds to the distance from C_A to C_B)

   d_L = actual distance of the calibration object from the camera baseline (along line OQ)

   p = distance as the number of pixels between the star images (at D_A and D_B)

   p_L = length as the number of pixels of the image of the calibration object

5. To use this formula, you first need to use an image processing programme to find *p,* the number of pixels (on the horizontal axis) that separate the positions of the star's image between the two photos when you view them on screen. You can also use the programme to find p_L, the length of the calibration object as the number of pixels on screen.

When you have worked out a value for *d*, you have successfully used parallax measurement to determine the distance to the star.

Now use the tape measure to find the distance *d* directly, and compare this to the value calculated from the parallax measurement. How accurate was the calculated measurement?

You can repeat this activity with the 'star' placed at different distances, to find out whether the accuracy of parallax measurements changes with distance (see section below, 'What accuracy can we expect?').

Parallax photography with a reference point

For even more astronomical realism, we can adapt the parallax photography method to use a reference object outside the classroom, which should be considerably further away than the 'star'. With this procedure, instead of relying on the camera pointing in the same direction after having been moved from A to B, we choose a distant reference object that is visible in each of the two images. We then measure the star image's pixel distance from the reference object in each image. This alternative approach, which we describe here, should yield more accurate results.

Procedure

1. For the reference object, find a small feature of the most distant object visible in both images – this must be much more distant than the model star. In our case, we chose a reference feature on one of the observatory domes of the Max Planck Institute for Astronomy as a marker, which was located about 80 m from our camera.
2. Draw a vertical line through the reference feature in each image. This is the reference line. We can

Image courtesy of HdA / M Pössel

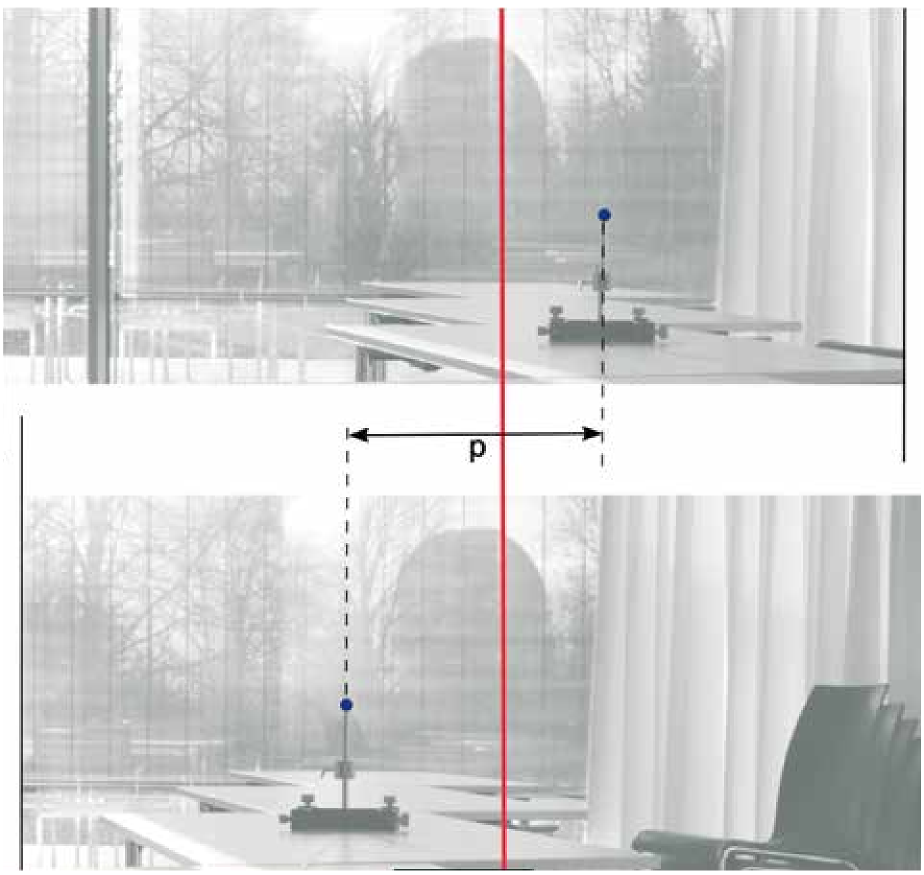


Figure 4. Two sample images from the camera activity, showing a horizontal pixel shift p. In the images, the reference object (a feature on the dome in the background) lies on the red reference line.

now use the reference line to find the pixel shifts between the two images, as shown in figure 4.

3. To work out *p*, the on-screen distance in pixels, you first need to find the model star's horizontal pixel distance from the reference line in both images separately. Then simply add these (corrected) horizontal pixel values to each other to find *p*. For example, –24 px would be 24 pixels to the left of the reference mark, while +36 px is 36 pixels to the right, giving a distance *p* of 60 pixels.
4. From this point onwards, the calculations are the same as in the earlier method (see the section above, 'Calculating the star distance').

What accuracy can we expect?

So, how accurate are the results obtained using this improved method? Our data suggest that they can be remarkably accurate (compared with directly measured distances), as shown in figure 5. The largest relative error amounts to just 3.2%.

Note that, at larger distances, there is an increase in the relative error as well as the actual error. This is because the geometry changes: the distance to the model star becomes larger compared with the distance of the reference object, so the error introduced by the parallax of the reference object becomes ever greater.

With the simple angle-measuring method described in the previous article (Pössel, 2017), the accuracy of distance measurements was significantly lower – generally within about 10%, as shown in figure 6. So the method described in the current article provides a significant improvement in accuracy from the previous method, where the dominant sources of error are the angular measurements.

Reference

Pössel M (2017) Parallax: reaching the stars with geometry. *Science in School* **39**: 40-44. www.scienceinschool.org/2017/issue39/parallax

Web reference

w1 An algebraic derivation of the formula for calculating the star distance using similar triangles can be downloaded from the *Science in School* website. See: www.scienceinschool.org/2017/issue40/parallax

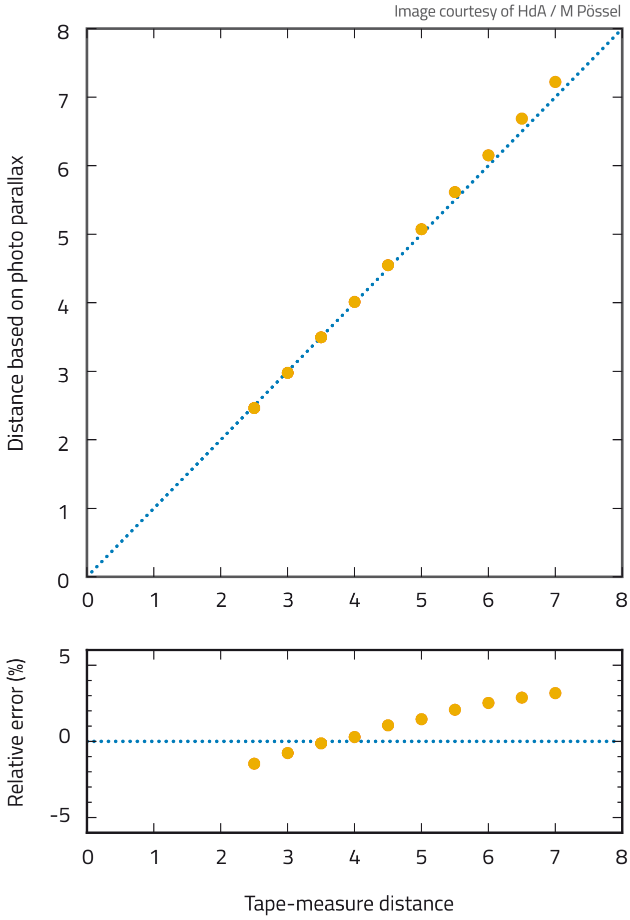


Figure 5: Top: distances to the model star measured by the parallax method plotted against tape-measure distances
Bottom: relative errors of distances measured using the reference point parallax photograph method, compared to the tape-measure distances

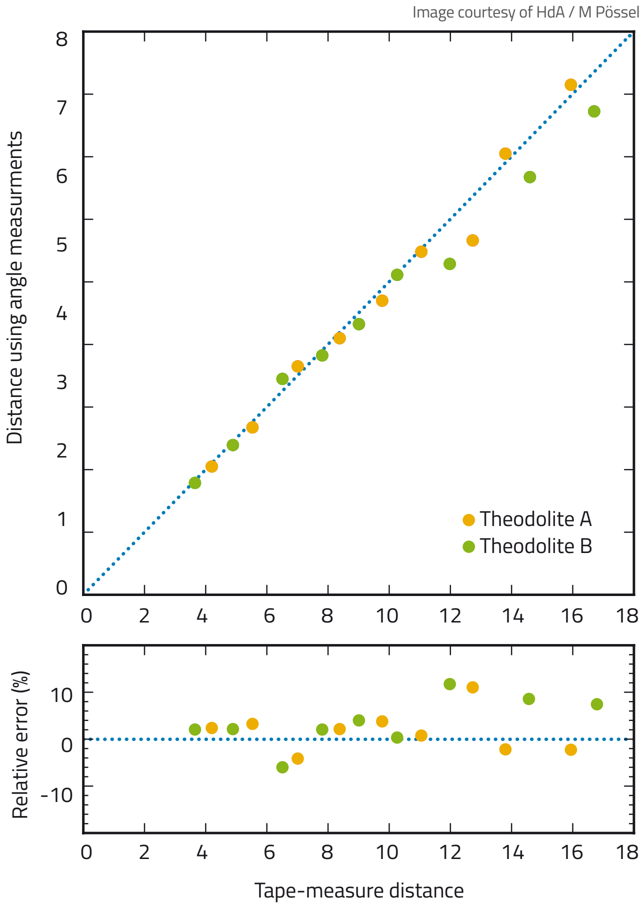


Figure 6: Top: parallax distances measured using theodolites plotted against tape-measure distances. (For perfect accuracy, all data points would lie on the dotted line.)
Bottom: relative errors of distances measured using the theodolites, compared to the tape-measure distances

Resources

For information on how to carry out real astronomical parallax measurements with small instruments, see:

Cenadelli D et al. (2016) Geometry can take you to the Moon. *Science in School* **35**: 41-46. www.scienceinschool.org/2016/issue35/parallax

Cenadelli D et al. (2009) An international parallax campaign to measure distance to the Moon and Mars. *European Journal of Physics* **30**: 35-46. doi: 10.1088/0143-0807/30/1/004

Hirshfeld AW (2013) *Parallax: The Race to Measure the Cosmos. Mineola, NY, USA: Dover Publications.* ISBN: 9780486490939

Variations of these experiments have been in use in astronomy laboratory courses for a long time. For example:

De Jong ML (1972) A stellar parallax exercise for the introductory astronomy course. *American Journal of Physics* **40(5)**: 762-763. doi: 10.1119/1.1986635

Deutschman WA (1977) Parallax without pain. *American Journal of Physics* **45(5)**: 490. doi: 10.1119/1.11009

Markus Pössel is Managing Scientist of the Haus der Astronomie (the centre for astronomy education and outreach) and Senior Outreach Scientist at the Max Planck Institute for Astronomy, both in Heidelberg, Germany.

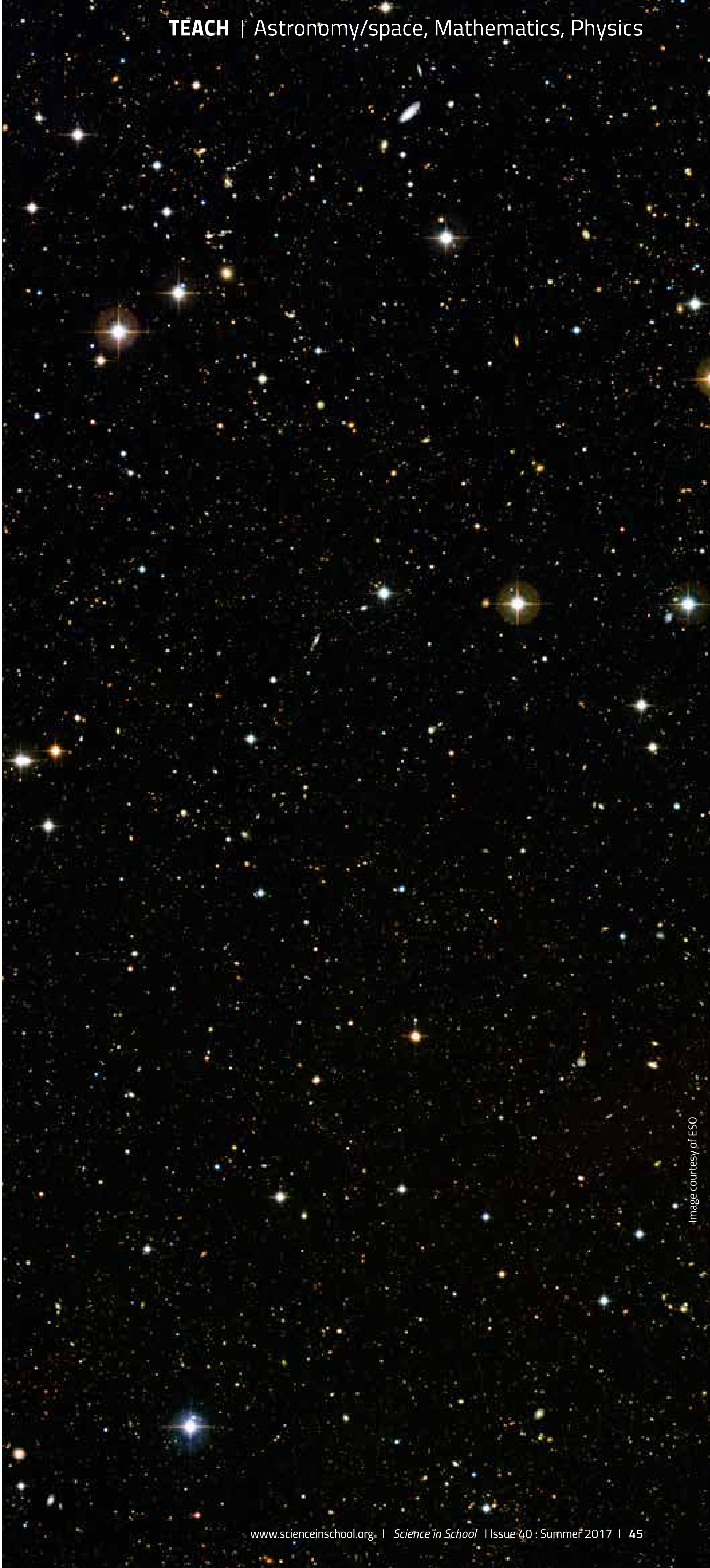


Image courtesy of ESO

Who murdered Sir Ernest? Solve the mystery with spectral fingerprints

Image courtesy of Nicola Graf

Introduce your students to acoustic and optical spectra with a hands-on murder mystery.

By Ernst Hollweck and Johannes Almer

This collection of forensic activities highlights the power of spectral analysis and the links between acoustic and optical spectra. In the first activity, students use sound to solve a murder mystery, analysing acoustic spectral 'fingerprints' to identify the murderer from his wine glass. The second activity requires the student detectives to investigate optical spectra by carrying out flame tests of single metal ions and compounds. In the third activity, students vary the voltage applied to light-emitting diodes (LEDs) to understand the link between photons and spectral colours. Finally, all three activities are brought together in a poster session.

The activities are suited for students aged 14–16 and use readily available laboratory or domestic materials. The three activities plus the poster session require no more than three hours.

Image courtesy of Nicola Graf / Johannes Almer and Ernst Hollweck

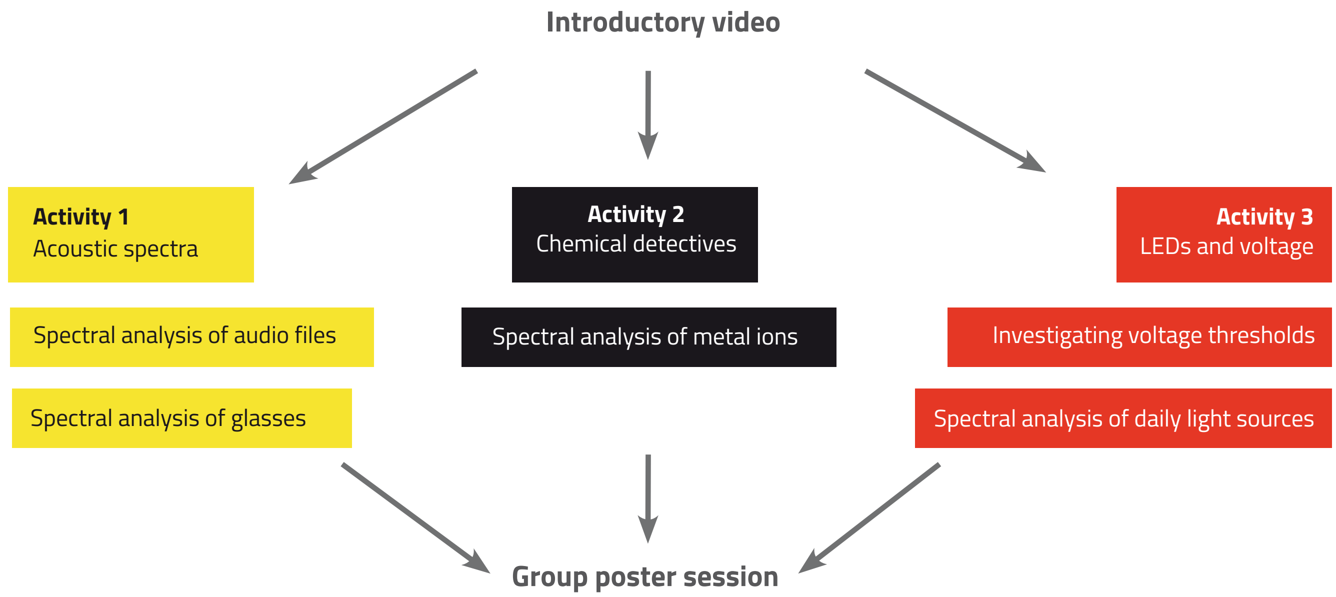


Image courtesy of Johannes Almer

Figure 1: The interdisciplinary activities start with a video before groups of students work on three interrelated topics. The lessons conclude with poster presentations

Activity 1: Acoustic spectra

At a grand ball last night, the host, Sir Ernest, was murdered. Now it's up to your students to find the murderer, using acoustic spectral fingerprints.

The search for the murderer starts with a video[w1] (figure 2). Sir Ernest greets his first guest – "Nice to see you, Mr Darcy" – and they clink wine glasses.

The scene is repeated for another two guests, Mr Bennet and Mr Bingley, each of whom is associated with the sound of a specific glass. When making the video, rather than clinking each guest's glass with Sir Ernest's, we actually struck them gently with a hammer. This produced an identifiable sound for each glass, uncomplicated by the sound from Sir Ernest's glass.

Next comes the murder scene, during which Sir Ernest talks to one of the three guests without mentioning his name. The two men clink glasses once again, before the murderer pulls out a knife and kills Sir Ernest. This time, the recorded sound really does come from both the murderer's wine glass and Sir Ernest's.

Now the young detectives can begin solving the mystery. The three activities (a, b and c) in this section can be assigned to different groups of students according to their abilities. At the end of the lesson, each group should present their results to the class as a poster.

REVIEW

- ✓ Chemistry
- ✓ Physics
- ✓ Acoustics
- ✓ Criminology
- ✓ Spectroscopy
- ✓ Quantum mechanics
- ✓ Ages 14–19

Experimental activities can offer students the opportunity to feel like real scientists and can make science more appealing. In the three interdisciplinary activities outlined in this article, students use concepts from both chemistry and physics to solve a murder case.

Before starting the activities, students could think about the different tests used in criminology and the disciplines on which they are based. All the materials required for the experiments are readily available and the instructions are easy to follow. The activities provide options for students of different abilities and can be performed in small groups. Students can share their conclusions and learn how to work co-operatively.

The text could be used as a starting point for discussing the importance of science and interdisciplinary collaboration to find solutions for everyday problems.

Mireia Güell Serra, Spain

Images courtesy of Johannes Almer and Ernst Hollweck

Figure 2: Scenes from the introductory video, showing Sir Ernest greeting a guest (top), and the murder (bottom)

a) Matching acoustic spectra

In this part of the activity, the students use audio software to analyse the characteristic sound of each guest's glass and identify the murderer by comparing the resulting acoustic spectra. They will need about 45 minutes.

Materials

- Computer with Audacity or other audio software[w1]
- Audio files from the murder scene[w2]

Procedure

Ask your students to:

1. Use the audio software to analyse the four audio files (Mr Darcy's glass, Mr Bingley's glass, Mr Bennet's glass, and the murder scene). For each file, they should produce an acoustic spectrum: a plot of frequency (in hertz) against relative loudness as perceived by the human ear (in A-weighted decibels, or dB(A)). Using the acoustic spectra, they should identify the single spectrum of the murderer within the spectrum of the murder scene.
2. Compare these spectra (figures 3 and 4) to determine the murderer: the spectrum of the murderer's glass resembles the spectrum from the murder scene.

Further instructions on how to use Audacity can be downloaded from the *Science in School* website[w2].

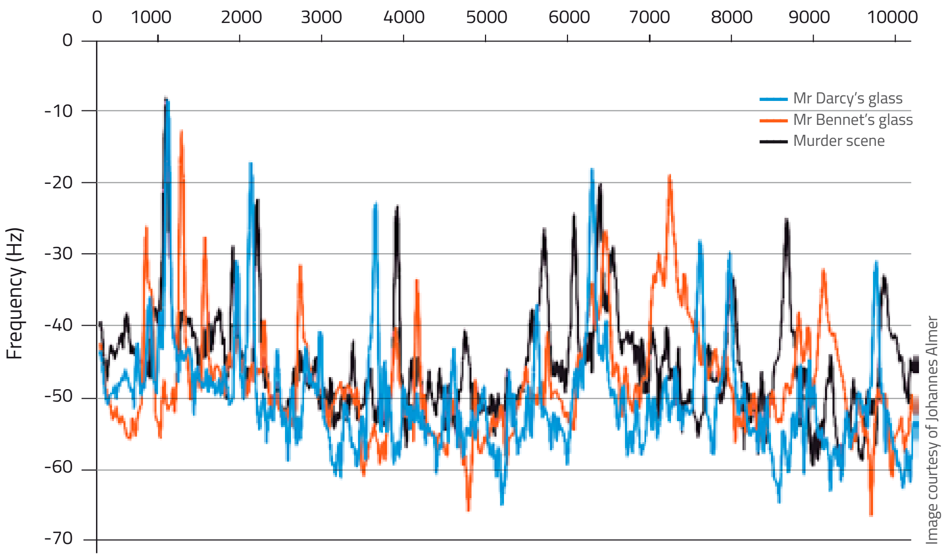


Figure 3: Frequency analysis reveals the innocent guests: the spectra for Mr Darcy and Mr Bennet's glasses do not match the spectrum from the murder scene.

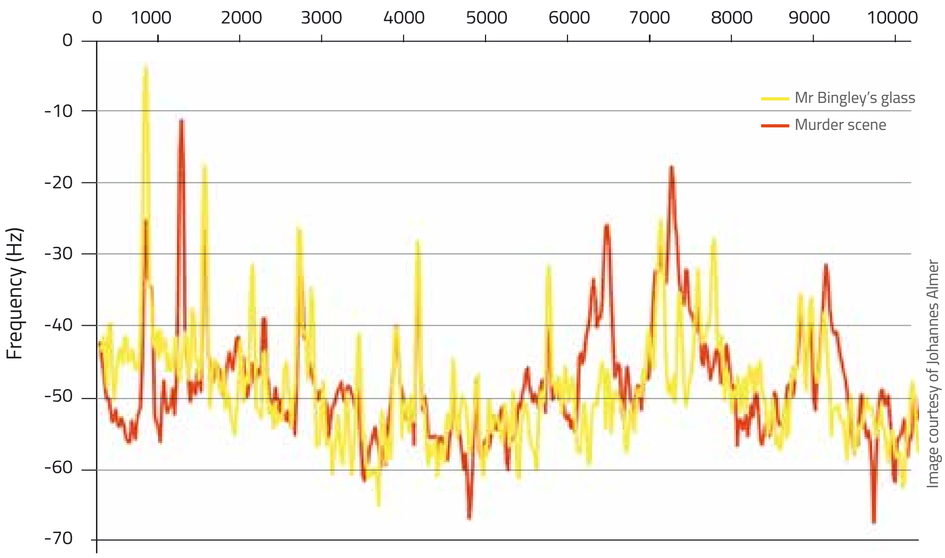


Figure 4: Frequency analysis reveals that Mr Bingley is the murderer.

b) Smartphone spectra

Using smartphones, the students analyse the characteristic pitches of different glasses. The activity takes about 30 minutes.

Materials

- A selection of assorted glasses (e.g. wine, champagne, water)
- Hammer (or other object to strike the glasses)
- Smartphone with a frequency analysis app[w3]
- Paper and pencil

Procedure

Ask your students to:

1. Strike each glass gently with the hammer. Use the smartphone app to record the acoustic spectrum of each glass.
2. For each glass, record the frequency of the most noticeable peaks in a table.
3. Using paper and pencil, sketch the spectrum (frequency against amplitude) for each glass, using the values recorded in your tables.

Alternatively, your students could analyse the audio recordings from the murder video and sketch the spectra.

c) Playing with pitch

In the last part of this activity, the students use smartphones to investigate the effect that the fullness of a glass has on its pitch when struck with a hammer. They will need about 30 minutes.

Materials

- At least five identical wine glasses
- Hammer (or other object to strike the glasses)
- Smartphone with a tuner app[w4]
- Water
- Measuring cylinder (or other means of measuring the volume of water)

Procedure

Ask your students to:

1. Pour a different volume of water into each glass, noting the amount in each glass.
2. Strike each glass gently with the hammer. Use the smartphone app to record the frequency of the resulting pitch.
3. Display the results graphically, for example as a histogram (figure 5).

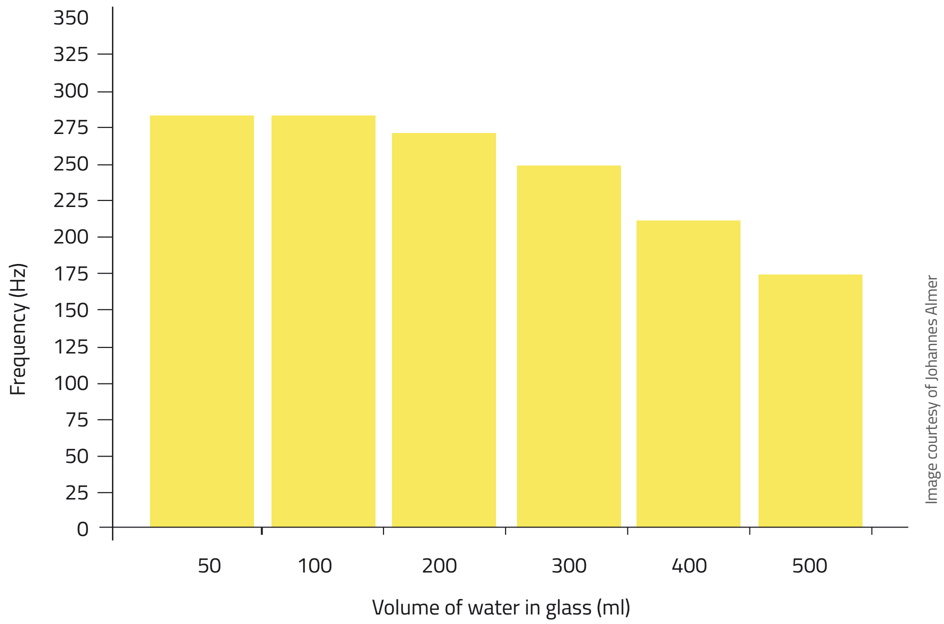


Figure 5: Example histogram showing that the pitch of the glass decreases with increasing volume of water

Activity 2: Chemical detectives

Not only has Mr Bingley been accused of murder, but now the food hygiene at his home, Netherfield Hall, has been called into question!

After dinner, a guest called Mr Wickham sprinkles the remains of the chicken on his plate with lithium chloride (LiCl). The next day, he and his wife are served chicken soup. Mr Wickham dips a rod of magnesium oxide into the soup and holds it into the flame of an alcohol burner. The flame turns red. What does this tell him?

In this activity, the students observe spectral emission lines for various cations by performing flame tests. Using their findings, the students determine the composition of two mixtures. This activity takes about 30 minutes.

Image courtesy of Alan Cleaver; image source: Flickr

Materials

Each group of students will require:

- Bunsen burner
- Clamp stand and clamps
- Tongs
- Magnesium oxide (MgO) rod
- Spot plate
- Hand-held spectrometer
- Safety glasses
- 5 ml 0.1 M hydrochloric acid in a small porcelain bowl
- In the spot plate, a spatula tip each of:
  - Sodium chloride (NaCl)
  - Calcium carbonate ($CaCO_3$)
  - Lithium chloride (LiCl)
  - Potassium chloride (KCl)
  - Mixture 1 (NaCl and $CaCO_3$)
  - Mixture 2 (LiCl and KCl)

Mixture 1 should be finely ground in a mortar so that the students cannot recognise the ingredients. Prepare this immediately before the lesson because calcium carbonate is hygroscopic.

Image courtesy of Johannes Almer

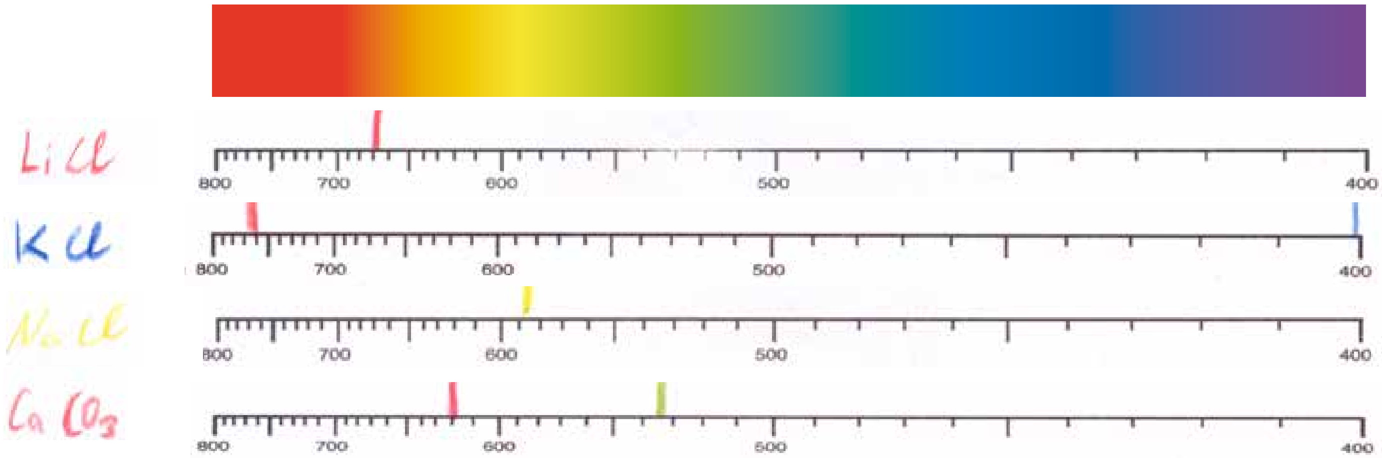


Figure 6: Students record the wavelength and colour of each cation (Li^+, Na^+, K^+ and Ca^{2+}).

Procedure

Ask your students to:

1. Hold the magnesium oxide rod in the flame of the Bunsen burner until the colour of the flame remains unchanged.
2. Dip the rod into hydrochloric acid, then into one of the named metal salts (LiCl, NaCl, KCl or $CaCO_3$) on the spot plate. Hold the rod in the hottest part of the flame. Note the colour of the resulting flame and observe it with the spectrometer.
3. Once the flame colour has returned to normal, repeat the flame test with another salt until all four have been tested.
4. Record the resulting colours and spectral emission lines for each cation (Li^+, Na^+, K^+ and Ca^{2+}; see figure 6).
5. Repeat the flame test with mixtures 1 and 2. Compare the results with the previous data and identify the cations present in the two mixtures.
6. Consider the story that introduced this activity. What was Mr Wickham trying to test? How likely do you think he is to get reliable results from his experiment, without using a spectrometer?

Activity 3: LEDs and voltages

This activity further investigates the topic of spectral colours. Students determine the energy required to light up different coloured LEDs using the following equation:

energy (E) = voltage (V) x charge (Q)

LEDs are produced by the junction of two 'doped' semiconductor materials, one of which has an excess of electrons and the other a lack of electrons (André & André, 2014). When an electrical current is injected through the junction, the recombination of electrons releases energy in the form of photons. Each colour of LED has a different threshold voltage at which photons are released, which determine the colour of the light emitted by the LED; changing the chemical composition of the semiconductor materials thus changes the colour. Optionally, students also compare spectral emissions lines for various other light sources. They will need about 30 minutes to complete the activity.

Materials

- LEDs of different colours and (optionally) other light sources
- Power supply with current limiter (rheostat)
- Multimeter (for voltage measurement)
- Spectrometer

Procedure

Ask your students to:

1. Set up the circuit by connecting the multimeter in parallel to the LED to measure the voltage across it. The applied voltage can be changed using the rheostat.
2. For each LED, increase the voltage of the power supply in small steps (e.g. 0.05 V) until sufficient voltage is applied to light up the LED. Students should not apply more than 3.5 V to the circuit.
3. Use the multimeter to measure the voltage applied directly to the LED. Note the minimum voltage required to light up the LED.
4. Use the spectrometer to observe and record the spectral emission lines for each LED (figure 7). Optionally, compare this with other light sources (e.g. ceiling light, Bunsen burner).

Safety note: We use a current-limited power supply with a maximum current of 100 mA to avoid overvoltage and damage to the LEDs. Alternatively, arrange the LEDs in a parallel circuit with a 100 Ω protective resistor for a red or orange LED.

Poster presentation

When your students present their posters to the class, encourage them to consider the implications of the three activities and the links between them, highlighting the power of spectral analysis. Acoustic spectra can be used as 'fingerprints' (e.g. for wine glasses) in much the same way as light spectra can be used to identify atoms. In particular:

- Would they have been able to identify the murderer if he had drunk from his glass after clinking glasses with Sir Ernest?

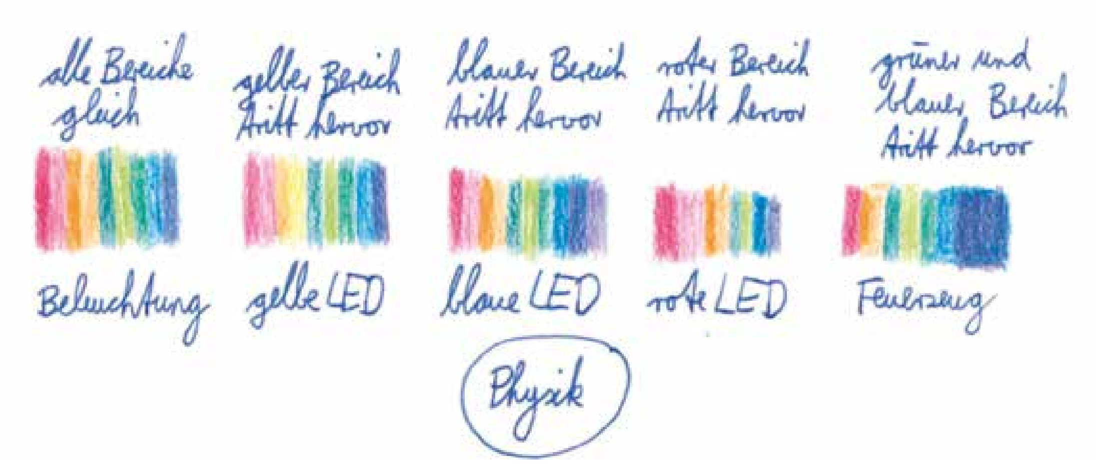


Image courtesy of Johannes Almer

Figure 7: Students draw the spectral emission lines for each light source they observe through the spectrometer. From left to right: ceiling light, yellow LED, blue LED, red LED, cigarette lighter

- Why would changing the volume of water in a glass change its pitch?
- Using two different spectra, explain how you can identify a glass with a higher pitch.
- What was Mr Wickham testing with the chicken at Netherfield Hall, and why?
- How are emission lines related to the energy level of the atoms involved?
- What is the relationship between voltage and LED colour?

Acknowledgement

This article is based on a project that was presented at the German Science on Stage festival in 2016. Science on Stage[w5] is the network for European science, technology, engineering and mathematics (STEM) teachers, which was initially launched in 1999 by EIROforum, the publisher of *Science in School*. The non-profit association Science on Stage brings together science teachers from across Europe to exchange teaching ideas and best practice with enthusiastic colleagues from 25 countries.

SCIENCE ON STAGE EUROPE

Reference

André MRASF, André PSB (2014) Classroom fundamentals: measuring the Planck constant. *Science in School* **28:** 28–33. www.scienceinschool.org/2014/issue28/planck

Images courtesy of Nicola Graf

Web references

w1 The Audacity software is free to download for Linux, Mac and Windows. See: www.audacityteam.org

w2 The introductory video is available on YouTube. See: www.youtube.com/watch?v=yqzgfDr9XKQ. Audio files, worksheets and other materials are available on the *Science in School* website. See: www.scienceinschool.org/2017/issue40/murder. German versions of the materials are also available. See: www.edu-maphy.de

w3 Suitable free frequency analysis apps include:

Android Spectral Audio (download from Google Play)

w4 Suitable free tuner apps include:

Android DaTuner (lite) (download from Google Play)

Apple iOS Soundcorset (download from Apple App store)

Apple iOS SpectrumView (download from Apple App store)

w5 Visit the Science on Stage website. See: www.science-on-stage.eu

Resources

To learn more about how spectra were discovered and how different spectra can be used to identify the composition of stars, see:

Ribeiro C, Ahlgren O (2016) What are stars made of? *Science in School* **37:** 34–39. www.scienceinschool.org/2016/issue37/stars

For instructions on how to build your own spectrometer, see:

Westra MT (2007) A fresh look at light: build your own spectrometer. *Science in School* **4:** 30–34. www.scienceinschool.org/2007/issue4/spectrometer

Examples of real-life applications of spectral analysis, further worksheets about Fraunhofer and the ChemCam of the Mars Curiosity rover are available on the authors' website. See: www.edu-maphy.de

Ernst Hollweck and Johannes Almer are teachers at the Ludwig-Thoma-Gymnasium of Prien am Chiemsee in Bavaria, Germany. Ernst teaches chemistry and biology, and Johannes teaches mathematics and physics. They are both members of the German delegation for the international Science on Stage festival to be held in Debrecen, Hungary, this year. Ernst and Johannes also regularly write articles for science journals and magazines.

Disease dynamics: understanding the spread of diseases

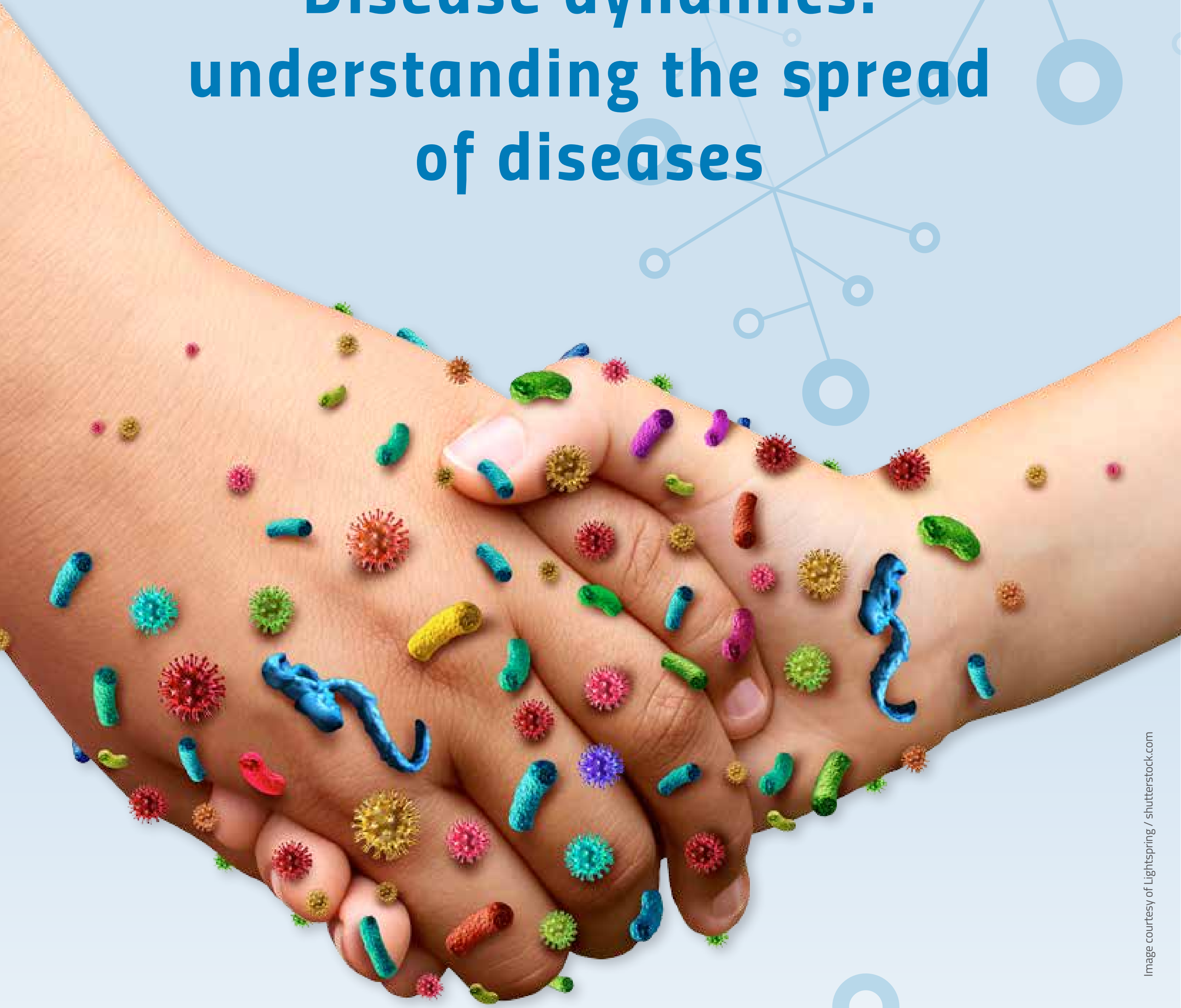


Image courtesy of Lightspring / shutterstock.com

Get to grips with the spread of infectious diseases with these classroom activities highlighting real-life applications of school mathematics

By Adam Kucharski, Clare Wenham, Andrew Conlan and Ken Eames

Schools are breeding grounds for infections: students are constantly interacting with each other, and often they have not yet built up immunities to disease. Understanding these interactions is vital for predicting how an infectious disease – such as influenza – will spread. For school students, it is important to think about their social interactions and to understand the types of analyses that can be used to determine disease dynamics.

These cross-curricular activities are for students aged 12–15, although some may be suitable for younger or older students too. The activities can be carried out by teams varying in size from small groups to the whole class. The resources do not require anything more than the slides that can be downloaded from the *Science in School* website[w1], paper and dice.

Activity 1: The standing disease

This short, whole-class activity simulates the outbreak of a disease, the symptom of which is standing up. The objective is to see how quickly the disease spreads exponentially across the classroom. With each step, the number of students that are infected doubles (see figure 1). This will help students to understand that it doesn't take many steps for an outbreak to spread through a susceptible population.

Students will see that the rate at which a disease spreads is dependent on the number of individuals that are susceptible or infected. This is only a simple mathematical model for determining the spread of disease, however, since it assumes everyone is susceptible to infection and that exactly two individuals are infected by each person.

Procedure

1. Start with the whole class sitting down. Ask for one volunteer to be the first case.
2. This first volunteer should then stand up and 'infect' two classmates by pointing to them.
3. These two students then also stand up, having been infected.
4. Each of those two students then infects two more students in the classroom, and so on, until the whole class is standing up.
5. Ask the students how many steps it took to infect their class.

Discussion

- Ask your students to estimate how many steps it would take to infect their school, town, country or the world. It takes approximately 33 steps to infect the world with

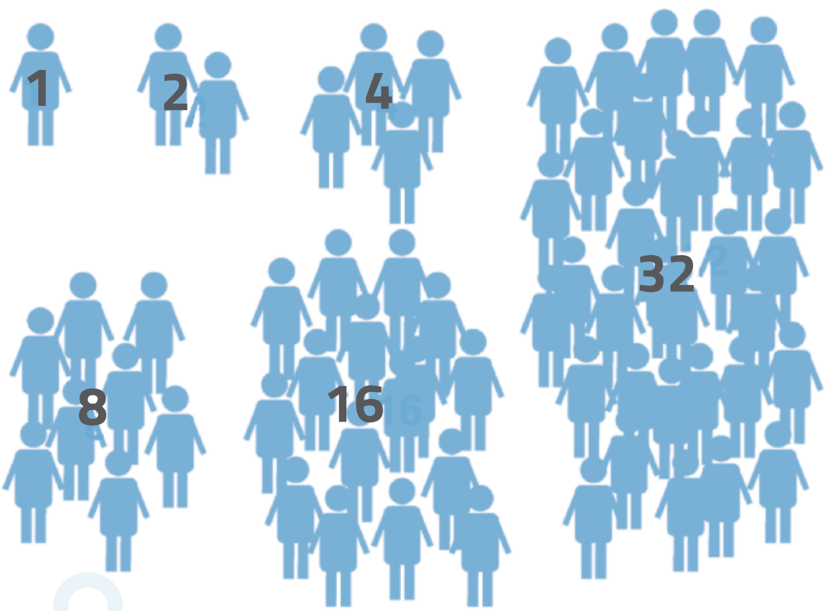


Image courtesy of NRICH

Figure 1: With each step of the standing disease activity, the number of infected students doubles.

REVIEW

- ✓ Biology
- ✓ Health
- ✓ Health and social care
- ✓ All sciences
- ✓ Ages 10–19

Modelling the spread of disease within a population requires knowledge of social contacts and the disease's mode of transmission. This article gives students the opportunity to understand and model disease within a community such as their school and social network. It will stimulate discussion on disease transmission, tracking outbreaks of disease and how quarantine may work. The embedding of mathematics in this activity will stretch and challenge students, showing them that maths is an essential part of science and a key part of epidemiological studies.

Dr Shelley Goodman, UK

a population of 8.5 billion (as there are 2^n new cases in generation n of the outbreak).

- What would happen if each person pointed to 3 or 4 people instead of 2?
- What can this tell us about how infectious diseases spread?
- What are the limitations of this simulation of an outbreak?

R_0 and networks

R_0 (otherwise known as the reproduction number) is a measure used in epidemiology to indicate the average number of people that an infected person infects during the course of the contagious period (assuming that no-one in the population is immune to the disease). If R_0 is greater than one, the disease will spread through the population. If R_0 is less than one, the cases of the disease will decrease and the outbreak will die out.

R_0 varies depending on how long the patient is contagious, the number of susceptible people in the population, and the method of transmission. Airborne diseases, such as measles, generally have a higher R_0 than those spread by bodily fluids, such as Ebola.

For epidemiologists, it is important to know not only the number of people that any one person may infect (R_0), but also how the outbreak may spread through a population. Thus, it is vital to understand the dynamics of the community or population. This is done by looking at how individuals interact with each other: who comes into contact with whom, and how often. Mathematical modellers can then build this information into their simulations to understand how an outbreak has spread through a population. This is vital for health researchers, as it helps them to trace individuals who may have become infected. It can also suggest which patterns of social behaviour may need to be changed if an outbreak does begin, such as social distancing or quarantine.

Although Ebola has the same low R_0 as flu, it quickly turned into a major outbreak in West Africa with a high mortality rate – something that would usually limit the spread of a disease, because people die too quickly to infect a large group. What, then, were the major causes of the spread?

The epidemic was partly triggered by chance; the first person to be infected happened to be a traditional healer in Sierra Leone, whose funeral attracted a large crowd (Freiberger, 2015). The cultural tradition of washing the dead for burial led to increased transmission, and people who touched the infectious body took the disease with them as they travelled to other places. The outbreak was also in an area with weak health systems that were unable to enforce infection control.

This example shows that the R_0 of a pathogen can vary in different outbreaks. The spread of flu, for example, is likely to be different in a group of 4- to 5-year-olds than in a group of 10- to 11-year-olds. Figure 2 shows the interactions between individuals in these two age groups on a particular school day. In the younger age group, there are fewer interactions between multiple individuals overall, compared to the older age group, in which two larger cliques of each sex are evident. The individual nodes with no interactions indicate that a student was absent on that day.

Activity 2: R_0 ranking

Procedure

1. In small groups, ask your students to list five infectious diseases (rabies, flu, Ebola, chickenpox and measles) in order of which they think has the highest and lowest reproduction number. Then reveal each R_0 (0, 1–2, 1–2, 10, 16–18, respectively) – were they what the students expected?

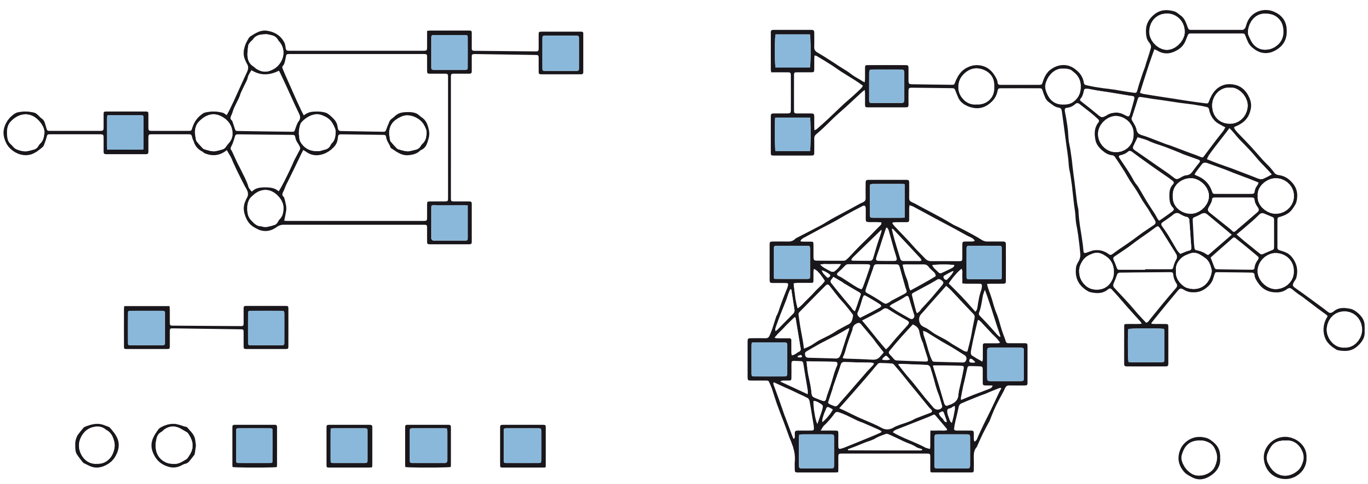


Image courtesy of Andrew Conlan; data source: Conlan et al. (2011)

Figure 2: Social networks for a group of students aged 4–5 (left) and 10–11 (right). Lines between nodes (blue square: male; white circle: female) indicate an interaction between two students.

Discussion

- Is there a connection between the severity of symptoms and R_0?
- What can you say about the diseases with high R_0 (e.g. measles and chickenpox) – why are they so high?
- Why is the R_0 for rabies 0? There is no known human-to-human transmission.
- Why is Ebola cause for concern, when it has a low R_0 value?
- Why can the R_0 of the same pathogen vary in different outbreaks?

Activity 3: Comparing networks

Procedure

1. Show the whole class the diagrams[w1] of two different social networks: one with 4- to 5-year-olds, and one with 10- to 11-year-olds (see figure 2). Ask them what they think the difference is.
2. Discuss why these networking patterns may differ over time.

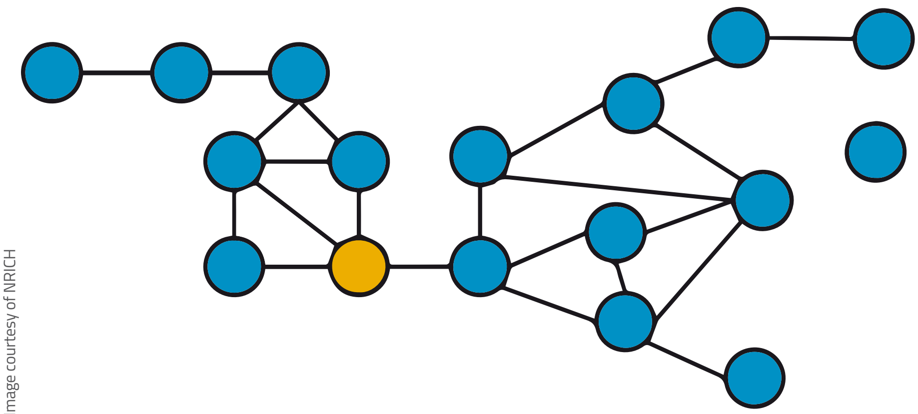


Image courtesy of NRICH

Figure 3: In this social network activity, everyone starts off susceptible (blue), apart from one infected person (yellow).

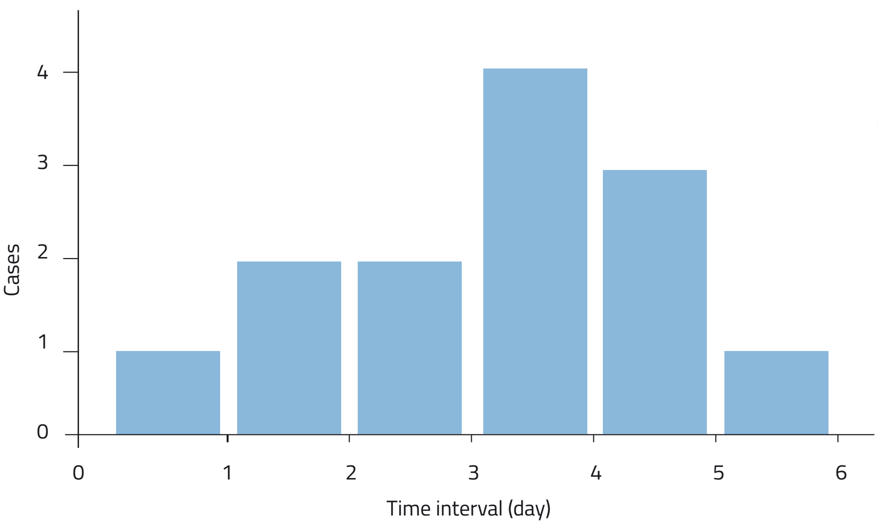


Image courtesy of Nicola Graf

Figure 4: An example graph showing the number of cases against time

Discussion

- How/why does the social network change between 4- to 5-year-olds and 10- to 11-year-olds?
- Would you expect this network to change again for 16-year-olds? What about for adults?

Activity 4: Disease spread through a network

Procedure

1. Separate the class into pairs or small groups. Give each group printouts of a social network[w1] (figure 3) along with a dice.
2. Everyone starts off susceptible; pick one point of the network on the printout to be the first infected person.
3. Go around the infected person's contacts in turn. For each one, roll the dice; if they roll a 1 or a 2, that person also becomes infected. If they roll any other number, they are immune.
4. Repeat for the new infected cases – and so on, until you have rolled the dice for every infected person's contacts.
5. Count how many cases in the group are infected, and how many steps it took in total to infect them all.
6. Repeat the exercise several times, with different starting points. Note the number of cases each time.
7. These data can then be used for further analysis, e.g. mean, median, mode, distribution. Get students to plot graphs (e.g. figure 4) and analyse their results amongst their small group – or as a whole class.

Discussion

- Why are we only infecting those nodes when a 1 or 2 is rolled?
- What would happen if we allowed 1, 2, 3 or 4 to infect someone?
- What happens if you start in different places around the network?

- Why does the outbreak change in size each time it is simulated?

Extension activity: targeted vaccination

Students can consider these questions individually and then feed back to the whole class:

- Who would you vaccinate in the network?
- If you only had 2 or 3 doses of vaccine for the network, who would you choose to vaccinate and why?
- Would you protect people with the greatest number of links, or concentrate on breaking the network in certain places?

Acknowledgement

The teaching activities in this article are adapted from the NRICH[w2] Disease Dynamics series. Additional activities are available in this collection, which aims to show how maths can be used to understand epidemics, social interactions and vaccination.

References

Conlan AJ et al (2011) Measuring social networks in British primary schools through scientific engagement. *Proceedings of the Royal Society B: Biological Sciences* **278(1771):** 1467–1475. doi: 10.1098/rspb.2010.1807

Freiberger M (2015) Ebola in numbers: using mathematics to tackle epidemics. *Science in School* **32:** 14–19. www.scienceinschool.org/content/ebola-numbers-using-mathematics-tackle-epidemics

Web references

w1 Slides and other additional materials are available to download from the *Science in School* website. See: www.scienceinschool.org/2017/issue40/disease

w2 To view the complete Disease Dynamics series, visit the NRICH website. See: www.nrich.maths.org

Resources

Play the pandemic game and attempt to wipe out the world's population as a disease-causing organism. See: http://pandemic2.org

Stimulate the spread of sexually transmitted diseases with a class activity. Visit: www.cpet.ufl.edu or use the direct link: http://tinyurl.com/n3tkpfs

Understand how infectious agents can be transmitted from animals to humans. See: Heymann J (2013) Evolving threats: investigating new zoonotic infections. *Science in School* **27:** 12–16. www.scienceinschool.org/2013/issue27/zoonosis

Discover how archaeology and genetics combine to reveal what caused the Black Death. See: Bos K (2014) Tales from a plague pit. *Science in School* **28:** 7–11. www.scienceinschool.org/2014/issue28/black_death

For more information on infectious diseases and to find infectious disease fact sheets, visit the World Health Organization website. See: www.who.int/topics/infectious_diseases/en/

'Stop the spread' is a STEM challenge from Practical Action where pupils research infectious disease and design and build a model of a handwashing device for a school in Kenya. See: http://practicalaction.org/stop-the-spread

The NRICH Project aims to enrich the mathematical experiences of all learners. To support this aim, members of the NRICH team work in a wide range of capacities, such as providing professional development for teachers wishing to embed rich mathematical tasks into everyday classroom practice.

Image courtesy Nicola Graf

Heroes and villains: the science of superheroes

Challenge your students to work out which exploits of comic-book heroes like Superman might actually be possible – given a miracle or two.

Image courtesy of Maxim Maksutov / Shutterstock.com

Image courtesy of Bonezboyz / Shutterstock.com

By Mike Follows

As a trained scientist, you probably enjoy applying your scientific knowledge to everyday topics, because of the insight this provides into how the world works – and the subtlety involved in deciding which principles to apply.

As a physics teacher, I wanted to allow my students a similar freedom to break out of the school curriculum for a while and consider the science in situations that are intrinsically interesting to them – if not exactly everyday. Prompted by the book *The Physics of Superheroes* (Kakalios, 2009), I decided *to* try incorporating comic-book superheroes into my physics lessons to make the learning experience more engaging for students. The experiment was a success, and while my classes expressed a real enthusiasm for the topic, they also got down to work on some quite challenging science.

In this article, I describe some of the materials I used with my classes, including questions and worked answers, plus some background information on the superheroes themselves for those less acquainted with these colourful characters. These materials are suitable for students aged 16–19, or as a challenge for some able younger students. Discussions and calculations could occupy a class for an hour or longer.

What's science got to do with it?

Superheroes can perhaps best be used in lessons as problem-solving examples, where real science is applied to the heroes' proclaimed abilities to test how coherent these are, and what consequences follow logically from their supposed superpowers. As with any fiction, appreciating comic-book superheroes demands some suspension of disbelief. But for superheroes that are based on science fiction (as opposed to pure fantasy), if we grant them what James Kakalios calls one or more 'miracle exceptions', their powers may become plausible. For example, if we allow that Superman can leap tall buildings in a single bound, what does this tell us about the force of gravity on his home planet, Krypton? We will look at this question later.

REVIEW

✓ Physics
✓ General science
✓ Ages 14–19

This teaching activity is ideal to show how the 'superpowers' of comic-book heroes and villains can be investigated (or proved to be impossible) using scientific facts. The article encourages teachers to look at the surreal adventures experienced by these characters from a new perspective. Some examples provide introductory exercises to use before starting a new topic, such as mechanics, magnetism, materials or light waves – or at the end of these same topics, so that the students can use their newly acquired scientific knowledge to theorise, predict and test whether such superpowers are remotely possible in real life.

Catherine Cutajar, St. Martin's College, Malta

Image courtesy of Nicola Graf

Another possibility is to look at a specific superpower and use this as a context for describing or explaining science. Below I discuss some possibilities based on Marvel Comics' X-Men characters, and also that most enduring superpower: invisibility.

X-Men and their superpowers

The X-Men team of superheroes was created in 1963 by Marvel Comics editor Stan Lee and artist/co-writer Jack Kirby. The X-Men are a mutant subspecies of human who are each born with a different superpower. Let's look at some of the main characters.

- **Charles Xavier, the leader of the X-Men,** is also known as Professor X. Confined to a wheelchair, he has the superpower of telepathy. A class discussion on whether this is plausible could focus on the nature of nerve impulses, and the fact that brain activity involves ions moving within the neural network of our brains. This links to electromagnetism, as the moving ions constitute an electric current that generates a magnetic field, causing low-frequency electromagnetic waves to be radiated from the brains. In principle, it might be possible to 'read' someone's mind – although how detailed this could ever be is an open question.
- **Magneto, the arch-villain of the X-Men,** is a mutant who can generate and control magnetic fields. This superpower provides an opportunity to introduce the different forms of magnetism: ferro-, para- and diamagnetism. The class could also look at how diamagnetism can produce levitation, and whether it would be possible to levitate a person (yes, if the magnet is strong enough: at least 40 tesla, which is some 40 times stronger than a junkyard magnet for lifting cars).
- **Wolverine** is a mutant with a powerful regenerative ability, known as the healing factor, and six retractable bone claws in his hands tipped with the indestructible material adamantium. This fictional metal alloy could prompt students to think about what an 'indestructible' material would be like. Materials have three

Image courtesy of Jeanne Menjoulet; image source: Flickr

Image courtesy of Michelle Tribe; image source: Flickr

Spider's web silk and diamond are both strong materials, but in different ways.

Image courtesy of Nicola Graf

basic mechanical properties: strong materials bear heavy loads; hard materials resist changing shape or being scratched; and tough materials resist fracturing, often by changing shape to absorb energy. For example, although spider silk is tough, it is not hard. While the covalent bonds within diamond make it extremely hard, it is not as tough. Students could be asked to research which real materials (natural or synthetic) excel in each of these properties and why, as well as what new, stronger materials are being developed.

The invisibility cloak

The idea of using a cloaking device to achieve invisibility was first suggested in a 1966 episode of Star Trek. Ask students to discuss: is this something that could actually be achieved? If so, how? What would need to happen for a cloak to make an object invisible? Perhaps ask students to draw ray diagrams that show how this could be achieved.

In principle, if light could be bent around an object, rather than reflected or refracted by it, the object could appear invisible. Metamaterials (real materials designed with properties that natural materials do not have) are now being developed to do just this, by allowing electromagnetic radiation to pass around a 'cloaked' object, like a river flowing around a rock. An observer looking at the cloaked object would then see light from behind it, making the object appear invisible. Although this approach shows promise, only tiny objects have been successfully cloaked so far.

Superman: an exercise in problem solving

Superheroes are a fruitful source of questions on the motion of projectiles and other physics topics. Superman made his debut in the first issue of *Action Comics* in 1938. Readers were informed that he could leap one-eighth of a mile (200 m) high, which can be used as a starting point for finding out other physical facts, if we add some plausible assumptions.

Below are some Superman questions for students to consider, along with their solutions.

1. If Superman jumps 200 m high, show that his launch speed is about 60 ms^{-1}.

There are two possible approaches to this problem: via an equation of motion or via energy conservation. Ask students to solve the problem using both approaches, as this is a good technique for checking answers. It also illustrates what professional physicists do – if alternative approaches give consistent answers, this provides confidence in the result.

Equation of motion approach

Equations of motion used in school physics are often called 'suvat' equations, as they involve the following quantities:

s = displacement

u = initial velocity

v = final velocity

a = acceleration

t = time

Remind students that, if Superman jumps vertically upwards, when he reaches his maximum height he will come to a momentary stop, so his final velocity $v = 0$ ms^{-1}. Assuming that upwards motion is positive, the values of the variables are:

s = 200 m

u = ?

v = 0 ms^{-1}

a = -10 m^{-2} (acceleration due to gravity)

t = irrelevant

Image courtesy of Nicola Graf

Image courtesy of Bonezboyz / Shutterstock.com

So the most suitable suvat equation is:

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

Using the values we have, we can see that:

$0 = u^2 + 2\ (-10 \times 200)$

$u^2 = 4000$

$u = 63.2\ \text{ms}^{-1}$

Energy conservation approach

We assume that, at the top of Superman's jump, all kinetic energy has been transformed into gravitational potential energy. So:

$\frac{1}{2}mv^2 = mgh$

where *m* is the mass of Superman, *v* is his launch speed and *h* is the height he gains above the ground.

Simplifying and substituting values gives:

$v = \sqrt{2gh}$

$= \sqrt{2 \times 10\ \text{ms}^{-2} \times 200\ \text{m}}$

$= 63.2\ \text{ms}^{-1}$

2. When he jumps, what force would Superman experience pushing off from the ground?

Force, *F*, is defined as the rate of change of momentum, *p*. Momentum is the product of mass and velocity, so the rate of change in momentum is Superman's mass *m* multiplied by his launch velocity *v*, divided by the time taken, *t*.

Let's assume Superman has a mass of 100 kg. For *t*, a standard value for 'push-off time' often used in textbooks is 0.25 s.

This gives us the following equation:

$$F = \frac{p}{t}$$

$$= \frac{100\ \text{kg} \times 63.2\ \text{ms}^{-1}}{0.25\ \text{s}}$$

$$= 2.53 \times 10^4\ \text{N}$$

3. If Superman can jump 200 m on Earth, what is the likely gravitational strength of his home planet, Krypton?

When most people jump, they can apply a force approximately equal to their standing weight. On Earth, Superman's standing weight, *W*, is his mass, *m*, multiplied by the gravitational field strength, *g* (which is approximately 10 Nkg^{-1}). Superman has (we assume) a mass of 100 kg, so:

$W = 100\ \text{kg} \times 10\ \text{Nkg}^{-1} = 1000\ \text{N}$

From the question above, we know that when Superman jumps, he applies a force of 2.53×10^4 N, suggesting that this is his weight on Krypton. This in turn suggests that the gravitational field on Krypton is some 25 times stronger than it is here on Earth.

Superman was physiologically adapted for life on Krypton, with its much higher gravitational field strength. On Krypton, he would have seemed average; on Earth, he appears to have superpowers.

4. What can we deduce about Krypton from its gravitation?

This question could be used as a simple introduction to mathematical modelling for students aged 16+. The strength of a planet's gravitational field is proportional to its radius, if the density is uniform. Students can find this relationship themselves, given the equations for gravitational field strength, $g = Gm/r^2$, and for the volume of a sphere, $V = 4/3\pi r^3$.

This means that if Earth and Krypton have similar density and the strength of Krypton's gravitational field is 25 times stronger than that of Earth, then the radius of Krypton is also 25 times that of Earth's.

From this we can draw conclusions about Krypton's mass. Again, assuming uniform density, the mass of a planet is proportional to the cube of its radius. Thus, a 25-fold increase in the Earth's radius would increase its mass by a factor of $25^3 = 1.56 \times 10^4$.

Assuming a value of 5.97×10^{24} kg for the mass of Earth, this means that the mass of Krypton would be:

$5.97 \times 10^{24}\ \text{kg} \times 25^3$

$= 9.33 \times 10^{28}\ \text{kg}$

Image courtesy of Bonezboyz / Shutterstock.com

This is a mass some 15 000 times that of Earth, and around 50 times that of Jupiter. In fact, if Krypton were a gas planet (rather than a rocky planet like Earth), this would be just a little below the mass required to allow the thermonuclear fusion of hydrogen – the process that produces the Sun's energy. So if Superman's creators had made him a little more mighty, his home 'planet' could in fact have been a star.

Ant-Man and other scenarios

It's possible to come up with many similar questions and scenarios based on comic-book characters to exercise students' scientific imagination. For example, the Marvel character and biophysicist Dr Henry 'Hank' Pym discovers a chemical substance (Pym particles) that makes him shrink to the size of an insect, becoming Ant-Man. When Ant-Man gets sucked up by a vacuum cleaner, would he be able to punch his way out of the bag?

This question is really an exercise in scaling. The force with which someone can punch is proportional to the cross-sectional area of muscles in their arms. But because the force of Ant-Man's punch and the area of his fist are both reduced by the same factor, the pressure he could exert on the paper bag would – perhaps surprisingly – be the same as that for Dr Pym.

Of course, this requires the 'miracle exception' of Dr Pym's volume shrinking while all other attributes (including mass) are kept constant – a scenario that leads us into a completely different area of science: atomic structure. Which shows that, with a little imagination, superheroes can take you anywhere. Enjoy the journey!

Reference

Kakalios J (2009) *The Physics of Superheroes* 2nd edition. New York, NY, USA: Gotham Books. ISBN: 1592405088

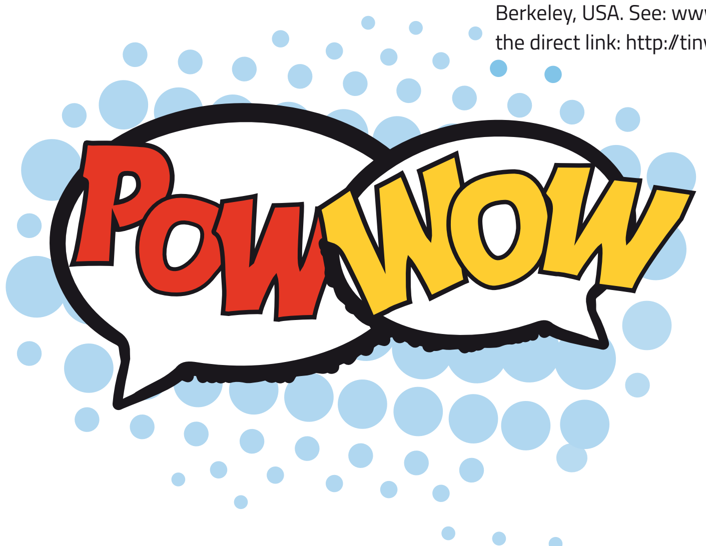


Image courtesy of Nicola Graf

Resources

For a review of *The Physics of Superheroes*, see:

Featonby D (2006) The Physics of Superheroes, by James Kakalios. *Science in School* **2**: 81. www.scienceinschool.org/2006/issue2/superheroes

For another book looking at the science associated with superhero characters, see:

Gresh LH, Weinberg R (2002) *The Science of Superheroes*. Hoboken, NJ, USA: Wiley. ISBN: 0471024600

Watch a video showing frogs being magnetically levitated. See: www.youtube.com/watch?v=KlJsVqc0ywM

For information on metamaterials and invisibility cloaks, see:

The website of the UK's Institute of Physics: www.iop.org/resources/topic/archive/metamaterials

Invisibility shields one step closer with new metamaterials that bend light backwards, a press release from the University of Berkeley, USA. See: www.berkeley.edu or use the direct link: http://tinyurl.com/mqv4xxc

- The student-run *Journal of Special Physics Topics* has papers on a huge range of fun, non-standard physics topics. Volume 14(1), for example, covers Superman, Santa and Cinderella. See www.physics.le.ac.uk/journals/index.php/pst/issue/view/17 or use the direct link: http://tinyurl.com/mev3r8m
- In entertaining videos, Kyle Hill describes and explains the science of superheroes. Search 'Because Science with Kyle Hill' at www.youtube.com or use the direct link: http://tinyurl.com/lay48ul

Mike Follows teaches physics at King Edward's School in Birmingham, UK. He has a PhD in ultralow-temperature physics, and he enjoys developing interesting ways of teaching physics to students, including finding unusual contexts (such as superheroes). He is also drawn to global issues and how physics helps to explain them – and might help solve them.

Image courtesy of Bonezboyz / Shutterstock.com

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- Good laboratory practice is observed when chemicals or living organisms are used
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- Pupils and students are taught safe techniques for activities such as handling living organisms, hazardous materials and equipment.

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