WELCOME

Physics World – free sample issue

Welcome to your complimentary copy of the March 2022 issue of *Physics World* magazine.

As a service to the physics community, we're offering you complimentary access to the March 2022 issue of *Physics World* magazine. As usual, there's a great mix of in-depth features, comprehensive news and analysis as well as incisive opinion pieces, careers articles and book reviews.

The cover feature of this free sample issue looks at how physicists are using X-rays to create a zoomable "Google Earth" of the human body (p33).

There's a great feature about the life of the pioneering astronomer Cecilia Payne-Gaposchkin, who battled sexism and discrimination to succeed (p39).

You can find out how researchers on big-physics experiments are lowering the "carbon footprint" of their supercomputing calculations (p46).

And don't miss our take on the cultural impact of the Netflix movie *Don't Look Up* (p29), see why physics awards need to be as fair as possible (p25), and explore how firms are trying to build commercial fusion reactors (p27).

If you've enjoyed this sample issue, why not visit the *Physics World* website where you can enjoy daily updates on the latest physics breakthroughs as well as our weekly and monthly podcasts. You can also create a free account to unlock all the content on the site and subscribe to our range of e-mail newsletters.

Matin Durrani
Editor-in-chief, *Physics World*

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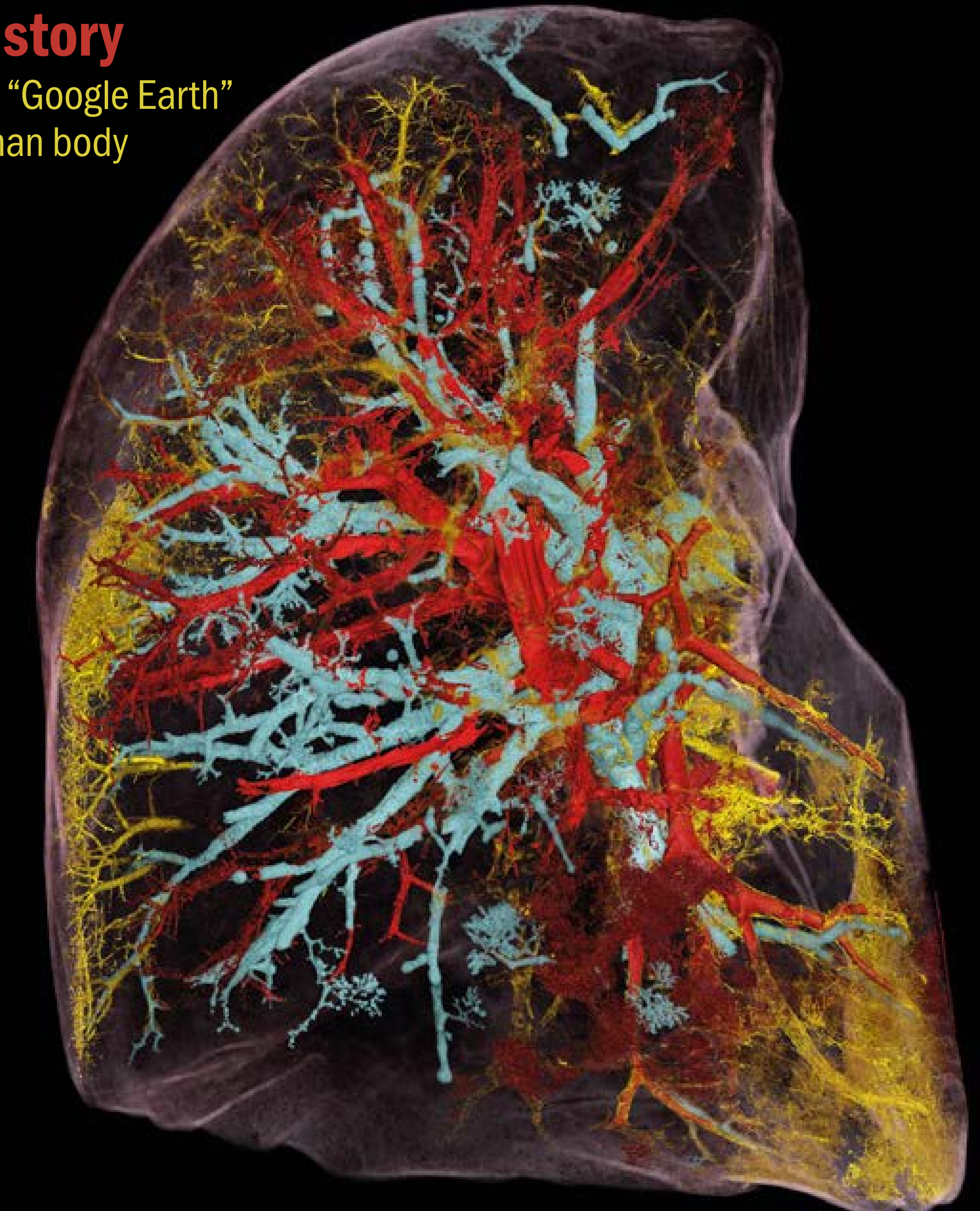
Inside story
Creating a "Google Earth" of the human body



Breaking barriers The life and times of Cecilia Payne-Gaposchkin
Nuclear potential Why companies are seeing the power of fusion
Green difficulties The carbon cost of computing and simulation

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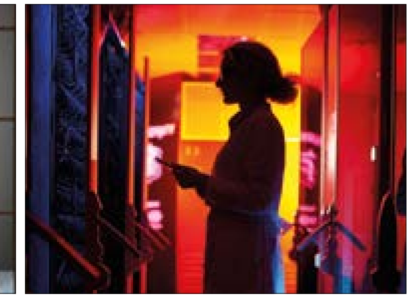

Features

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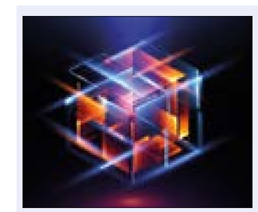
Multimedia



Listen to the *Physics World Weekly* podcast of 17 February to find out all about the physics of "time crystals"

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IOP Publishing

Quanta

For the record

The amount of energy released by the eruption was equivalent to somewhere between 4 and 18 megatonnes of TNT

NASA scientist **Jim Garvin** *quoted by the* Independent

Garvin was commenting on the powerful volcanic eruption in Tonga in late January that destroyed hundreds of homes and cut off communication on several islands.

It's been dead – just following the laws of gravity

Jonathan McDowell *from the US-based Harvard-Smithsonian Center for Astrophysics quoted by the BBC*

A piece of space debris is expected to crash into the Moon on 4 March.

The scientific reward will be immense

Monica Colpi, *an astrophysicist at the University of Milan–Bicocca in Italy, quoted in* Nature

Colpi was commenting on the possible discovery of a gravitational-wave background that could reveal how black holes interacted with dark matter, stars and gas clouds in their galaxies.

That's something that I constantly have to battle with

Farrah Simpson, *a PhD candidate at Brown University, quoted in* Symmetry

Simpson notes that intersectional identities such as being a Black woman in quantum physics are not welcomed in "certain spaces" as "people want you to be just one thing" or "don't want you to be your whole self".

If there comes a day when the influence of the fringy people overrides the influence of people like me and other sober-minded scientists on the team, then I'm gone

Kevin Heng, *an astrophysicist at the University of Bern, quoted by* Science

Heng says he is concerned that some of the "research affiliates" on the $1.8m Galileo Project, which aims to search for evidence of extraterrestrial technology, have no background in science, instead being UFO enthusiasts.

I don't think anybody's beliefs are strange

US actor **Halle Berry** *quoted by Sky News*

A new film – *Moonfall* – that stars Berry explores several Moon conspiracy theories.

Seen and heard

Bernard DUPONT/CC BY-SA 2.0

How the lizard got its spots

A leopard might not be able to change its spots, but the ocellated lizard certainly can. Found in south-western Europe, it sports green or black scales that act as camouflage to evade predators. As the animal matures, individual scales change from one colour to the other, eventually forming a labyrinthine-like mosaic at adulthood. Researchers at the University of Geneva simulated this pattern a few years ago as a "cellular automaton" – the computing system invented by the mathematician John von Neumann in which each element changes according to the state of neighbouring elements. The model agreed with observations, but it contained a whopping 14 parameters, prompting the researchers to look for something simpler. They have now turned to the antiferromagnetic Ising model, which was developed in the 1920s to describe the behaviour of magnetic spins that can be in two states and only interact with their neighbours. Surprisingly, when the researchers modelled this onto a hexagonal arrangement, this simple two-parameter model was able to explain the lizard's labyrinthine pattern (*Phys. Rev. Lett.* **128** 048102). You could say it was spot on.

Here's your chance of love

You may remember in late 2020 when physicist Steven Wooding created an online resource to persuade "flat-Earthers" that the Earth is spherical and not a disc (December 2020 p3). Wooding is now back with a new project about something just as tricky – finding your chances of love. Released just before Valentine's Day, the Drake Equation for Love Calculator is an adaptation of the famous Drake equation, which estimates the number of alien civilizations in our galaxy with whom we could communicate. The love calculator – created with the help of data scientist Rijk de Wet – asks users to input their location, social skills and attractiveness as well as the age range of potential partners and whether they are university educated (bit.ly/34Ldcnu). The output is then compared to the possibility of an alien civilization existing within 1000 light-years of the Earth. Wooding told *Physics World* that his own odds of finding love are 2.1 times better than the possibility of alien life. Is he being perhaps a bit picky?

AI overtakes humans

Computers are already advanced enough to beat the best human players at games such as chess and poker. But now artificial intelligence (AI) has been taken to the next level by outcompeting four world-champion-level human players in the head-to-head car-racing game *Gran Turismo*. Peter Wurman and colleagues from Sony taught an AI "agent" named GT Sophy to play *Gran Turismo* using deep reinforcement learning. It was trained to accelerate and brake the car efficiently over a course, as well as find alternative paths in different conditions or when blocked by opponents. The system can also work out how to avoid penalties that would be incurred by breaching race etiquette (*Nature* **602** 223). As well as giving humans a good beating, which it did over three car and track combinations, the findings could have applications in robotics, aerial drones and self-driving vehicles. E-sports players, watch out!

ESA

A toy's trip in space

The International Space Station (ISS) had an unusual guest in late January. – ROBert the Playmobil "robotic genius". The tiny toy was first greeted by European Space Agency astronaut and materials scientist Matthias Maurer. ROBert then had a guided tour of the ISS and, in a video report, Maurer discussed what astronauts do in a typical day, where they sleep and what activities they can do in the microgravity environment. But it wasn't all just hard work: in the video ROBert can be seen enjoying a spectacular view of Earth from the ISS's panoramic "cupola" window. "I learned how small and fragile our planet is," remarked ROBert, "and that we only have this one."

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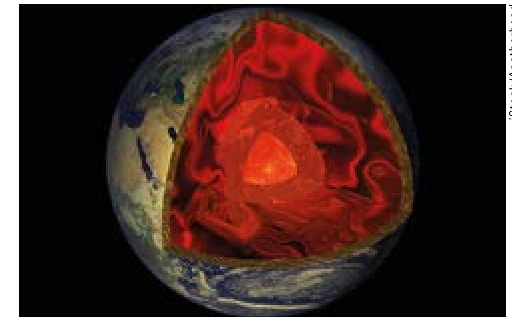
Magnetic fields may protect life on Earth-like planets

The extreme pressures and temperatures found in the cores of Earth-like planets have been recreated using an ultrahigh-power laser at the Lawrence Livermore National Laboratory in the US. The findings suggest that rocky planets larger than Earth should have strong magnetic fields that are sustained over billions of years. The work could also be helpful in the search for life on Earth-like exoplanets (*Science* **375** 146).

When a rocky planet forms, material below the surface crust separates into a lighter silicate mantle that floats on a dense iron core. The molten core gradually loses heat to the surrounding mantle and, in the case of Earth, the inner core solidifies – releasing even more heat. This movement of heat occurs via convection in Earth's molten outer core – activating a dynamo process that generates a strong magnetic field. This field shields life on Earth from deadly radiation, and astrobiologists believe this process could be a prerequisite for organic life to emerge on other planets. However, questions remain surrounding the conditions that allow this convection to occur and remain stable over billions of years.


iStock/Anetherhood

Magnetic shield Ultrahigh-power laser experiments show that rocky planets larger than Earth should have strong magnetic fields that are sustained over billions of years.

In the high-pressure, high-temperature environments of planetary interiors, molten iron convection is adiabatic. This means that it has a well-defined temperature profile as it flows. At the same time, iron's melting point is known to depend on its pressure, in a relationship described by the iron "melting curve". Within a planet's core, temperature and pressure change as a function of depth, and iron will solidify where the temperature and pressure intersect the melting curve. Within the Earth, this intersection occurs close to the centre – resulting in a solid inner core and processes that can drive a magnetic dynamo for billions of years.

If the intersection occurs further from the centre, crystallization will occur in a "top-down" process – a bit like ice forming on a lake. Here, solid "snowflakes" of iron form close to the edge of the core, leaving a molten centre. In this snowflake scenario, a magnetic dynamo is not expected to be sustained for long periods. In their study, Kraus's team recreated these varying conditions by heating iron with an ultrahigh-power laser at Livermore's National Ignition Facility. This generated pressures exceeding 1000 GPa, which is three times that experienced by Earth's inner core. Using X-ray diffraction, the researchers could then analyse the melting curve of iron.

The team discovered that the strongest magnetic fields emerge in planets with roughly 1.5 times the radius and around five times the mass of the Earth. Such conditions generate a strong temperature gradient between the molten outer core and the mantle. This in turn drives strong convection patterns in the molten iron, generating and sustaining magnetic fields for billions of years.

Sam Jarman

Space

Astronomers watch the death of a red supergiant in real time

Astronomers have captured the death of a red supergiant star in real time revealing a dramatic surge in brightness in the months preceding its final explosion. The event, which was far more violent than would be expected from previous observations, could transform astronomers' conceptions of how massive stars behave in the last few months and days of their existence (*ApJ* **924** 15).

To study the evolution of massive stars in their final moments, astronomers can observe the material surrounding them at the instant that they collapse and explode in dramatic Type II supernovae. This material is supplied as the star loses mass, and after the supernova produces an intense flash, it becomes ionized by highly energetic photons. By analysing the resulting emission spectra following this explosion, astronomers can model the evolving environment surrounding the star in its last few months. In turn, this can shed light on how the star's internal structure is changing.


W M Keck Observatory/Adam Makarenko

Champagne supernova New images could help astronomers understand how massive stars behave in the last few months and days of their existence.

Observations by the Pan-STARRS survey in Hawaii in 2020 detected excessive amounts of light emanating from a red supergiant roughly 10 times the mass of the Sun, located in the galaxy NGC 5731. At first, this brightness remained remarkably stable and persistent. But after 130 days, observations from the W M Keck Observatory, also in Hawaii, recorded the star suddenly collapsing and exploding in real time. By modelling the photoionization observed in the dense material surrounding the star, Wynn Jacobson-Galán at the University of California, Berkeley, and colleagues showed that it had shed large amounts of mass prior to going supernova at a rate of roughly 0.01 solar masses per year. Such violent behaviour was particularly surprising for a red supergiant.

This suggests that at least some red supergiants must experience turbulent changes to their internal structures prior to going supernova. Jacobson-Galán's team also determined that the power that generated the star's bright emission likely originated from the burning of neon, oxygen or silicon. The products of this burning may then trigger buoyancy-balancing gravity waves – which would deposit energy into the star's outer envelope, intensifying both its brightness and mass loss.

Sam Jarman

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Astronomy

Lone black hole found wandering the Milky Way

An international group of astronomers believe they have discovered the first "isolated" stellar-mass black hole wandering through interstellar space. The team used the Hubble Space Telescope to reveal the black hole, which lies roughly 5000 light-years away in the constellation Sagittarius (arXiv:2201.13296).

Black holes with masses comparable to stars have been detected in our galaxy before, but their presence has always been inferred either by their interactions with a companion star, which create a glow at X-ray wavelengths, or from the gravitational waves that are produced when they collide. This new finding, however, is the first time that one has been clearly identified in isolation. The discovery was made using a technique known as "astrometric microlensing", which uses the fact that a mass moving through space can act like a gravitational lens. This lens distorts both the brightness and, crucially, the apparent position of stars along the line of sight of the observer far beyond the mass itself.

For years astronomers have been carefully watching Milky Way "star fields" looking for these characteristic deflections and brightness changes. In 2011 such a warping of a distant star was caught by telescopes in New Zealand and Chile. A follow-up study with Hubble examined how the background star's light was being shifted and what might be causing it. "We had to continue observing once every six months to a year, for six years," says Kailash Sahu from the Space Telescope Science Institute in Baltimore, US, who is lead author of the new study. Hubble's capabilities allowed Sahu and colleagues to measure the apparent tweaking of the star's position with a precision of roughly 0.2 milli-arcseconds – about 10 million times smaller than the diameter of the full Moon.

ESO/S Guisard

I wandered lonely The Hubble telescope has been used to study a fast-moving black hole roughly 5000 light-years away in the constellation Sagittarius – it is thought to be travelling at 162 000 kilometres per hour.

The amount of deflection observed during the six-year study suggests that the object creating the gravitational lens has a mass about seven times that of the Sun. The scientists argue this mass cannot be a regular star or a multiple star system because there would be radiation visible from those phenomena – and no such light has been detected. It's also too hefty to be a stellar remnant known as a white dwarf. "Moreover, the inferred mass is too large for the gravitational lens being a binary neutron star," the team adds. This and other evidence, they say, points to the object being a solitary stellar-mass black hole.

One intriguing quirk of the black hole is that its speed through the Milky Way is a staggering 162 000 km/h. That, according to Sahu, means it is outpacing "almost all" the stars in its surroundings. "Since none of the other stars are moving this fast, we think this must be because [the black hole] got a 'kick' during the supernova explosion that produced [it]," he says.

Will Gater

Animal physics

Magnetic crystals in the noses of salmon could aid navigation

Tiny crystals of iron-based magnetite have been found in specialized receptor cells in the noses of salmon, suggesting that the crystals are used by the fish to navigate by Earth's magnetic field. The research was done by an international team of scientists who have also discovered a possible evolutionary link between the magnetic sensory mechanisms of animals and magnetotactic bacteria that contain tiny "compass needles" (*Proc. Natl. Acad. Sci.* 119 e2108655119).

Salmon hatch in rivers before migrating to the sea and then returning as adults to their riverbed of birth to spawn. This migration can extend over thousands of kilometres and studies in which young salmon were exposed to magnetic fields suggest that the fish use an internal compass to navigate. Scientists believe that this response could be related to magnetite, which is a magnetic material present in some organisms. However, a specific magnetite receptor has not been found in animals – and how animals sense Earth's magnetic field remains a mystery.

Renee Bellinger at Oregon State University and colleagues have now used a combination of techniques to find magnetite crystals in salmon cells taken from nose tissue. First, they probed the cells using ferromagnetic resonance – which measures the coupling between electromagnetic waves and the magnetization of a substance. Then they used a combination of atomic and magnetic force microscopy – which each involve probing the samples with a tiny mechanical cantilever – to create extremely high-resolution images of the cells and the magnetic structures they contain. The team discovered that magnetite within the salmon cells exists in compact, egg-shaped clusters.

Zureks/CC BY-SA 3.0

Living compasses Researchers have found that the ability of salmon to use magnetic fields to navigate could have ancient origins.

Each of these clusters measures around 200–300 nm in diameter, and contains roughly 100–200 individual crystals.

The growth of crystals inside living cells – known as biomineralization – is used by magnetotactic bacteria to grow chains of magnetite crystals. The bacteria use these tiny "compass needles" to orient themselves with respect to Earth's magnetic field, possibly to move to regions of optimal oxygen content. Through subsequent genetic analysis, Bellinger and team discovered that the biomineralization genes expressed in salmon receptor cells were like those found in bacteria containing magnetite. This, they say, suggests that several billion years ago a magnetite-containing bacteria may have been incorporated into a more complex organism in a process called endosymbiosis – creating a distant ancestor of the salmon.

Sam Jarman

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KATRIN sets neutrino mass limit

Björn Lehnert from the Lawrence Berkeley National Laboratory talks to Richard Blaustein about what a new measurement of the upper mass of the neutrino means for particle physics

Based at the Lawrence Berkeley National Laboratory in the US, Björn Lehnert is a neutrino physicist who originally did a PhD at the Dresden University of Technology in Germany on the GERDA experiment. Following a postdoc at Carleton University in Canada, he moved to California in 2018, where he works on the double-beta-decay experiment LEGEND. He is also part of KATRIN (the Karlsruhe Tritium Neutrino Experiment), which last month reported a new upper limit on the mass of the neutrino (*Nature Physics* 10.1038/s41567-021-01463-1).


Björn Lehnert

Weighty matters Physicist Björn Lehnert performed parts of the analysis to determine the upper limit of the neutrino's mass using the Cori supercomputer at Berkeley Lab's National Energy Research Scientific Computing Center.

Can you explain what KATRIN is designed to do?

KATRIN, which is based at the Karlsruhe Institute for Technology in Germany, was inaugurated in 2018 and is a collaboration between the Czech Republic, Germany, Russia, the UK and US. It consists of about 130 scientists and is the only experiment that can make direct measurements of neutrino mass.

How do you measure the mass of a neutrino?

Neutrinos are the most abundant – and elusive – particles in the universe and measuring neutrino mass is very difficult. There are several approaches, some of which are model dependent in that they are based on assumptions about the universe. First there is the cosmological approach, which considers where neutrinos have influenced the evolution of the universe, specifically in the creation of large-scale structures such as galaxy clusters. If neutrinos are light, it would favour the formation of smaller-scale structures, while heavier neutrinos disfavours smaller structures. By measuring the distribution of smaller and larger structures in the universe, it is possible to infer the neutrino's mass. Another method is double-beta-decay experiments, which search for whether neutrinos are their own antiparticles, so called Majorana particles.

So how does KATRIN measure mass?

KATRIN's main component is the world's largest spectrometer (measuring 23 metres long and 10 metres wide) to boast an ultrahigh vacuum. Tritium – an isotope of hydrogen – undergoes beta decay, producing an electron and an antineutrino. We then guide the electrons into the spectrometer without changing their energy. We cannot measure the neutrino directly because it is so weakly interacting, but we can precisely measure the electron's energy. As both particles share energy, it is possible to resolve the small influence from the neutrino's mass by looking at the electrons with the highest energies in the spectrum.

KATRIN has just announced an upper limit for the neutrino mass of 0.8 eV. What does this signify?

KATRIN started its five-year run in 2019 and this is the first time any lab experiment has produced the required sensitivity to rule out the mass of the neutrino being greater than 0.8 eV. That is a real advance as it breaks the "psychological barrier" that we had in not knowing whether the neutrino is heavier than 1 eV. Importantly, we now know that the neutrino is at least 500 000 times lighter than the electron.

In 2019 the KATRIN experiment provided a first stab at the mass of a neutrino. How is this result different?

This year's finding is the result of more data with the experiment also running at a higher tritium source strength. The initial tests showed that KATRIN worked and that we could improve the mass limit by a factor of two compared to previous experiments. This finding improves that mass limit by close to a factor of three.

What was your role in the experimental analysis?

I was involved in carrying out the statistical analysis using a Bayesian approach and co-leading the group looking at how electrons scatter on their way to being detected. The probability of scattering and the amount of energy the electrons lose when they scatter is crucial to obtaining a high-precision reading that allows us to then extract the neutrino mass.

What's next for KATRIN?

KATRIN will run for another three years and in that time we will get better statistics. We then expect the uncertainty from the measurement statistics to be roughly the same as systematic uncertainties from the experimental set-up. We will then stop the measurement expecting a final sensitivity of about 0.2 eV.

And what about beyond KATRIN?

The limiting factor of KATRIN is chemistry because we use molecules of tritium (T_2). Molecules are complex objects – they have more degrees of freedom than atoms – so every decay is a little bit different, and the final state of electrons have a distribution. At some point, we cannot improve neutrino-mass measurements because the initial decay has an uncertainty. The only way to improve this is to use atomic tritium. This is planned for a future experiment called Project 8, which is promising, but will be some years yet before it comes online.

JET smashes fusion energy record

The Joint European Torus has achieved 59 megajoules of fusion energy in a single fusion "shot", more than doubling the previous record. **Michael Banks** reports

The Joint European Torus (JET) nuclear-fusion experiment based in Oxfordshire, UK, has more than doubled the amount of fusion energy produced in a single "shot" – smashing a previous record that JET held since 1997. Officials last month announced that during an experiment in late 2021, JET achieved 59 megajoules (MJ) of fusion energy, beating the previous record of 22 MJ.

JET, which was built in 1983, is operated by the Culham Centre for Fusion Energy (CCFE) – the UK's national fusion research laboratory. It is a fusion reactor that uses magnetic confinement to hold a hot plasma reaching temperatures of 150 million kelvin, 10 times that in the centre of the Sun. Fusion, which powers stars, occurs when two light nuclei, such as hydrogen and its isotopes, fuse together to produce a heavier nucleus while releasing energy. Designed to study the conditions approaching those in a fusion power plant, JET is the only device currently operating that can use the deuterium–tritium fuel mix, of the kind that will be used for commercial fusion power.

Experiments on JET are funded by the EUROfusion consortium of 30 member institutes from across Europe including the UK, Switzerland and Ukraine. JET famously carried out the world's first controlled release of deuterium–tritium fusion in 1991. Six years later it produced a five-second shot that produced 22 MJ of total energy and a peak 16 MW of fusion power for about 0.15 seconds. As the pulse was driven by 25 MW of input power, this gave a ratio of fusion power to heating power as 0.64 – a world record that remains today.

Following that experiment, JET went back to using a deuterium plasma and much of JET's work since has been in preparation for the ITER experimental fusion reactor, which is currently under construction in Cadarache, France. This includes plasma-physics research, systems testing and materials investigations. A £60m upgrade to JET was completed in 2011 that involved replacing the carbon tiles from the inner reactor wall with beryllium and tungsten – to test the materials that ITER will use.

UKAEA

Hotter than the Sun Researchers on the Joint European Torus nuclear-fusion experiment have produced about 11 MW of power over five seconds.

Over the past few years, JET has been upgraded to begin operating with tritium again. On 21 December researchers at the facility created a deuterium-tritium fusion shot that produced an energy of 59 MJ over five seconds. The 11 MW produced (with 40 MW of input power) is lower than that achieved in 1997, resulting in a ratio of fusion power to heating power of about 0.3. However, the power was sustained over a longer period of five seconds. Indeed, officials say that they now want to focus on producing "sustained" fusion energy rather than optimizing a brief peak performance.

"These landmark results have taken us a huge step closer to conquering one of the biggest scientific and engineering challenges of them all," says Ian Chapman, chief executive of UKAEA. "It's clear we must make significant changes to address the effects of climate change, and fusion offers so much potential. Our world needs fusion energy."

These landmark results have taken us a huge step closer to conquering one of the biggest scientific and engineering challenges of them all

Some physicists have, however, questioned the breakthrough, asking why it has taken 25 years to only double the energy. Yet Steve Cowley, director of the Princeton Plasma Physics Laboratory in the US, disagrees with the sentiment. "JET hasn't got bigger and the magnetic field hasn't got stronger," Cowley told *Physics World*. "So the improvements have come from a fundamental understanding of the physics and the skill of the operational team in coaxing the old machine along. It's a triumph."

Future aims

When ITER begins using deuterium and tritium in 2035, it will seek to generate about 500 MW over 300 seconds using a plasma heating of 50 MW, and the results by JET not only agree with predictions but give further confidence that ITER will meet those targets. "A sustained pulse of deuterium–tritium fusion at this power level – nearly industrial scale – delivers a resounding confirmation to all of those involved in the global fusion quest," says ITER director general Bernard Bigot. "For the ITER project, the JET results are a strong confidence builder that we are on the right track as we move forward toward demonstrating full fusion power."

The CCFE says that the experience of operating with tritium is also helping to prepare to operate a new facility on the Culham campus – H3AT – that will be one of the largest R&D facilities for tritium in the world once opened in 2024. It will be required when the UK's prototype fusion power plant – dubbed the Spherical Tokamak for Energy Production – comes online in the 2040s.

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Climate

Neutrino collaboration publishes green policy to help reduce emissions

A planned neutrino project has published details of how it will reduce its carbon footprint over the coming decade. The green policy for the Giant Array for Neutrino Detection (GRAND) experiment follows research last year that found that its annual greenhouse gas emissions could be equivalent to that from building 1000 cars. The researchers behind the neutrino array believe that the environmental document is the first of its kind by a large-scale physics experiment.

The GRAND project aims to detect ultrahigh-energy neutrinos originating from deep space using 200 000 antennas spread across mountainous regions around the world. A small-scale prototype started in 2020, while a mid-scale experiment is planned for 2025. Last year the project's team estimated that when the full-scale experiment comes online in the 2030s it could produce 13 385 tonnes of CO_2-equivalent annually. This is on par with the emissions from almost 8000 return flights from France to Western China or the manufacture of 1000 cars, they claim.

The green policy, signed in January, outlines how the collaboration intends to improve its environmental performance. It focuses on three areas: travel; digital technologies such as computers, simulations and data storage; and hardware including the neutrino-detecting radio antennas. Carbon emissions from each area are expected to change during the three stages of the project. Once the main experiment starts, however, most of the emissions will be shared between hardware (48%) and digital technologies (45%) with the remaining 7% coming from travel.

GRAND Collaboration

Green deal The Giant Array for Neutrino Detection's green policy outlines how the collaboration intends to work to improve its environmental performance.

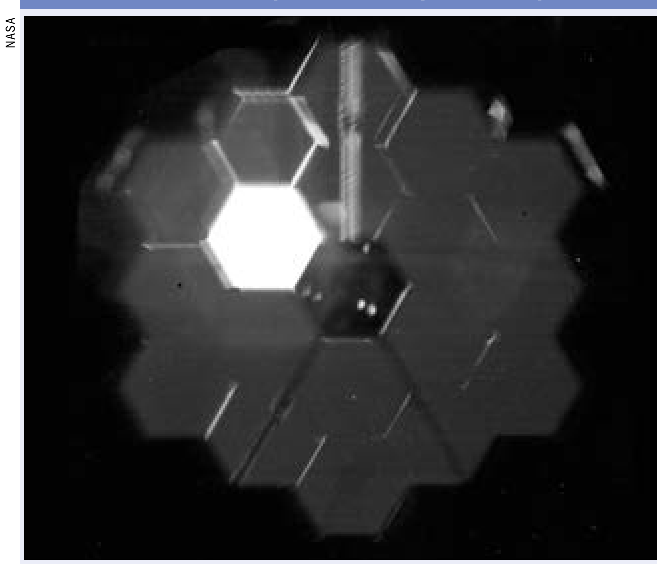
To reduce travel-based emissions, the project will, where possible, use local collaborators for on-site work. It will also combine trips for different work activities as well as host meetings in locations that reduce the environmental impact of travel, such as travel hubs. The guidelines for hardware include optimizing detectors to reduce material and electricity consumption; using local manufacturing; and establishing recycling plans for equipment. The digital section of the policy, meanwhile, focuses on cutting data volumes to lower emissions from transfer and storage; using low-carbon-emitting data centres; reducing repeat or unnecessary simulations; and encouraging longer use of devices like computers and considering repairability when buying new devices

Kumiko Kotera, a physicist from Sorbonne University in Paris who co-founded the GRAND project, told *Physics World* that the collaboration hopes that having published policies will encourage members to take action to reduce their climate impact. Kotera also hopes that other experiments will be inspired to develop similar polices, adding that none of the actions they are proposing are novel or ground-breaking, just sensible. "The best thing we can do as scientists today is to talk about [global warming] and show that we are concerned, and we are paying attention and trying our best to work on it," she says.

● See pp46–50

Michael Allen

NASA's James Webb Space Telescope takes space 'selfie'



NASA

NASA has released a "selfie" of the primary mirror on the James Webb Space Telescope (JWST), which blasted off in late December and is now at its destination – the L2 Lagrange point, 1.5 million kilometres from Earth. The picture was taken using a specialized "pupil-imaging lens" that is inside the observatory's Near Infrared Camera (NIRCam). The lens was designed to take images of the primary mirror segments to aid the alignment process rather than take images of space. Last month, NASA released the first unaligned images from the JWST that were also taken by NIRCam (bit.ly/3GZMkO5). The mosaic image shows a star called HD 84406 in the constellation Ursa Major. As the telescope it not yet aligned, however, the photo shows starlight from the star 18 times, once from each of the 18 primary mirror segments. The blurry starlight will be used to align and focus the telescope and over the coming months the team will gradually adjust the mirror segments until the 18 images become a single star. "The entire Webb team is ecstatic at how well the first steps of taking images and aligning the telescope are proceeding," says Marcia Rieke from the University of Arizona who is principal investigator for the NIRCam instrument. "We were so happy to see that light makes its way into NIRCam." The picture is a crucial step towards the instrument coming online in June where it will begin collecting light from celestial objects.

Michael Banks

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Nuclear energy

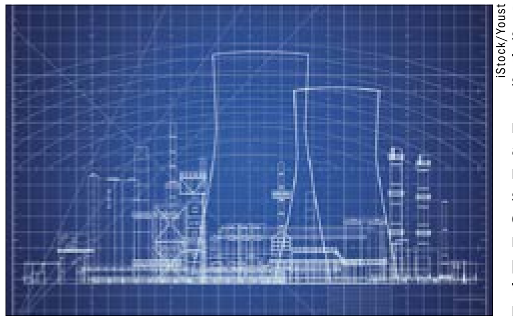
Ex-regulators dismiss a nuclear solution to climate change

An international quartet of former nuclear power regulators has issued a statement opposing the idea that nuclear energy represents a viable strategy against climate change. In the statement, the group disputes the often-repeated message that a new generation of nuclear will be clean, safe, and cheap, adding that nuclear power has the potential to "cause significant harm".

The statement comes in the wake of November's COP26 meeting in Glasgow, where alternative sources of green energy, including nuclear power, were pitched to world leaders. New generations of nuclear power have convinced the European Union and others of its ability to provide energy while being "green". In February, for example, the European Commission announced plans to classify nuclear (and natural gas) reactors as sustainable sources. And a letter from 79 scientists – including physics Nobel laureate Steven Chu, who is a former US energy secretary – called on California governor Gavin Newsom to reverse the state's decision to prematurely close its Diablo Canyon nuclear power plant, which the group claims is "California's single largest source of carbon-free electricity".

However, four former nuclear power regulators – including Gregory Jaczko, former chair of the US Nuclear Regulatory Commission and Wolfgang Renneberg, former head of the reactor safety, radiation protection and nuclear waste division in Germany's Federal Environment Ministry – released a statement in late January disagreeing with nuclear's ability to provide green power.

"The central message, repeated again and again, that a new generation of nuclear will be clean, safe, smart and cheap, is fiction," their statement asserts, which was written with Bernard Laponche, former director general of the French Agency for Energy Management, and Paul Dorfman, former secretary of the UK's committee examining radiation risk from internal emitters.


iStock/Yousf

Nuclear fallout Four ex-members of the nuclear industry say that nuclear power is too expensive and complex to be a viable method to tackle climate change.

"The reality is nuclear is neither clean, safe or smart; but a very complex technology with the potential to cause significant harm."

The quartet also points out that nuclear would also have to be built at scale. "Perhaps most importantly nuclear is just not part of any feasible strategy that could counter climate change," the statement says. "To make a relevant contribution to global power generation, up to more than ten thousand new reactors would be required, depending on reactor design."

Representatives of the nuclear industry, however, have hit back. "It's clear that increased use of nuclear energy, combined with major investments in wind turbines, solar panels and energy storage, is the key to affordable, reliable and increasingly clean energy supply," John Knox, senior vice president of public affairs and policy development at the Nuclear Energy Institute in Washington, told *Physics World*. Knox emphasizes that nuclear is a continuous source of energy and says that building a new generation of smaller, modular reactors can be more cost effective than producing power with renewables and energy storage alone.

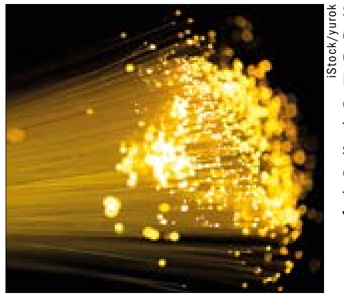
Peter Gwynne
Boston, MA

Materials

International Year of Glass gets cracking in Geneva

The International Year of Glass (IYoG2022) kicked off last month with a two-day opening ceremony at the Palace of Nations in Geneva, Switzerland. IYoG2022 will celebrate this versatile material, which underpins many technologies that have transformed the modern world. Events throughout the year will also highlight why glass is critical in achieving the United Nations' 2030 Agenda for Sustainable Development.

The IYoG2022 is chaired by Alicia Durán, a physicist at the Spanish Research Council in Madrid. Durán played a key role in building support for the project while serving as president of the International Commission on Glass between 2018 and 2021. The global glass industry and cultural institutions are also backing IYoG2022, which now has 2100 endorsements from 90 nations.


iStock/yurok

Something to celebrate Glass optical fibres have revolutionized communications and their impact on society will be celebrated during the International Year of Glass.

One of the aims for IYoG2022 is to highlight the role of glass in advancing civilization and modern science. This year is the centenary of the discovery of Tukankhamun's tomb in Egypt's Valley of the Kings. To mark the occasion, Egypt will inaugurate its new Grand Egyptian Museum just outside Cairo, which showcases ornamental glass from Ancient Egypt. Egypt will also host an IYoG2022 event "From Pharaohs to High Tech Glass" on 18–20 April.

This year's major glass fairs will have a focus on IYoG2022. China, the world's biggest producer and consumer of glass, will host China Glass 2022 in Shanghai on 11–15 April, while the centenary of the German Glass Technology Society will be marked on 2–8 July in Berlin. The US will celebrate the National Day of Glass Event on 3–5 April in Washington, DC, while Mexico will host GLASSMAN in Monterrey on 11–12 May.

Events will highlight how glass-based technologies can contribute to the UN's 17 sustainable development goals. Glass is widely used in renewable energy for concentrated solar power, photovoltaics and the fibreglass of wind turbines. Glasswool is used for insulating houses, while new window technologies can make buildings efficient and light.

James Dacey

Ethics

US science adviser Eric Lander steps down

The mathematician and geneticist Eric Lander has resigned as science adviser to US president Joe Biden following an investigation that found "credible evidence" Lander had mistreated and demeaned staff at the Office of Science and Technology Policy (OSTP). The investigation, which was prompted by a complaint from OSTP lawyer Rachel Wallace, revealed that Lander had overseen a toxic work environment in which he frequently bullied, cut off and dismissed subordinates.

In a move that has surprised much of the American scientific community, Biden responded by splitting Lander's job into two. Francis Collins, who retired as director of the National Institutes of Health in December, becomes the interim science adviser, while Alondra Nelson, a sociologist who is OSTP's deputy director for science and society, will head OSTP for now.

In a strongly worded editorial entitled "Biden doesn't get it", *Science*'s editor Holden Thorp asserts that Nelson should have both jobs. Meanwhile, Neal Lane, who was president Bill Clinton's science adviser, argues that the arrangement could cause bureaucratic confusion. John Holdren, president Barack Obama's science adviser, however, thinks that Collins and Nelson will be able to work together, particularly in "domains where Francis is not an expert".


Cameron Smith, White House Photographer

Double trouble? Eric Lander (left), who had been US president Joe Biden's science adviser since June 2021, will be replaced by Francis Collins and Alondra Nelson.

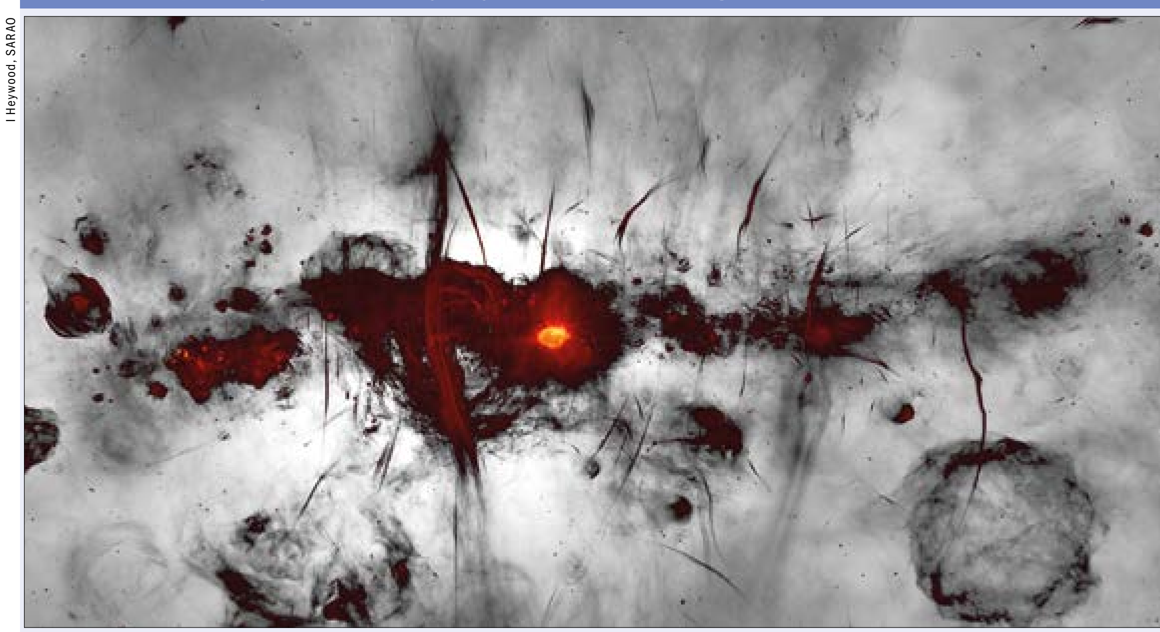
Before becoming director of the OSTP last year, Lander had a successful career co-heading the effort to sequence the human genome, and founding and leading the Broad Institute for genomic research. As the first presidential science adviser to be a member of the president's cabinet, Lander headed a new Cancer Moonshot initiative intended to cut cancer's death rates and had led efforts to create a new Advanced Research Projects Agency for Health to fund potentially significant biomedical advances. He had also played a key role in the administration's response to tackling COVID-19.

Scientists with experience in government saw the resignation as inevitable following the findings of the report, which tallied with his reputation as an excessively demanding manager who has little patience with colleagues. "I am devastated that I caused hurt to past and present colleagues by the way in which I have spoken to them," Lander wrote in his resignation letter. "That was never my intention. Nonetheless, it is my fault and my responsibility."

Peter Gwynne
Boston, MA

Radio telescope image reveals Milky Way's centre in stunning detail

I Heywood, SARAO



The MeerKAT radio telescope in South Africa has taken an image that shows the centre of the Milky Way in unprecedented detail. Colour in the image represents bright radio emissions while fainter emissions are shown in greyscale. Running horizontal across the picture is the galactic plane while the brightest object in the image is the galactic centre, which is home to a supermassive black hole that has a mass four million times that of the Sun. The image also includes other sources of radio emissions such as supernova remnants, mysterious radio filaments and radio "bubbles" that span 1400 light-years across (seen as a broad vertical feature above). The image was created from a mosaic of 20 separate observations using over 200 hours of telescope time. MeerKAT is a radio telescope inaugurated in 2018 that consists of 64 antennas spread over a diameter of 8 km in the Northern Cape province of South Africa.
Michael Banks

Diversity and inclusion

New Dutch childcare programme to support 'quantum mothers'

Two Dutch organizations have teamed up to announce a programme to help new mothers continue working in quantum technologies. The Quantum Childcare Pilot Programme is funded by the Dutch organization Quantum Delta NL and the professional body Women in Quantum Development (WIQD) and is aimed at women working in quantum-related fields in the Netherlands. It will offer grants to help parents find childcare so they can attend quantum-related events and conferences.

Women in science face many barriers and obstacles to their careers, and setbacks that can have repercussions for decades. The problems are especially acute for women with young children. On average, women spend more time taking care of their young children than men – an effect that has been compounded by the impact of the COVID-19 pandemic (December p11). This results in further obstacles when women are usually at the start of their career, finding themselves struggling to keep their career on track while also providing childcare.


iStock/damircudic

Support network The Quantum Childcare Pilot Programme will award 20 grants throughout 2022 for mothers to attend events and conferences.

Several university-led initiatives already exist to support women while pregnant or when they become a parent, such as offering funding for childcare so that women can attend conferences. However, quantum researcher Stacey Jeffery from the Dutch national research institute for mathematics and computer science, CWI, says that there is often more talk than action when it comes to addressing the real practical problems that women in science and technology are currently facing. "It is not the responsibility of women to take on all childcare and the responsibility should be shared equally," she says. "But we know that, in practice, this issue does impact the careers of women more than men."

The new quantum childcare programme will be a national initiative and will award 20 grants throughout 2022. Applicants will need to submit a "short proposal" outlining how they would use the funding to allow them to travel to a specific event and their proposal will be reviewed by a "small selection committee". Applicants are not restricted to academia, so women from industry, start-ups or government positions that are active in quantum development can apply. "Our programme is by no means the only way to solve the problem, but it is one where we know at least part of the solution: money," says Jeffery, who co-founded the WIQD programme in 2020. "The idea behind the pilot programme is to figure out the rest of the equation."

Martijn Boerkamp

Call for greater investment in lab accessibility

The physics community must do more to increase investment so that laboratories are more accessible to those with disabilities. That is according to a group of 15 US-based physicists who have written a 51-page report calling on the physics education community to improve the accessibility of school and research labs to help people with disabilities to stay in physics (arXiv:2202.00816).

The authors, who include staff and students with and without disabilities, were commissioned by the American Association of Physics Teachers' committee on laboratories. The report includes ideas to improve physics labs, and testimonials of disabled students describing their experiences, as well as information about how labs that do not make accommodations create barriers for students with various disabilities.

Although the report encourages investment to improve accessibility at all levels of education and work, the specific examples covered by the report focus on labs in undergraduate courses, which is where the authors have the most experience. The document's list of ideas for how to invest in accessible labs includes suggestions for lab instructors and staff; education researchers; physics departments; online content creators; conference planners; and member societies. These range from including disabled staff and students as partners in the planning of lab courses and regularly seeking their feedback, to paying for staff to train in accessibility, and providing travel grants for disabled conference attendees.


iStock/SolStock

Widening participation The report aims to improve the accessibility of labs at all levels from schools through to research labs.

In the report, the authors distinguish between "proactive" and "reactive" investment that can be made by universities or institutions. The former is defined as unprompted action, such as creating a programme that is designed to be accessible for the greatest number of students and is the default for all classes, regardless of whether they include disabled students. Reactive investment, on the other hand, is defined as action in response to an individual or group that is requesting certain accommodations. The report states that while "neither type of investment eliminates the need for the other", proactive investment can create lab courses "that support a broader range of students and communicate the expectation of a diverse student body".

The report also includes four testimonials of current and former physics students about their experiences in undergraduate labs. Report author Sheila Xu, a deaf physicist who graduated from the Massachusetts Institute of Technology in 2014, describes the difference it made having good sign language interpreters who were willing to work with her to develop new signs for lab-specific terms. "Because of my instructors and interpreters," she says, "I had a positive experience in the lab."

Laura Hiscott

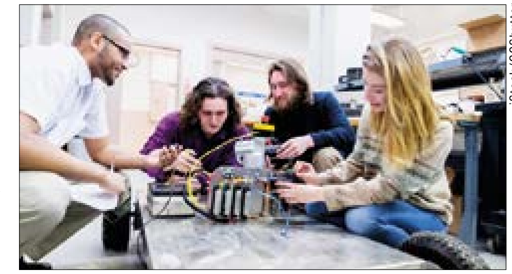
Diversity and inclusion

Lab gender roles not due to personal choice, finds study

Male and female preferences for carrying out certain tasks during experimental laboratory work are largely the same – and do not support stereotypical gender roles that are often seen in lab settings. That is according to a study carried out by Natasha Holmes from Cornell University and colleagues, who say the tasks that students choose to do in inquiry-based lab sessions could be due to biases and different levels of confidence among men and women (*Phys. Rev. Phys. Educ. Res.* **18** 010106).

The new study follows on from research published by the same team in 2020, which found that when students make their own decisions about experimental design in inquiry-based lab sessions, male students are more likely to handle equipment while female students spend more time taking notes and in communication roles. This gender disparity seemed to develop implicitly, as individuals were not allocated roles by instructors, and group members rarely discussed which tasks they would each be doing.

To find out if personal preferences for different tasks are driving this trend, the researchers surveyed 100 undergraduates and carried out interviews. They discovered that male and female preferences for each of the tasks are largely the same. Crucially, female students have a similar level of preference for handling equipment as that of male students.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Unequal outcomes Male and female students have similar preferences for handling equipment, but this is not always reflected in lab sessions.

What is odd about the 2020 paper is that it found a gender bias in inquiry-based lab sessions, but not in traditional structured lab classes. This difference presents a conundrum for the researchers , who previously found that inquiry-based labs boost students' engagement and encourage them to take more "ownership" of their learning.

"We think the gendered behaviours emerge during that subtle, collegial volunteering," Holmes told *Physics World*. "We think the bias is related to students' desire to be friendly and not wanting to argue with group mates who volunteer for certain roles, as well as male and female students having different levels of initial confidence to jump into a particular role."

Holmes and colleagues are now focusing on how to retain the educational benefits of inquiry-based labs while reducing the likelihood of gender bias emerging. "We're planning to test out different instructional interventions to see what is most effective," she says.

Those include assigning roles to the students and instructing them to rotate during the session or between labs; having open discussions about how some students might be more comfortable jumping into the equipment roles; and having students write down in their experiment designs how they are all going to contribute. "We think that this will make them explicitly reflect on ways to get everyone involved and make effective use of their group members."

Laura Hiscott

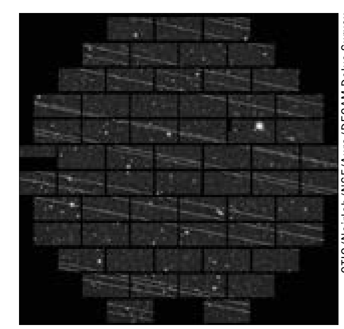
Astronomy

New centre aims to limit satellite interference on observations

The International Astronomical Union (IAU) has created a new collaboration to co-ordinate international efforts to mitigate the impact of satellite constellations on optical and radio astronomy. The Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference will begin operation next month, initially with seven staff members.

The initiative stems from a recommendation by SATCON2 – an international workshop held last year between astronomers and space firms whose satellites threaten the quality of astronomical observations in the optical and radio bands (see December 2021 p9). The satellites' trails on optical and radio astronomical images pose what IAU president Debra Elmegreen calls "an existential threat to observation from the ground".

The Square Kilometre Array Organisation (SKAO), based at Jodrell Bank Observatory in the UK and the National Optical-Infrared Astronomy Research Laboratory (NOIRLab) in Tucson, Arizona will jointly co-ordinate the centre. According to its director, Piero Benvenuti, an astronomer at the University of Padua and a former commissioner of the Italian Space Agency, the centre will aim to "arrive at and implement feasible solutions" to mitigate the issues posed by the satellite constellations. It will do so by unifying the astronomical community's voices on the issue and by linking astronomers, industry, regulators and the wider community to protect the dark and quiet skies. It will also produce and disseminate information and resources about the impact satellite constellations are having on astronomy.


CTIO/Noirlab/NSF/Aura/DECAM Delve Survey

Blurred vision The Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference aims to reduce the impact on astronomy of the 2800 or so craft that currently make up satellite constellations.

According to Benvenuti, initial funding for the centre will consist of "a few thousand euros" from the IAU together with support from NOIRLab and the SKAO. However, Lowell University director Jeff Hall, who co-chaired SATCON2, warns that the centre will require "substantial support" to have an impact. Indeed, Benvenuti agrees that fundraising will be crucial and hopes that constellation operators will contribute "either directly or in kind".

Peter Gwynne
Boston, MA

Comment

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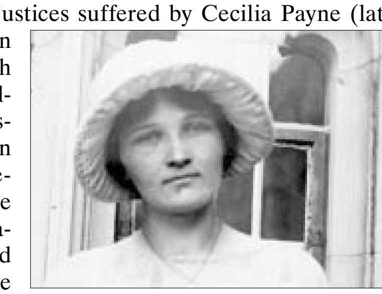
Breaking through

The life of Cecilia Payne-Gaposchkin is a reminder of the biases and barriers in science

Imagine being forced to sit in the front row of lectures where you're the only woman in class. A Nobel-prize-winning scientist – Ernest Rutherford – gazes at you every time he lectures and makes mocking remarks. The other students (who are all male) clap and stamp their feet in response to his supposed wit. You plough on and finish your studies but come away empty-handed because your university – Cambridge – doesn't allow women to be awarded degrees.

Those were some of the many injustices suffered by Cecilia Payne (later Payne-Gaposchkin) as documented in Sidney Perkowitz's feature this month (pp39–43). Despite her passion and talent for astronomy, she saw no professional opportunities for her, a woman scientist, in 1920s Britain. Payne-Gaposchkin was forced to move to the US, taking a post at Harvard Observatory in Massachusetts, where she used stellar spectra to calculate the relative proportions of different elements in the cosmos.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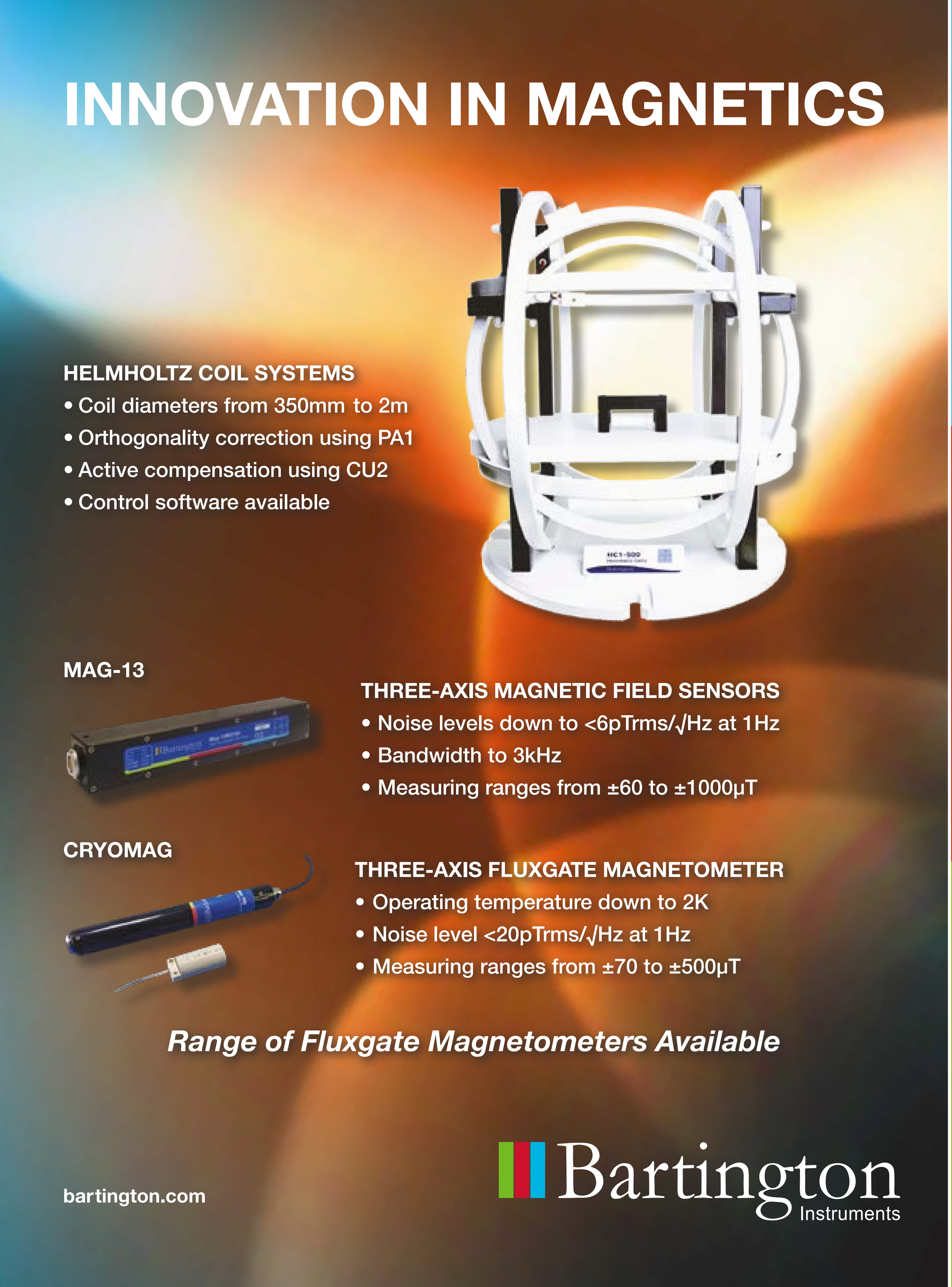
Amazingly, she found that hydrogen is a million times more abundant than any other element, while helium is a thousand times more common. It was a stunning discovery – especially for a PhD student – indicating that the Sun is made almost entirely of hydrogen. But Henry Russell, the then director of the Princeton Observatory, was having none of it. He believed that the Earth and Sun have the same composition and dismissed her finding as "clearly impossible".

Now scientific disagreements are the lifeblood of science. But Payne-Gaposchkin knew that her thesis needed Russell's blessing if it was to be accepted. It's almost heart-breaking therefore to discover that she watered down her findings, concluding that the abundance she'd derived was "almost certainly not real". Later, when Russell did his own calculations, which confirmed her analysis, he cited her work but never said he'd originally rejected her results – and it was he who ended up being credited with the discovery.

Payne-Gaposchkin was then denied being awarded a PhD from Harvard, having to do make do with one from Radcliffe, Harvard's women's college. She did postdoc work (but was dubbed a "technical assistant"), taught graduate courses (which went unlisted), and was put forward as Harvard's first chair of astronomy (but was overlooked). It was only in 1956, aged 56 and having published hundreds of papers, that she became one of the first female professors at Harvard.

Payne-Gaposchkin showed huge dedication to succeed through such adversity. It's remarkable to think that her PhD thesis, which actually sold 600 copies, was later referred to as "the most brilliant ever written in astronomy". But how many other physicists from under-represented groups are there who – when faced with such hurdles – will give up and follow a career path with fewer barriers? Sure, a lot has changed for the better since Payne-Gaposchkin's day, but not everything is rosy.

Matin Durrani
Editor-in-chief, *Physics World*



We need to rethink scientific awards

Jess Wade and **Maryam Zaringhalam** say that prize processes must be reformed to avoid discrimination

A scientific award reflects what the community values. It can raise the profile of a scientist's work, create opportunities for career advancement and increase researcher morale. Awards can motivate scientists to perform high-risk, high-reward research – to make breakthroughs and change how we understand the world. Prizes can also strengthen community bonds and establish role models as well as transform interest, investment and participation in a particular discipline.

But there is a problem. The application process for prize nominations is often broken, as is the way that they are awarded. The outcome is that women and gender-minority scientists, scientists of colour and those from smaller, less well-known institutions are less likely to receive the recognition they deserve.

The Nobel prizes are a perfect example of these discrepancies. Women make up only four out of the 219 Nobel laureates in physics, while no Black scientist has ever been recognized by a Nobel science committee. The Nobel prizes also overemphasize the contributions of individuals, which perpetuates an incorrect view that science advances via the "lone genius" rather than through collaboration and co-operation. By uplifting only one or a small number of people, the Nobels effectively erase the contributions of colleagues who are typically early-career scientists and arguably have more to gain from such recognition.

The Nobels are not alone. Most awards require nomination packages and references, which can be onerous and intimidating to put together. Unless careful and conscientious advocates are willing to seek out awards and write statements to diversify the pool of nominees, then nominator and institutional bias determines who gets put forward.

The Matilda Effect is the (un)conscious bias that attributes the contributions of female scientists to their male counterparts. It shows how easy it is for award programmes to deny recognition to women scientists and scientists from historically marginalized groups, writing them out of history. And even if self-nomination is possible, it can favour over-confident scientists or those who have time to gather the required nomination materials. When women self-nominate, they


Shutterstock/focal point

Bringing into reach How can we ensure science prizes more fairly reflect the whole community?

are often derided for being self-promoting.

Ultimately, however, it is the biases and interests of those on the awarding panel that determine who succeeds. Reviewers bring their own expertise, experiences and priorities to their role as jurors. If the panel isn't diverse – and the names of the committee members not made public – their narrower experiences and perspectives have been shown to solicit less diverse nominations. Then there's the Matthew Effect, which recognizes high-profile scientists while withholding recognition for those who have yet to make their mark. It explains why winners of early-career awards (typically given to scientists who had access to and chose the "right" supervisor, topic or institution) are more likely to receive more established prizes later on.

A more equitable future

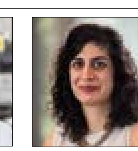
There have, however, been some welcome reforms to counter these effects. The Institute of Physics (IOP), for example, now has a diversity and inclusion initiative as well as the opportunity to self-nominate for awards. Yet some of its awards still request the nominee's h-index – a citation metric that is inherently biased against people in certain disciplines, women, people of colour, people from low-resourced countries and those who do not prioritize publishing. The IOP's Bronze early-career medals, meanwhile, require two referees from outside the nominee's department, which can prove challenging to less well-connected researchers at the start of their career.

So, what more can be done? When the American Geophysical Union noticed women and minorities were under-represented in its fellowship, it established a task force to review selection criteria, created canvassing groups and trained selection committees in implicit bias. The Royal Society of Chemistry's awards now place stronger emphasis on the science, not the individual scientists. It celebrates all members of scientific teams – from graduate students to technicians – and recognizes the work of educators in inspiring future chemists. Its prizes also come with a set of expectations and can be revoked if these are not met.

While an independent review sends a strong signal that an awards programme is taking reform seriously, there are steps professional bodies, academic institutions and learned societies can take in the short term. Transparency brings equitability and accountability. We need to collect and share data on who is and isn't being nominated, who wins, who is serving on selection committees and what the strategies are to correct any imbalances. We need to train selection committees on unconscious bias, have consistent evaluation processes with defined criteria and encourage membership to question their own stereotypes.

We also need to evaluate requirements for awards and make clear the rationale underlying those requirements. For example, is brilliance really best captured by a metric such as the h-index? Let's re-think what awards are for: do they need to champion an individual, or could you recognize team work instead? And we should encourage people to nominate more diverse candidates. Once clear requirements are established and outreach efforts in place, let's offer training programmes on how to put together nomination packages and how to write successful supporting statements.

The responsibility is on the scientific community, too. Take the time to nominate that phenomenal colleague, that extraordinary group leader, that inspirational lecturer or a remarkable technician. Awards are not only a chance to recognize the scientific breakthroughs that have brought us to where we are today, but opportunities to champion a vision for a more equitable future.

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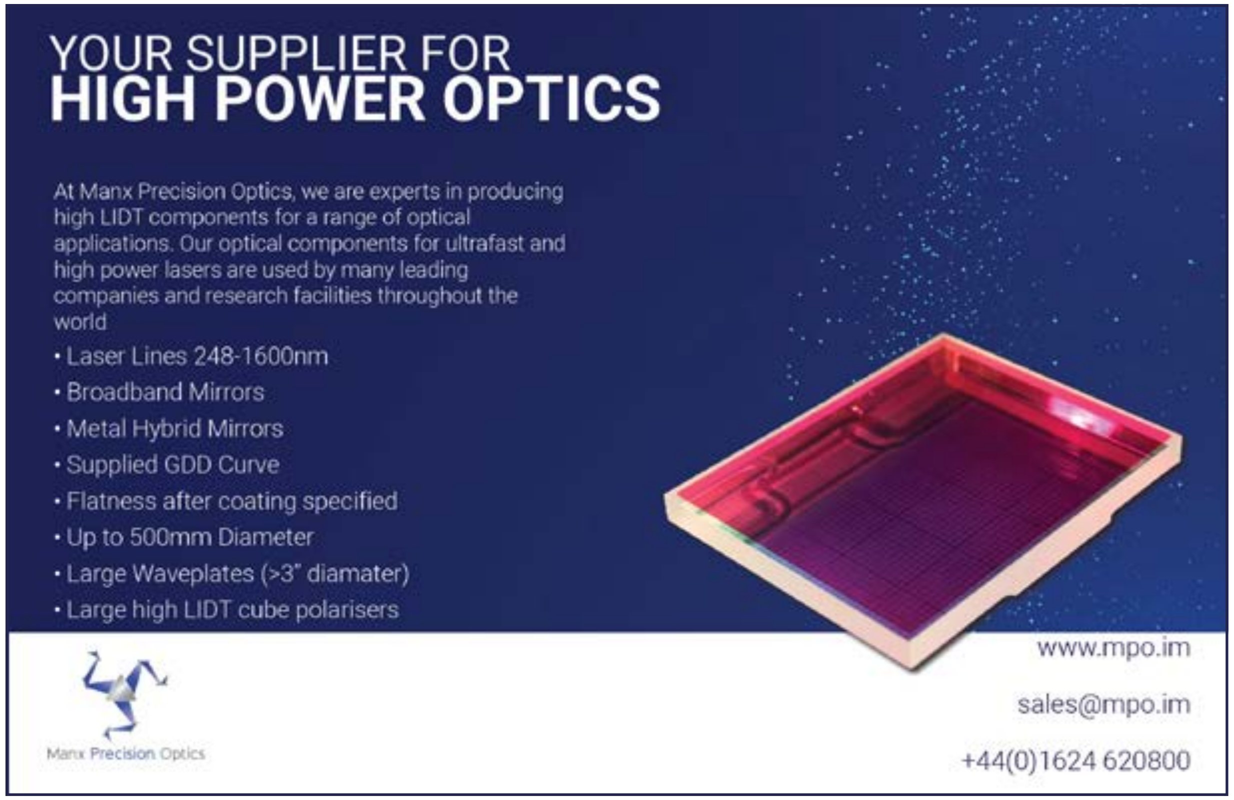
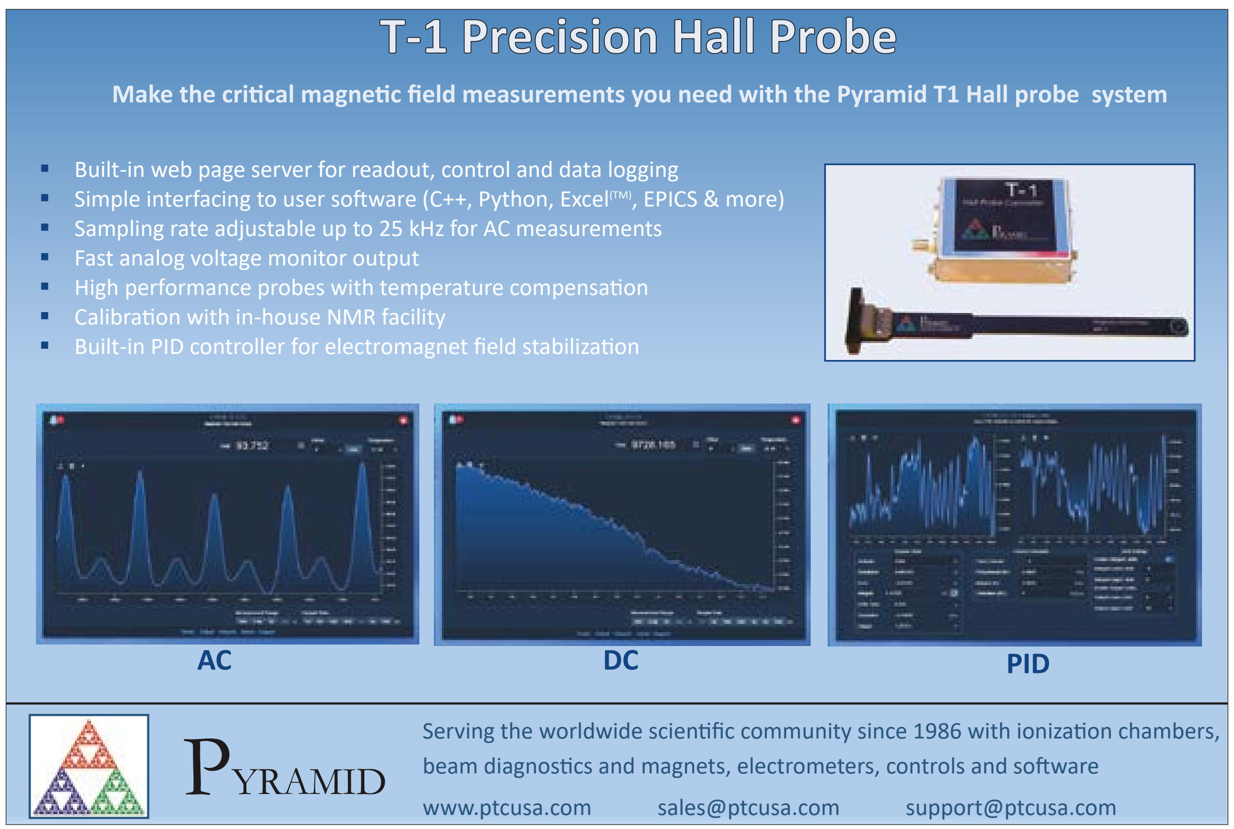




Transactions Fusion: it's hotting up

James McKenzie applauds recent record investments in commercial fusion power plants, which could help us to create a net-zero economy

Fusion is simple. Two light nuclei merge to form a bigger nucleus, releasing energy. It's what powers the stars, but building a fusion reactor that can deliver power in a controllable way isn't easy. Fusion needs high temperatures, high pressures and a decent confinement time. Those demands have, however, triggered some amazing approaches to make fusion power a reality.

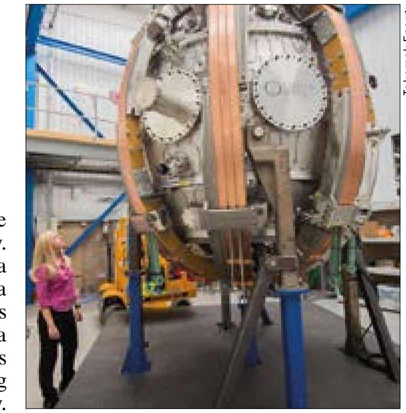
Trouble is, no-one really knows which will work best. What's more, once you achieve fusion, you need to generate more energy than you put in, so that the ratio $Q > 1$. But a "break even" result has so far never been achieved by a fusion reactor here on Earth. In fact, what you really want is a Q between 5 and 10 so that your reactor produces a useful amount of power.

The approach being taken at the ITER fusion reactor, which is currently being built by a huge international consortium in southern France, is to confine a hot plasma with large superconducting magnets in a doughnut-shaped tokamak. Set to come online in 2025, ITER will point the way to a commercial fusion reactor called DEMO, which will be built by 2060. I visited in 2019 and ITER is truly incredible to behold.

But it's not the only game in town. Last year, China's Experimental Advanced Superconducting Tokamak achieved a temperature of 120 million kelvin for 101 seconds. That beat the previous record of 100 million kelvin held for 20 seconds by South Korea's KSTAR reactor in 2020. There's also the Joint European Torus (JET) in Oxfordshire, UK – the forerunner to ITER – which still holds the record for the highest Q ever (it got to $Q = 0.67$ in 1997). JET has just run tests that produced more than 59 MJ of energy over five seconds, more than doubling the output achieved in 1997 (see p11).

Industrial effort

Fusion has an increasing commercial angle too. According to *The Global Fusion Industry in 2021* report, there are now 35 fusion firms around the world, which together have received more than $1.8bn of funding since the 1990s. The four biggest players – Commonwealth Fusion Systems (CFS), General Fusion, TAE Technologies and Tokamak Energy – account for 85% of that cash.


Tokamak Energy

Private practices As one of a growing number of firms, Tokamak Energy aims to develop commercial fusion energy with its ST40 compact spherical tokamak.

The report found that most private fusion companies expect fusion power to be supplying electricity to the grid in the 2030s. If their efforts succeed, that would put them well ahead of ITER, which largely froze its design in about 2001 and hasn't been able to exploit recent huge advances in high-temperature superconducting (HTS) magnets. Indeed, since the report was released, investment in private fusion firms has skyrocketed.

CFS – which was spun out from the Massachusetts Institute of Technology in 2018 – last year successfully demonstrated a 20 T HTS magnet. Simulations suggest that this magnet could be powerful enough to let the firm's SPARC Tokamak reactor achieve net energy from fusion. Since then, CFS has raised $1.8bn to build the reactor, which will pave the way for ARC – the first commercially viable fusion power plant. Development could begin in 2025.

As for Tokamak Energy, this British firm's ST40 spherical tokamak reactor with HTS magnets reached a stunning 15 million kelvin in 2018. The firm, which received its last funding of £67m in January 2020, is now targeting a 100 million kelvin plasma from its upgraded ST40 reactor. I wonder if 2022 could also be a big breakthrough year for the company?

Meanwhile, last year the UK government announced a short list for sites for a prototype fusion plant known as Spherical Tokamak for Energy Production, or STEP (November 2021 p10). Based on technology pioneered by the UK Atomic Energy Authority's Culham Centre for Fusion Energy (CCFE), STEP could be up and running by 2040. The final location is due to be decided this year.

CCFE, where JET is located, has also been chosen by General Fusion as the site for its fusion demonstrator plant. It uses a spinning liquid jacket to hold a plasma, which is compressed rapidly into a sphere using powerful pistons. The fuel fuses and the resulting heat is absorbed by the liquid metal and used to turn a generator. Having last November announced a further $130m investment, the firm hopes to start work this year on the reactor, which could be ready by 2025.

Another player in the market is First Light Fusion, which raised $25m in 2020 and last May installed a "hyper-velocity gas gun" on its "Machine 3". It fires a projectile at a fuel target, with the resulting shock waves squeezing the fuel so much that it gets hot enough to fuse. The average net cost of generating electricity over the plant's lifetime could be as little as $25/MWh – roughly half that of an onshore wind plant.

Then there's Helion, a US firm that last year announced the largest single fundraise in private-fusion history. It secured a $2.2bn funding package to build their seventh-generation fusion reactor called Polaris using deuterium and helium-3 fuel to directly produce electricity. Helion's reactors are expected to be about the size of a shipping container and could deliver about 50 MWe, with the plants in operation by 2024.

The race is on

Making sense of all these achievements – and knowing who will win the race – is not easy as each reactor is different and faces its own technical difficulties. One common challenge, however, is the "cycle-time" between each scale-up step as this will ultimately determine the speed at which the power plant hits the market. It's clear to me, though, that several approaches are looking more and more credible with each technical milestone achieved.

No-one is quite sure how big the fusion market will be as the timing, cost and power output of potential reactors are all so different. But fusion has many advantages over fission, including a great safety record, no long-lived waste, and the potential for cheap fuel. If fusion reactors can gain regulatory approval and show that they have a competitive price tag, we could see a commercial plant in as little as five to 10 years.

For fusion, it's not a case of if – but when.

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Critical Point Disaster signalling

Robert P Crease wonders what lessons we can learn from movies about comets and asteroids heading towards Earth

"Look up…get your head out of your ass
Listen to the goddamn qualified scientists"

Those aren't lyrics you'd expect to hear from the normally saccharine pop star Ariana Grande, who sings them in the recent hit movie *Don't Look Up* (reviewed in February pp44–45). A comet roughly 9 km in size is heading straight towards Earth and the words come in response to the strangely uninterested reaction of politicians, media and many members of the public to the imminent planet-ending event.

The comet was discovered by astronomy PhD student Kate Dibiasky (played by Jennifer Lawrence) and her supervisor Randall Mindy (Leonardo DiCaprio). But most people – including the US president Janie Orlean (Meryl Streep) – don't accept the two scientists' knowledge. Despite the duo's best efforts, reactions range from attempts to turn a profit to outright denial. Those in power are so misled that humans take no effective action. The collision occurs and (spoiler alert) disasters ensue.

Things are different in the much older movie *Deep Impact* (1998). After scientists say that an 11 km comet is heading our way, the US president listens, relays the news to citizens, and they trust him and the scientists. (As I said, the movie was made a long time ago.) Partially successful measures are taken, including a crew of astronauts sacrificing themselves to blow up the bulk of the comet. While the collision happens, much of humanity survives.

There's a different twist in *Seeking a Friend For the End of the World* (2012), another comet-collision disaster movie. This time the comet is 112 km wide and nobody questions its truth. But some people riot, others turn criminal, while a few kill themselves. The protagonists, played by Steve Carell and Keira Knightley, are reflective about their fate, with no illusions there's a future.

Their honest and genuine reactions reminded me of Nietzsche's beautiful image of what happens just before the departure of an emigrant ship. The passengers and those they are leaving behind, he wrote, "have more than ever to say to one another, the hour presses, the ocean with its lonely silence waits impatiently behind all the noise". If looming death can't make humans candid and heartfelt, nothing can.

Niko Tavernise/Netflix

We have a problem Why does the scientists' message of an impending comet disaster not get through in *Don't Look Up*?

Processing disaster

These three films are just a small selection of the dozens of planetary disaster movies that can be streamed online. You can take your pick from countless others, where existential threats stretch from comets, asteroids, aliens and other space-based dangers to home-grown hazards too, including pandemics, zombies and nuclear weapons.

Asteroid and comet movies have some common threads. The bad news generally appears first as simply numbers: co-ordinates, orbits, trajectory predictions. The scientists then interpret the data, informing people in authority, who tell the public. What's interesting, though, is that the scientists' message – that there's a likely impending catastrophe – passes intact all the way down the line to the public. That happens even though it's progressively transformed for the consumption of each audience along the way.

My favourite way of describing this process is with the physics phrase "impedance matching". It describes what you need to do to send a signal from a low-impedance region to one with high impedance. If you want to lose as little of the signal as possible, you have to step it gradually down. It's what happens when you blow into a trumpet. Pressure pulses from your mouth (low impedance) can be heard in the open air (high impedance) only because the instrument's horn gradually modifies those pulses as they travel outwards.

Don't Look Up is different – and more interesting. Conspicuously and entertainingly revised for the current reception of existential threats like climate change and pandemics, it's all about what you could call "impedance mismatching". It starts conventionally enough. After DiCaprio and Lawrence have plotted their comet's coordinates and concluded it'll collide with Earth in six months with a 99.87% probability, they tell a NASA official, who tells the US president.

But the twist is that she appears more worried about the impending mid-term elections than about the Earth being destroyed, deciding she is going to "sit tight and assess". The president digs in even more strongly when a charismatic businessman promises to alter the collision to deliver $32 trillion worth of rare minerals.

Trying to bypass the president, the two scientists decide to spread the news on a TV talk show, but find that its motto is "We keep the bad news light". DiCaprio is told to "Keep it simple. No math." To which he replies, "It's all math." Lawrence is ignored on camera when she's calm, and ridiculed when she's passionate. The TV host calls her "the yelling lady" and says she needs "media training".

Political realities, media practices and vested interests create the substantial load that produces an impedance mismatch. In that media-saturated and politically permeated world, science is only one voice – and not one that can be easily understood. The signal is all but lost, leaving a grisly truth. If the world were somehow saved, it would only be because Ariana Grande's celebrity, not scientific authority, was strong enough to make people "look up".

The critical point

The morning after I saw *Don't Look Up*, the front page of the *New York Times* carried two science-related stories. One was about the launch of the James Webb Space Telescope, the largest and most expensive space-based observatory ever, which was expected to be widely welcomed. The other was about a protest against the wearing face of masks by people opposed to scientifically recommended mandates.

It seems we need little impedance matching when the science poses no danger and the public is enthusiastic, as with the JWST. But the impedance can be strong when there are serious lifestyle or existential costs at play. It might sound like an exaggeration but impedance mismatch is a much greater threat to our planet than comets and asteroids could ever be.

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Feedback

Letters and comments that appear here may have been edited, and do not necessarily reflect the views of *Physics World*.

Please send us your feedback by e-mail to pwld@ioppublishing.org

When a name is not just a name

In response to Matin Durrani's comment article "What's in a name?" (January p17), which discusses the question of whether to rename projects and scientific terms that have been called after historical figures who might have held views we would now consider harmful. Two examples discussed are the James Webb Space Telescope, named after a former NASA administrator who has been accused of involvement in anti-LGBT+ activity, and the Stark effect, named after Johannes Stark, who was an anti-semite and early supporter of Adolf Hitler.

I agree wholeheartedly with Durrani that we should "make amends" for naming discoveries or artefacts in honour of scientists like Stark and Webb, whose beliefs and actions outside the realm of science make them unworthy of the honour. But I would go further and suggest that we stop honouring individual scientists altogether, and not just because of questionable political associations, important though those are.

For one thing, physics has been a collective endeavour for at least a century now; to single out one scientist for a particular honour is unfair on all the others who helped them – including many who were not scientists themselves but may still have made significant contributions to a discovery.

An even stronger argument for ditching this practice becomes clear to anyone studying the history of science: the names of individuals get attached to specific discoveries, laws and units for many different reasons, often far removed from what the person concerned actually did. These associations, which are often taught as though they were perfectly natural and correct, frequently turn out to be somewhat tenuous and arbitrary in nature.

Some readers may be aware that the phenomenon often referred to nowadays as "Ampère's law" – one of at least three laws to have borne that name over the years – received the name not from André-Marie Ampère himself or any of his contemporaries, but from his admirer, James Clerk Maxwell, who was the first to articulate the law. It's not clear what Ampère would have thought of that, since the law he himself championed – a completely different relation for calculating the force between current elements – had by then fallen into disuse.

Probably fewer readers will be aware that the British Association's (now the British Science Association) original scheme for naming electrical units, published in 1861, included a unit to be called the volt – as a measure of resistance.

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Durrani suggests that certain phenomena shouldn't bear their discoverers' names, because of those scientists' views.

Apart from setting a very strange precedent (would species names also be changed?), would we reject their theories and insights as well? It is to me the ultimate hubris and arrogance to do so. In my opinion, we quite rightly criticize colonialists who went to other nations and looked down on them because they didn't subscribe to the colonizers' beliefs and values.

By even thinking about renaming, we are doing exactly the same; we are assuming that our current values and beliefs are all good and correct and that different perspectives are therefore "wrong". Really? How do we think people will view us in 100 years or more? As some ethical and moral high spot, or as flawed people with flawed beliefs that change over time?

It is an arrogance that is becoming pervasive in so many academic fields and is infiltrating science. Scientists who don't conform to the current mainstream paradigms are attacked, belittled and often vilified. Science is not about consensus or an agreed world view.

So I am pleased that NASA refused to change the name, but profoundly concerned that it was even suggested.

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I suspect that over several centuries there might eventually be extremely few names that could survive, for all kinds of culturally changing reasons. Phenomena such as the Stark effect should never be renamed, since, whatever the sins of the man, he was the person who discovered that thing, and generations of textbooks and learned articles would become confusing if terminology changed.

What I would like to see is missions like the James Webb Space Telescope not being named after recent people. We had Voyager and Pioneer; we had Mars Rover names like Spirit, Opportunity and Perseverance. So why Edwin Hubble and James Webb?

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Durrani asks if the effect named after Stark, who was a Nazi supporter, should be retitled. But there is a slippery slope here. What about Communists? Donald Trump supporters? Joe Biden supporters? In the end it becomes impossible to draw a clear line.

I think that we give these acknowledgements for people's achievements in physics, not for their personal qualities. Renaming units or effects just sweeps the history under the carpet. Better to keep the name but remind people of the blemishes when necessary. Everyone has faults, and history cannot be undone. That also includes historical physics achievements, of course.

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I view it as horribly disrespectful, extremely short-sighted, and abominable to change any of the names that those of earlier generations wanted to honour. No-one is perfect. To require that of anyone, particularly "those giants on which we now stand", amounts to "casting stones" not knowing we too live in glass houses. So I cast my vote to leave names unchanged.

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Treatment in practice

In response to Alexander Mendelsohn's feature article "A physicist's experience of the mental-health system" (February pp34–38), which describes the author's poor experience of treatment and explains his views that the system's approach to researching mental illness and diagnosing and treating patients is not scientific, as compared with how physics research is done.

I am truly sorry that Mendelsohn has had such a dreadful time with the treatment of his mental health, but I can assure him that not everyone experiences poor treatment.

My experience of poor mental health goes back a long way, as my paternal grandmother, father, paternal uncle and I have all suffered from manic depression (I was aged about seven when I first realized that I had a problem and I am now 62). I can assure you that modern treatment for mental-health issues is considerably better than it was in my poor father's day.

The treatment of mental illness cannot be carried out in the same way as a physics experiment simply because of how the brain functions. I once had a brilliant chat with my father's psychiatrist (a Jungian) who explained that everyone's brain works in a different way and that treatment is often a hit-and-miss affair. Initially my father was diagnosed with schizophrenia, but if he were alive today, he would be diagnosed as bipolar. Psychologists are constantly trying to figure out how our brains work, but two people can have the same symptoms and not respond in the same way to drugs. Similarly, some people can respond to talking while others can't.

I have been lucky with my doctor, who was able to come up with a treatment regime that avoided going down the psychiatric route (my condition is admittedly minor compared with my father's and has been put down to an inherited problem with serotonin). But one type of medication did make me want to kill people, which was not very good for a secondary-school physics teacher.

If you publish my letter I don't mind if you use my name, as it might explain to my PhD supervisor why he had this odd student for three years, and why I failed to write up my thesis.

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Preparing the quantum channels

In response to Philip Ball's feature article "Setting the scene for a quantum marketplace" (December pp35–39), which discusses recent developments in the commercialization of quantum technologies and the question of whether the industry will live up to the hype surrounding it in the coming years.

This was a well-balanced piece addressing an exciting research field that just might be about to change the world. There is a very tight focus on applications pervading the UK "quantum ecosystem" of university research groups, national labs and start-up companies. So it was good to be reminded by Ball's article, and others in the same issue, that although real applications for this technology do exist, it is still mostly scientific research.

Reading the article, I was reminded of my surprise on watching a video of the physicist John Martinis delivering a lecture at Caltech shortly after Google's announcement of "quantum supremacy" in computation in October 2019 (mercifully, the community has since dropped the "supremacy" from its rhetoric). While the result was presented by both Google and the scientific press as primarily a technological milestone, Martinis remained a consummate scientist. He repeatedly reminded the audience that the Google quantum computer was an experiment, testing, for example, our understanding of the physics of coupled quantum systems.

The UK is crackling with talented quantum scientists and engineers. For the field to flourish, though, it is important that their efforts should not be channelled too prematurely into narrow technological niches chasing a fixed canon of applications. We don't know what this is yet, and history shows that the developers and early promoters of new technology do not always foresee the uses of it. Having said that, I am pretty sure that in 10 years' time at least one of the applications discussed in the issue will be working out in the real world, but I would not like to bet on which one.

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Back to basics

In response to the special issue on quantum technologies (December 2021), which explored various "quantum 2.0" technologies currently being developed and what impacts they might have if practical, more widely usable devices are achieved.

This issue shows how far progress in computing has come in the last few decades. I clearly remember when the only calculation instrument I possessed was the humble slide rule.

In the seminar "Development of physics applied to medicine in the UK, 1945–1990" (2006 *Wellcome Witnesses to Twentieth Century Medicine* **28**), Peter Williams (former director of physics at the Christie Hospital, Manchester) said "The power of the computer gives you the speed. Sometimes I wonder whether it gives you too much accuracy and you lose sight of what's important. The slide rule has got exactly the right precision for calculations in our business, you can get a slide rule to operate at around about 1%, which is good enough, and as David Greene [medical physicist and former assistant director of physics at the Christie Hospital] used to say to me when pocket calculators came into use in the 1970s, you can't scratch your back with a pocket calculator."

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Correction

In the Transactions article "Space for all" (January p21) we reported that, by 2020, SpaceX had reduced the cost of launching objects into space to below $1/kg. This should in fact have been $1000/kg.

The body, exposed

A new synchrotron-imaging technique is letting researchers create a "Google Earth" of the human body. **Jon Cartwright** zooms in

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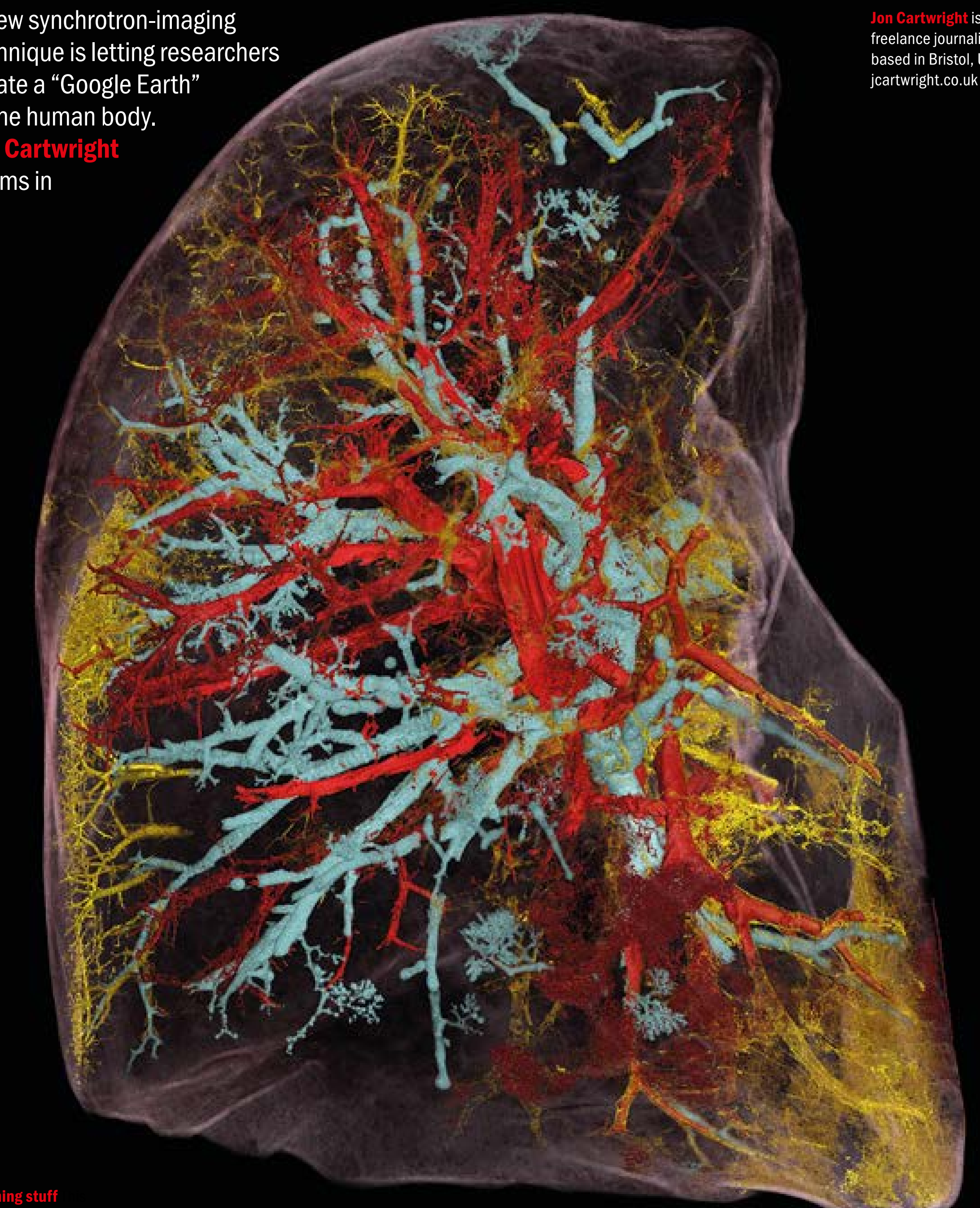

Stunning stuff
This 3D image of a human lung was taken using the new Extremely Brilliant Source at the European Synchrotron Radiation Facility.

ESRF/HiP-CT: C L Walsh, P Tafforeau, W L Wagner *et al.*

In this age of information, we expect to have knowledge at our fingertips. If we're looking to obtain a first impression of someone, many of us head straight to their social-media pages. If we want to understand a new topic, we don't buy a textbook – most of the basics are waiting for us on Wikipedia. And if we want to explore a new city, we can do much of it by moving around in Google Earth. Information that was once costly or exclusive is now free to all.

But what about medical images? Suppose you want to explore what a real human heart looks like, from the entire organ down to the smallest blood vessels. Currently, for most of us, that's impossible. True, a heart surgeon could obtain radiological images of a patient's heart, and order biopsies of specific volumes. But even then, the doctor will be easily frustrated by the limitations of individual imaging methods.

Clinical computed tomography (CT), which uses X-rays to build up 3D images slice by slice, is restricted to millimetre resolution. So too is magnetic resonance imaging (MRI), which peers inside the body using magnetic fields and radio waves. Microscopy of biopsies, meanwhile, is usually limited to millimetre-sized volumes. The dream of seeing an organ – or the entire human body – with micron or near-micron resolution has simply been out of the question, whether you are a specialist or not.

Not any more. For the last two years, dozens of scientists in Europe have been busy compiling the most detailed 3D views of real organs ever seen. Like a Google Earth of the human body, the Human Organ Atlas, as the team's project is known, is both simple and astonishing. Its goal is to create a freely accessible, online image bank of highly "zoomable" human organs, revealing everything from their biggest features (on the scale of centimetres and metres) all the way down to micro-scale structures.

The project has already led to the creation of 3D images of lungs, a brain, a heart, a kidney, a spleen and a liver (see human-organ-atlas.esrf.eu). By 2025 the Human Organ Atlas team wants to have imaged an entire human torso and, not too far beyond that, an entire human body. The work is impressive for scientists and non-scientists alike – so much so that the project is being bankrolled by some high-profile funding agencies in the UK, EU and US. Even Google has taken an interest.

One scientist who has been collaborating on the project is Danny Jonigk, a lung pathologist at Hannover Medical School in Germany. He feels as if he has spent his entire career doing research under candlelight, only for someone "to suddenly switch the lights on". Then there's Daniyal Jafree, a medical student at University College London (UCL) in the UK, who's doing a PhD in kidney imaging. When he heard what was being developed elsewhere at UCL, Jafree couldn't quite believe it. "I thought that sounds ambitious," he says. "Then I saw the images."

X-rays at your service

The Human Organ Atlas project wouldn't be possible without physics. It began at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, which has been one of the world's foremost X-ray light sources since it opened more than 30 years ago. Unlike the X-rays delivered by a clinical CT scanner, synchrotron X-rays have high energy and a high spatial coherence. That means their waveforms remain very much in phase with one another as they propagate, allowing researchers to exploit minute changes in X-ray phase to produce tomographic (section-by-section) 3D images of very high detail and contrast (see box below).

For many years, this phase-contrast X-ray technique has delivered incredible reconstructions of biological specimens. In 2011, for example, ESRF beamline scientist Paul Tafforeau helped produce what is still the most detailed scan ever of the inside of a skull of an early human ancestor, *Australopithecus sediba*. More recently, he has produced scans of small dinosaur fossils, ancient human teeth and even mummified crocodiles.

Then, in 2020, two things happened. The first was that the ESRF finished commissioning a new, "fourth-generation" source, making it the world's brightest synchrotron lab. More than a decade in planning and construction, the Extremely Brilliant Source (EBS) delivers X-rays that are 100 times brighter than before, and 100 times more coherent in the transverse (horizontal) plane, making them almost laser-like at low energies. The EBS has done wonders for tomographic imaging, enabling users to scan bigger objects, in more detail and at a greater range of scales.

The second big event of 2020 was, of course, the COVID-19 pandemic. For many scientists, the pandemic brought research to a full stop. Not for Tafforeau. Unexpectedly, he received a call from Peter Lee, a regular ESRF tomography user at UCL, who in turn had been approached by Jonigk. Could the ESRF be of help, Lee wondered, in reconstructing lung tissue samples from people who had died after catching COVID-19? It was a great question and almost overnight Tafforeau switched from studying ancient fossils to human organs.

"The COVID-19 pandemic changed a lot of things for many people," Tafforeau recalls. "I realized that several imaging techniques that we originally developed for palaeontology could open access to a new level of imaging precision on complete human organs. Then, while developing the techniques further, we realized that it may be a game-changer for biological imaging in general."

Swiftly, Lee composed an international, multidisciplinary team to see what could be done: synchrotron imaging scientists at UCL and the ESRF; mathematicians and computer scientists at UCL; medical scientists at Hannover Biobank, as well as the universities of Mainz and Heidelberg in Germany. As the apparent potential of the new tomographic imaging grew, so did the breadth of the collaboration: it now includes more than 50 people.

The scientists called the technique hierarchical phase-contrast tomography (HiP-CT), thanks to its ability to provide 3D reconstructions of entire intact organs that can then be explored anywhere down to the cellular level. As a result, the technique bridges the gap in scales between clinical CT and MRI, and the microscopy of biopsies. In November 2021 the project was formalized as the Human Organ Atlas, with a goal to provide a reference database of organ imagery that is accessible to all.

The atlas in action

A video of a human brain, as imaged by HiP-CT, gives an impression of the technique's capabilities (figure 1). It starts off conventionally enough, moving through cross sections of the entire organ. Here the brain looks like it does with a clinical CT scan, albeit at some 50 times the resolution. The various lobes are clearly visible, as are some of the external blood vessels. Then the "camera" zooms in to the back of the brain, the cerebellum, perfectly transitioning from big to small.

At 5 µm resolution, the smallest features of white and grey matter come into view; at 2.5 µm resolution, the tiniest blood vessels can be discerned. Even pyramid-shaped cells can be seen, known as Purkinje neurons, which are largely responsible for human motor function. Finally, the view retreats and the reconstruction morphs to depict blood vessels only. Now

> The goal of the Human Organ Atlas project is to create a freely accessible, online image bank of highly "zoomable" human organs, down to micro-scale structures

Hierarchical Phase-Contrast Tomography (HiP-CT) in a nutshell

Most simple imaging methods – including conventional computed tomography (CT) – involve measuring the loss of intensity (the attenuation) of an electromagnetic wave as it passes through a sample. In 1953, however, the Dutch physicist Frits Zernike won the Nobel Prize for Physics for developing an alternative – and potentially more illuminating – imaging method that involves measuring shifts in the phase of electromagnetic rays.

Zernike's "phase-contrast" microscopy was initially fit only for visible light. But in 1965 it started being extended to X-rays too thanks to the work of Ulrich Bonse and Michael Hart – two physicists at Cornell University in the US – who used a crystal interferometer to convert phase changes into interference patterns.

Limitations with interferometers meant that phase-contrast X-ray imaging of biological samples had to wait until the 1990s through the efforts of Atsushi Momose at Hitachi and Tohoru Takeda at the University of Tsukuba, Japan, and others. At roughly the same time, Anatoly Snigirev and others at the European Synchrotron Radiation Facility in Grenoble, France, realized they could deduce phase changes without an interferometer, simply from the interference of highly coherent synchrotron X-rays in free space. By combining many propagation phase-contrast 2D images in CT mode, they were able to produce 3D reconstructions of small biological samples with far more detail than that available from clinical CT scanners.

With the upgrade of the ESRF to a "fourth-generation" X-ray source in 2020, "hierarchical" phase-contrast CT (HiP-CT) became possible. The lab's ultra-coherent X-rays provide information on phase changes over very long propagation distances up to 40 m, allowing samples of up to 2.5 m × 1.5 m in size – including human organs, torsos, even entire bodies – to be imaged in 3D at micron resolution.

ESRF/Stef Candé

Seeing more deeply Claire Walsh from University College London (left) and Paul Tafforeau from the European Synchrotron Radiation Facility in Grenoble, France, are among the scientists to have developed the new imaging technique of Hierarchical Phase-Contrast Tomography (HiP-CT). Originally used to scan donated human organs, including lungs from a patient who died from COVID-19, the technique is central to plans for a zoomable Human Organ Atlas. It will provide 3D reconstructions of entire intact organs that can then be explored anywhere down to the cellular level.

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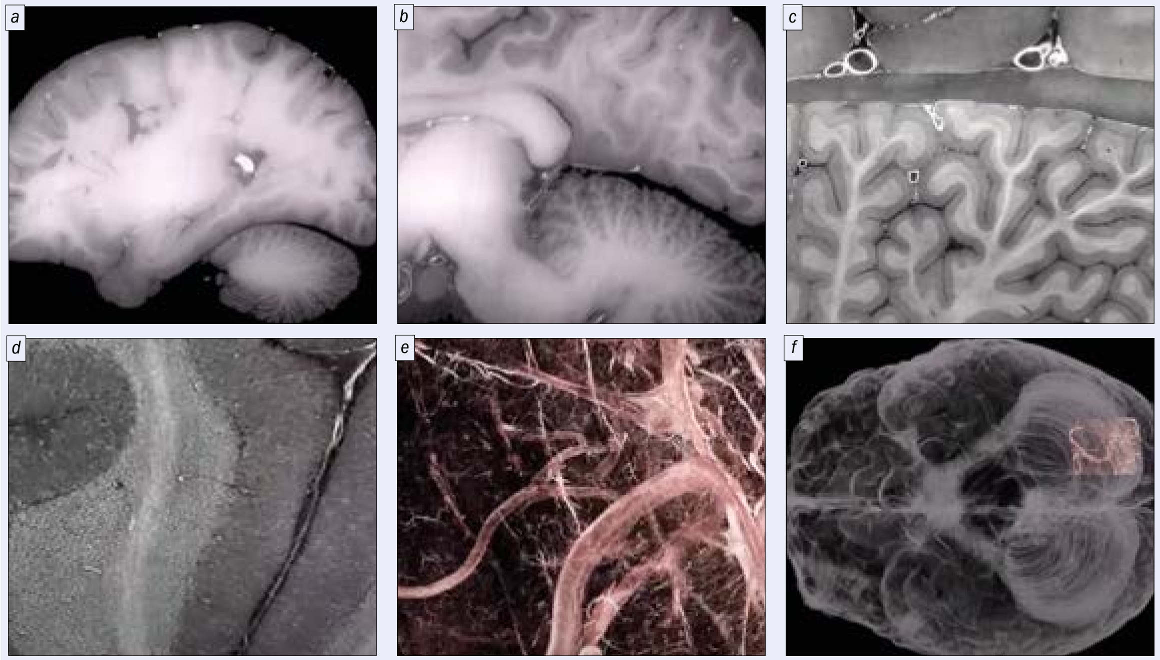
1 The Human Organ Atlas in action



ESRF/HiP-CT: C L Walsh, P Tafforeau, W L Wagner *et al.*

Stills from a video of a human brain imaged using Hierarchical Phase-Contrast Tomography (HiP-CT) shows what the technique can do as you zoom in and back out. *a* A cross-section of the entire organ reveals lobes and some external blood vessels. *b* A closer image of the back of the brain, the cerebellum. *c* At 5 µm resolution, white and grey matter come into view. *d* At 2.5 µm resolution, you can see the tiniest blood vessels. *e* As the view retreats, the reconstruction depicts the blood vessels only, revealing the full complexity of the brain's "vasculature". *f* Zooming back out again, the blood vessels *in situ*. See bit.ly/3LEoxXp for videos.

the incredible density and complexity of the brain's "vasculature" become apparent. As the system that delivers and receives the oxygen, glucose and metabolic waste, it keeps every one of us alive and thinking.

The HiP-CT video looks like the cutting-edge CGI you see in sci-fi blockbusters – yet it is perfectly real. What's more, as all the raw data have been collected and post-processed, it's possible for scientists to explore different parts of the brain at will. In fact, the sheer wealth of information in the imagery is so great that interpreting it is a major problem in itself. The team divides the work, with Tafforeau in charge of reconstructing the images and the UCL team trying to make sense of them.

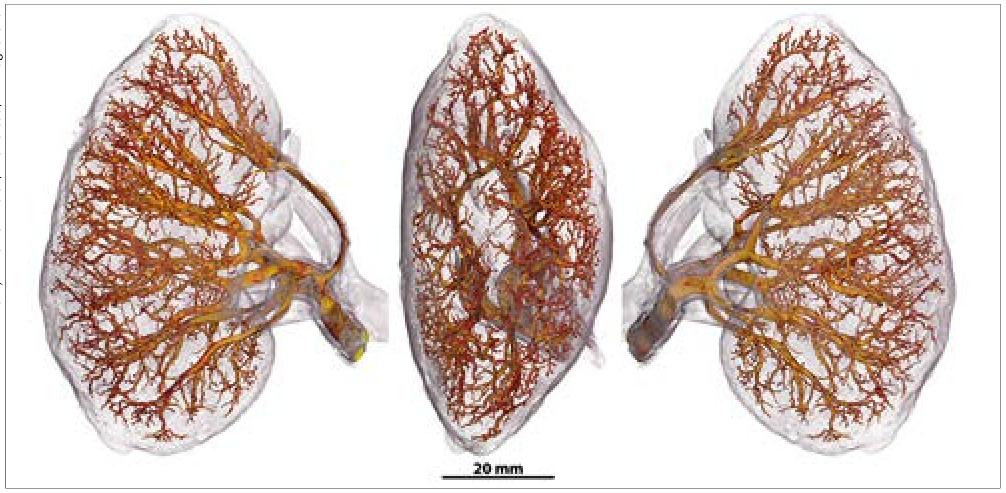
"It's a little bit overwhelming, like being a kid in a sweetie shop," admits Claire Walsh, a biophysicist in UCL's computational analysis team. "Medics and histologists can tell us when something looks weird, but we have to quantify that: exactly how weird?" One example is the size of alveoli, which has in the past been used to indicate the seriousness of lung disease. Previously, says Walsh, the alveoli were assumed to be roughly spherical, like grapes on a vine. But the new technique reveals them to be more irregular.

As a result, the researchers have had to define new parameters, with input from their medical collaborators, to capture the potential of the new information. Joseph Jacob, a chest radiologist who joined the UCL team early in the pandemic, stresses the scale of the interpretation challenge. "When I first saw the images, I felt amazement and apprehension – probably apprehension more than amazement," he says. "It was definitely what I wanted to work on, but the complexity of labelling it – obviously it would only be possible with computer science."

Fortunately, Jacob knows how vital the image-processing of X-ray data is, having developed algorithms to stitch together hundreds of CT images to see the lung in detail. He believes the reward now is well worth the labour. "[This new technique] is going to show us things we never knew existed," he says, which could be vital given how medicine is a very "organ-centric" discipline. "As a chest specialist, I just look at the lungs – I don't look at the heart, for instance. But disease doesn't necessarily work that way. If you could image a whole torso, you could understand how disease is affecting other organs; it would be a much more rounded approach."

The way ahead

As things stand, almost all the organs in the atlas have been imaged at the ESRF's long-serving BM05 beamline. In December 2021, however, the team acquired its first HiP-CT images at BM18 – a new ESRF beamline that has been designed to maximize the benefits of the EBS for microtomographic images of large objects. Although the beamline won't be fully operational until the end of 2022, it will eventually be able to image a torso – and even an entire human body.



ESRF/HiP-CT: C L Walsh, P Tafforeau, W L Wagner *et al.*

Vital signs These HiP-CT images of human kidneys could reveal if the volume or shape of blood-vessel networks affects the onset of kidney disease.

Imagine one day being able to explore, in virtual reality, human bodies of all ages, backgrounds, states of health and disease. As Lee points out, the damage wrought by new diseases could then be easily compared with that of existing conditions, to indicate possible known methods of treatment. People could see what sort of processes might be going on inside themselves. Medics could entertain pure curiosity, without having to resort to the knife.

We are not there yet, but preliminary images have already given some indication of the benefits of the large-scale, detailed view of HiP-CT. Reconstructions of several lungs from COVID-19 victims have revealed heterogeneous damage that appeared on previous clinical CT scans merely as a fuzzy, ground-glass texture (*Nature Methods* **18** 1532). The result is helping to determine whether it is the connectedness of lung damage, or the sheer amount of it, that is the cause of death by the virus.

Meanwhile, Jafree is keen to find out if HiP-CT can help us to give us a better understanding of the kidneys, the organs he specializes in. We know that the number of blood-vessel networks, or glomeruli, is a proxy for general kidney function. But no-one knows how losing some of these networks affects those that remain, or whether their volume or shape affects kidney health. "HiP-CT allows us to look at things in a different way," says Hafree. "It also encourages [students] like me to learn some of the image-analysis techniques. We need that expertise to generate something meaningful for biology and medicine – and we have an incentive now."

Sarah Teichmann, a cellular geneticist at the Wellcome Sanger Institute in Hinxton, UK, says she was "blown away" by the first HiP-CT images she saw, letting her view the cellular structures inside organs in exquisite detail, before zooming out to see the whole tissue. "Not only do these images and videos give a new appreciation of the beautiful complexity of the human body," she says, "they are also stocked full of information about how our bodies work."

Teichmann believes that the whole-organ or whole-body approach could benefit our understanding of diseases such as cancer. She also reckons that the Human Organ Atlas project ties in well with the Human Cell Atlas – an international consortium that she co-founded to create a comprehensive reference map of all human cells. "[It] could help us to see where these cell types – which we characterize at the molecular level – fit into the bigger picture of the organ. This will help to bridge the gap between cells and systems, painting a more holistic picture of the human body."

Beautiful times

Alongside the huge scientific impact of this imaging technique, there is also an inherent beauty to the images taken by the Human Organ Atlas. In December 2021 *National Geographic* magazine picked a HiP-CT image of a lung as one of its favourite science images of the year. Francesco Sette, the physicist who has been director-general of the ESRF since 2009, has even compared the advancement of the technique with Leonardo da Vinci's anatomical drawings of the early 16th century.

Those drawings gave unprecedented insights into the workings of the human body, especially its biomechanics. It is not yet clear what the ramifications of the Human Organ Atlas will be, although the concept is proving popular. The collaboration's *Nature Methods* paper has been downloaded more than 50 000 times, and is in the top 1% of *Nature* articles in terms of its Altmetric score, or reach.

The project is also gaining some serious backers, not least a $2.75m donation from the Chan-Zuckerberg Initiative (CZI), which was set up by Facebook founder Mark Zuckerberg and his wife Priscilla Chan. The CZI is independent of Facebook – which may be a good thing, as the Atlas team is just beginning a collaboration with Google to make its database available to the public. According to Lee, the plan is to create something like an anatomical version of Google Earth, with 3D "satellite" resolution of 40 µm resolution for a whole organ, and a 3D "street view" resolution down to 1 µm to expose individual cells.

After Google Earth, Google Maps and Google Sky, perhaps it is fitting that one day we will have a Google Body search tool too. ■

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Astronomical Society of the Pacific, courtesy AIP Emilio Segrè Visual Archives, *Physics Today* Collection

The woman who found hydrogen in the stars

Sidney Perkowitz delves into the work and life of Cecilia Payne-Gaposchkin, from her stellar astronomical findings to a career-long struggle with bias against women in the early 20th century

Hydrogen, the simplest atom, is a basic building block of the universe. We know that it existed soon after the universe was born and that it still appears as a large part of the interstellar medium in which stars form. It is also the nuclear fuel that keeps stars radiating immense amounts of energy as they evolve over eons to create the chemical elements.

But how did we learn that hydrogen is a widespread and fundamental component of the universe? Not enough people know that the cosmic importance of hydrogen was first grasped by a young PhD student, Cecilia Payne (Payne-Gaposchkin after she married), who in 1925 discovered hydrogen in the stars. Indeed, she earned a PhD at a time when it was still extremely difficult for women to do so, and did breakthrough research for her thesis. For all the success of her science, her story also demonstrates the barriers and sexism that made it difficult for women to fulfil their scientific aspirations, and affected their careers throughout.

Young scientist

Cecilia Payne was born in Wendover, England, in 1900. Her father died when she was four, but her mother Emma saw that she had a gifted child who wanted to be a scientist. Emma enrolled her daughter in St Paul's School for Girls in London, which was well equipped to teach science. The 17 year old thrived there and, as Payne-Gaposchkin later wrote in her autobiography *The Dyer's Hand*, she would

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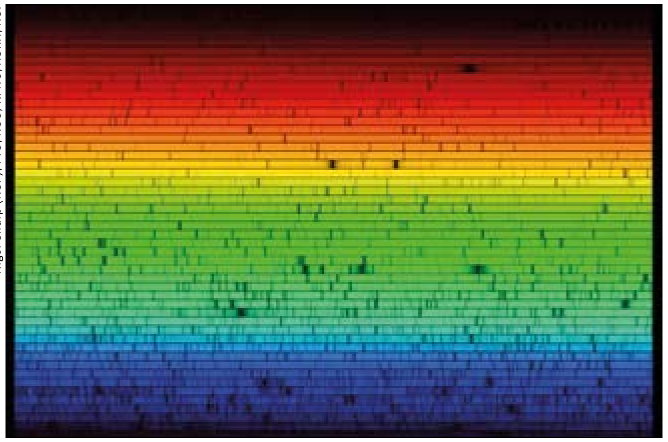
Nigel Sharp (NSF), FTS, NSO, KPNO, AURA, NSF

Sorting spectra Astronomers divide stars into different spectral categories, and early classification was based primarily on the strength of the hydrogen absorption lines in any spectra. Each line represents a particular chemical element or molecule, with the line strength indicating the abundance of that element, which varies mainly due to temperature. Today, most stars are classified under the Morgan–Keenan system, a sequence from the hottest (O type) to the coolest (M type). The original Harvard system was developed by Annie Jump Cannon, who re-ordered and simplified the prior alphabetical system. This image shows the visible spectrum of the Sun, and was created at the McMath-Pierce Solar Observatory.

steal up to the science lab for "a little worship service of my own, adoring the chemical elements".

Her advanced science education began in 1919 when she entered Newnham College at the University of Cambridge on a scholarship. There, she studied botany, her first love, as well as physics and chemistry – despite the fact that at the time, the university did not offer degrees to women. Nevertheless, it was an exciting time to study physical science as it absorbed the nascent areas of quantum mechanics and relativity.

At Cambridge the likes of Ernest Rutherford were exploring the atomic and subatomic worlds, and Arthur Eddington was studying the structure and development of stars. Indeed, Payne-Gaposchkin's physics instructor was Rutherford but as the only woman in his class, she found herself being humiliated. University regulations at the time required that she sit in the front row. As she relates in her autobiography, "At every lecture [Rutherford] would gaze at me pointedly…and would begin in his stentorian voice: '*Ladies* and gentlemen.' All the boys regularly greeted this witticism with thunderous applause [and] stamping with their feet…at every lecture I wished I could sink into the earth. To this day I instinctively take my place as far back as possible in a lecture room."

Instead, Payne-Gaposchkin found inspiration in Eddington. Almost by chance, she attended his lecture about his 1919 expedition to West Africa that confirmed Einstein's theory of general relativity. This so impressed her that she decided to choose physics and astronomy over botany. When later she happened to meet Eddington, as she writes in her autobiography, "I blurted out that I should like to be an astronomer…he made the reply that was to sustain me through many rebuffs: 'I can see no insuperable objection.'" He engaged her in his work on stellar structures, but he also cautioned her that after Cambridge, there would likely be no opportunities for a female astronomer in England.

New shores

Fortunately, a new possibility arose when Payne-Gaposchkin met Harlow Shapley, director of the Harvard College Observatory in Cambridge, Massachusetts, during his visit to the UK. He encouraged her efforts and she learned that he was instituting a graduate programme in astronomy. With a glowing recommendation from Eddington, Shapley offered her a modest stipend as a research fellow. In 1923 she sailed to the US to begin work on a PhD under Shapley's direction.

Women had long contributed to research at the Harvard Observatory. In the 1870s Shapley's predecessor as director, Charles Pickering, had begun hiring women known as the "Harvard Computers" (in the original sense of a person who does calculations) to analyse the stores of data the observatory was collecting. Women were preferred because they were thought to be more patient than men for work involving fine detail, and they accepted lower wages than men. Some of the computers were hired without a background in science, but even those with college degrees were paid like unskilled workers at 25–50 cents per hour (see "The universe through a glass darkly" April 2017 pp42–43).

The Harvard Computers were not independent researchers, but assistants with assigned projects. Nevertheless, these women made some of the most significant contributions to early observational astronomy. They included Henrietta Swan Leavitt – famous for her discovery of the period-luminosity relationship of Cepheid variables – and Annie Jump Cannon, who was internationally recognized for organizing stellar spectra.

It had been known since the mid-19th century that each element produces a unique pattern of spectral lines, and that the spectra of different stars showed both similarities and differences. This suggested that stars could be classified into groups, but there was little agreement over how best to do so.

In 1894 Cannon began the project of examining the stellar spectra collected at the observatory and putting them into a useful order. This daunting task occupied her for years. Spectra from different stars were recorded on glass photographic plates, with each image no more than an inch long. With a magnifying glass, Cannon read the details of hundreds of thousands of spectra and sorted most of them into six groups labelled B, A, F, G, K and M, with a minority placed in group O. The system was based on the strength of the Balmer absorption lines (which describe the spectral line emissions of the hydrogen atom) and reflected the spectral signatures of particular elements, such as metals in K stars.

Spectral studies

Cannon, however, did not probe the physical mechanisms that caused the spectra, nor did she extract quantitative information from them. In her PhD


Smithsonian Institution Archives

Stellar Cecilia Payne-Gaposchkin in the 1920s, location unknown.


Harvard University Archives

Cosmological computers A group of women working to process astronomical data at Harvard College Observatory in May 1925, including Annie Jump Cannon (fifth from left) and Cecilia Payne-Gaposchkin (fifth from right, seated at a draft board).


AIP Emilio Segrè Visual Archives, Shapley Collection

Curtain call On 31 December 1929 staff and graduate students at Harvard College Observatory put on a show dubbed *Pinafore at the Observatory*. The performers at the far left are Peter Millman and Cecilia Payne-Gaposchkin.


Smithsonian Institution Archives

Bright light Annie Jump Cannon at her desk at Harvard College Observatory, date unknown.

work, Payne-Gaposchkin drew on the physics she had learned at Cambridge to analyse this unique cache of data with the latest theories. The origin of spectral lines had been established only a decade earlier in 1913 by Niels Bohr's early quantum theory of the hydrogen atom, later extended by others. These theories applied to neutral atoms. Payne-Gaposchkin's great insight was to appreciate that spectra from excited or ionized atoms – such as would occur in the hot outer atmosphere of a star – differed from those of neutral atoms of the same species.

The relation among temperature, the quantum states of hot atoms and their spectral lines had been derived in 1921 by the Indian physicist Meghnad Saha. He could not fully test his ideas without knowing the quantum energy levels for each element, but these were being measured when Payne-Gaposchkin began her research. In a massive effort, she combined the new data with Saha's theory to fully interpret Cannon's stellar spectra including temperature effects. One significant outcome was the correlation of stellar temperatures with Cannon's categories, with results still used today: for instance, B stars glow at 20 000 K whereas M stars glow at only 3000 K. This result, part of Payne-Gaposchkin's remarkable 1925 thesis *Stellar Atmospheres*, was well received but another result in her thesis was not.

Compositional conundrums

Payne-Gaposchkin calculated the relative abundance of each element seen in the stellar spectra. For 15 of them, from lithium to barium, the results were similar for different stars and "displayed a striking parallel with the composition of the Earth". This agreed with the belief among astronomers at that time, that the stars were made of the same stuff as the Earth.

But then came a big surprise: her analysis also showed that hydrogen was a million times more abundant than the other elements. Helium, meanwhile, was a thousand times more abundant. The conclusion that the Sun was made almost entirely

AIP Emilio Segrè Visual Archives

Battle to the top
Cecilia Payne-Gaposchkin (right), with husband Sergei in Mexico City for the January 1979 meeting of the American Astronomical Society.

of hydrogen immediately ran into trouble with a respected outside examiner of her dissertation. This was Henry Russell, director of the Princeton Observatory and a strong proponent of the idea that the Earth and the Sun had the same composition. Russell was impressed until he read her result for hydrogen. Then he wrote to Payne-Gaposchkin that there must be something wrong with the theory because "It is clearly impossible that hydrogen should be a million times more abundant than the metals."

Without Russell's blessing, the thesis would not be accepted and so Payne-Gaposchkin did what she felt she had to do. In the final version of her thesis, she disowned that part of her work by writing "The enormous abundance derived for [hydrogen and helium] is almost certainly not real." But in 1929 Russell published his own derivation of the stellar abundance of the elements including hydrogen, using a different method. He cited Payne-Gaposchkin's work and noted that his results for all the elements including the great abundance of hydrogen agreed remarkably well with hers. Without saying so directly, Russell's paper confirmed that Payne-Gaposchkin's entire analysis was correct, and that she was the first to discover that the Sun is mostly made of hydrogen. Despite that, he never stated that he had originally rejected that result in her thesis.

It may be that Russell offered his comment about hydrogen to warn a young scientist that presenting results contrary to accepted ideas could hurt her career. Probably only a senior researcher of Russell's stature could have convinced the astronomical community of this new finding. Indeed, his later paper influenced astronomers toward accepting that stars are made of hydrogen to the point that he was credited with the discovery.

Even without proper credit, the power of Payne-Gaposchkin's thesis speaks for itself. Her lucid writing style, command of the subject and pioneering science shine through. Shapley had the work printed as a monograph and it sold 600 copies – virtually bestseller status for a dissertation. The highest praise came almost 40 years later, when the distinguished astronomer Otto Struve called *Stellar Atmospheres* "the most brilliant PhD thesis ever written in astronomy".

If Payne-Gaposchkin had any ill-will toward Russell, she gave no outward sign of it and maintained a personal relationship with him. In a review of his work that she contributed to a 1977 symposium honouring him (he died in 1957), she called his 1929 paper "epoch-making" without referring to her own work. What she did strongly regret was that she had not stood behind her result. Her daughter Katherine Haramundanis wrote that "through her life, she lamented that decision". In her autobiography Payne-Gaposchkin wrote "I was to blame for not having pressed my point. I had given in to Authority when I believed I was right...I note it here as a warning to the young. If you are sure of your facts, you should defend your position."

Battling bias and prejudice

After completing her thesis, Payne-Gaposchkin stayed on at the observatory under Shapley, but in an anomalous situation. She wanted to continue astrophysical research, but because Shapley paid her a (small) salary as his "technical assistant" he felt he could direct her as if she were a Harvard Computer, and he put her to work measuring the brightness of stars – a routine project that did not much engage her. Shapley also had her teach graduate courses, but without the title of "instructor", let alone "professor", and without having her courses listed in the catalogue. In an attempt to remedy this, Shapley approached the dean and Harvard's president Abbot Lawrence Lowell, but they adamantly refused. Lowell told Shapley that Miss Payne (as she was known then), "would never have a position in the University as long as he was alive".

Gender bias like this affected Payne-Gaposchkin at every stage of her career. Her PhD (the first in astronomy at Harvard) was not technically from Harvard. Shapley had asked the chair of Harvard's physics department to sign off on the dissertation, but as Shapley relayed to Payne-Gaposchkin, the chair refused to accept a woman candidate. Instead, Shapley had to arrange for her PhD to be awarded by Radcliffe, the women's college at Harvard. When later he began to build a true department of astronomy at Harvard, Shapley was convinced that Payne-Gaposchkin, his best researcher, was well qualified to serve as its first chair – but he realized that Lowell would never allow it, and so he brought in a male astronomer.

After decades of work at the observatory, publishing books and hundreds of research papers and becoming a sought-after instructor, Payne-Gaposchkin remained in a kind of career twilight – poorly paid and without a real academic position. This changed only in 1954, after Shapley retired and Donald Menzel, Russell's prize student at Princeton, became director of the observatory. He discovered how little Payne-Gaposchkin was paid and doubled her salary, and then did something truly significant. With Lowell and his anti-woman bias long gone (he had retired in 1933), Menzel was able to get Payne-Gaposchkin appointed a full professor of astronomy. This was big news: the *New York Times* reported on 21 June 1956 that "[Payne-Gaposchkin] is the

The power of Cecilia Payne-Gaposchkin's thesis speaks for itself. Her lucid writing style, command of the subject and pioneering science shine through

first women to attain full professorship at Harvard through regular faculty promotion." A few months later, she became chair of the astronomy department, the first woman to head a department at Harvard.

In retrospect, Payne-Gaposchkin's career was eminently successful with an outstanding dissertation, prolific research, excellent teaching and distinction for her "firsts" at Harvard and other honours. Along with all her academic work, she found room for her personal life. She wed the Russian émigré astronomer Sergei Gaposchkin in 1934 and with him raised three children while she continued astronomical research.

Exceptional drive

In some sense, one might say she "had it all" in combining science with family and children, but getting there was unnecessarily difficult and gruelling because of bias against women. She became a full professor only at age 56, much later than a man with similar achievements would have reached that status, and after being passed over for advancement, which must have taken a psychological toll. Only a person with exceptional drive and persistence, along with scientific ability, could have endured until final recognition.

Ultimately, Cecilia Payne-Gaposchkin, who died in 1979, was a pioneering scientist who did amazing work throughout her career, but was not treated professionally for most of it. Most of the Harvard Computers were employees, rather than researchers or graduate students. While Shapley gave Payne-Gaposchkin important opportunities and understood how good a scientist she was, he did also treat her merely as one more Harvard Computer, hired to support his own plans for the observatory. She advanced the position of women in astronomy beyond that of the computers, but she still encountered barriers that kept her from being the complete scientist she wanted to be, as women only began to achieve later in the 20th century. Her stellar work was often overlooked and her legacy forgotten, as she became one of the many "hidden" women in science who actually laid the foundation in their fields. It is only more recently that the significant contributions of the likes of Payne-Gaposchkin are being post-scripted into the history of science, and she should be remembered as a key transitional figure between older and newer possibilities for women in science. ■

Building a quantum future

The UK's National Quantum Computing Centre aims to create a collaborative working environment for building prototype quantum machines and developing innovative applications

STFC

Quantum horizons The UK's National Quantum Computing Centre is due to open its doors in 2023, but work has already started towards its goal of building a quantum computer with more than 100 qubits by 2025.

Construction has started on the UK's National Quantum Computing Centre (NQCC), the main aim of which is to accelerate the scale-up and exploitation of practical quantum computers.

Currently in the second year of a five-year, £93m programme, the NQCC's purpose is to help translate UK research strengths in quantum computing technology into innovative technology, thereby boosting the wider economy.

The NQCC is being built in Harwell, Oxfordshire, alongside several other top-tier scientific facilities operated by the Science and Facilities Technology Council (STFC), and is due to open in 2023. Its stated aim is to solve "some of the most complex and challenging problems facing society, having addressed the key scaling challenges – in technology as well as user adoption".

One of the NQCC's key deliverables is to demonstrate a quantum computer with more than 100 qubits by 2025, which means that the NQCC team has already started to commission its first tranche of R&D projects. "The building is important, but we couldn't wait for it to be finished because the technology is evolving rapidly and our international competitors and collaborators are moving forward at pace," says the NQCC's director Michael Cuthbert. "We need to do something tangible, to get started with some development work that we can learn from and that will shape our future technology programme."

The initial objectives and priorities for the NQCC have emerged from a detailed technology roadmap developed by around 20 of the UK's leading quantum experts over the last two years. The roadmap highlights current activities in quantum computing, identifies the key strengths of the UK's quantum community, and evaluates the maturity of different technology platforms and their potential over the next 10 years. Cuthbert and his team have now translated

A primary objective for the NQCC will be to accelerate the growth of that quantum economy by speeding up the migration of scientific research into commercial exploitation

the outcomes of that roadmap into a series of work packages across software, hardware and application development that are now being awarded competitively to both academic and industrial partners.

The NQCC is fortunate to have access to a thriving quantum community of research groups and start-up companies, as well as larger industrial organizations that could become important end-users for future quantum computers. That collaborative ecosystem has been fostered in large part by the UK's National Programme for Quantum Technologies, which has supported technology hubs in quantum sensing, imaging, communications and computing since 2014. While the UK is traditionally seen as strong in academic research but weaker on commercial exploitation, Cuthbert points out that this co-ordinated activity has already spawned 41 start-up companies that are already capitalizing on the emerging market for quantum technologies. "Between them they have raised more than £245m in investment funding," he says. "They are developing robust business models and making international connections that could enable them to become the major global players of the future."

A primary objective for the NQCC will be to accelerate the growth of that quantum economy by speeding up the migration of scientific research into commercial exploitation. "There is often a gap in skills and resources when going from purely academic research into the commercial sector, and the NQCC will be aiming to bridge that gap," explains Cuthbert. As well as incubating new start-ups and making connections with industry, an important role for the NQCC will be to nurture training and skills development – enabling academics to move into the commercial world and industry professionals with more general engineering and computing backgrounds to gain the knowledge they need to work with quantum technologies.

We need a whole range of skills and knowledge to deliver the future roadmap for quantum computing

STFC

Michael Cuthbert, director of the NQCC
"Quantum computing needs to deliver applications that make a real difference across different economic sectors."

When the building opens in 2023, it will offer collaborative working spaces along with laboratories for testing devices and building prototype quantum computers. As well as pursuing its own R&D projects, the NQCC will continue to commission external R&D from research groups and industrial partners, and in some cases will co-develop specific technologies or applications. "We want to accelerate our own roadmap, as well as those of the academic and industrial communities," says Cuthbert. "We don't want to duplicate work that's being done very successfully elsewhere."

Cuthbert is acutely aware that the path towards useful quantum computing will be long and challenging. The initial focus for the centre is to demonstrate a working quantum computer with more than 100 qubits, which will operate in the so-called noisy intermediate-scale quantum (NISQ) regime. Such early machines are vital for demonstrating capability and showing the promise of quantum computers, but they will not be able to challenge the performance of today's high-performance supercomputers.

"It is a much longer roadmap, perhaps 10 to 15 years, towards large-scale machines that will realize the fully transformative power of quantum computing," says Cuthbert. "Modest-scale machines are part of the journey to get there, and that long-term endeavour is one of the reasons we need a national facility."

A crucial element of that long-term vision is to catalyse a user community that will help to identify useful applications for quantum computers. "Until now we've mostly focused on technology development, but ultimately quantum computing needs to deliver applications that make a real difference across different economic sectors," he says. "The NQCC has an important role to play in providing access to third-party machines, particularly for the research community, and then providing applications support to develop a user community that can really explore the value that can be derived from quantum computing."

For that reason the NQCC is now commissioning a number of smaller projects to develop use cases for today's prototype machines. These projects will explore the impact that quantum computing might have in different business sectors and research fields, and attempt to translate complex problems in those different domains into tasks that quantum computing can address. "The outcomes from those projects will go to the heart of whether quantum computing is just a science project, or whether it will really deliver on the potential that everyone is talking about," comments Cuthbert.

Meanwhile, in its bid to build a prototype machine with more than 100 qubits, the NQCC will initially focus its efforts on two technology platforms – superconducting qubits and trapped-ion systems – that the roadmapping work identified as the most mature technologies with depth of UK activity. However, Cuthbert is quick to point out that other technologies could also play an important role in the future. "We have said all along that it's far too early to be picking winners. This was about identifying where we should start, rather than saying that this is the one and only technology decision we will ever take," he says. "We will be continuously assessing that roadmap and the ongoing development of alternative platforms, and figuring out how to bring frontier development work into the NQCC programme."

The most fundamental challenge for the developers of future quantum computers will be to scale the number of qubits without scaling their inherent noise. Current prototypes incorporate some level of error mitigation to reduce the effects of noise, but many more qubits will be needed to enable full-scale error correction. Some estimates suggest that as many as 10,000 qubits might be needed provide one operational qubit in a general-purpose quantum computer.

Another pressing priority will be to find a way to scale the control system and associated engineering infrastructure along with the devices themselves. The quantum computers that have already been demonstrated by the likes of Google and IBM require thousands of coaxial cables to switch and readout the state of each individual qubit, while trapped-ion systems require optical measurements that become increasingly complex as the machine gets larger.

"We will need some major technology breakthroughs to allow us to address the qubits more quickly and efficiently," says Cuthbert. "Many groups are already working on technologies to multiplex the signals that are used to control the qubits, and one major step forward would be to integrate some of the control systems into the cryogenic chamber so they are much closer to the physical qubits."

Overcoming those technology hurdles will require not just fundamental breakthroughs in quantum physics, but also significant innovations in systems engineering and computational science. "We need a whole range of skills and knowledge to deliver the future roadmap for quantum computing," says Cuthbert, who has just embarked on an ongoing recruitment process that will see 65 people join the NQCC by the time the building opens in 2023. "We need scientists with an academic background in quantum computing who want to play a role in translating the technology, as well engineers and computer scientists who want to work with us to understand and shape the future of quantum computing."

UKRI National Quantum Computing Centre

nqcc.ac.uk

This article was written by *Physics World* on behalf of National Quantum Computing Centre. Read more on *physicsworld.com*.

The huge carbon footprint of large-scale computing

Researchers have been able to cut their carbon footprint by jetting off to fewer international conferences, but physicists working on large-scale experiments may also have to consider the significant environmental impact of the computer power they require. **Michael Allen** investigates

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Simon Portegies Zwart, an astrophysicist at Leiden University in the Netherlands, is ecologically conscious. He hardly ever flies for professional reasons anymore, preferring to travel by train instead. "I like to be environmentally friendly by being a vegetarian, trying to reduce my carbon footprint, telling my children not to shower too long, switching to renewable resources." But once Portegies Zwart had decided to make those changes, he started considering other aspects of his carbon footprint too.

"I'm a heavy user of large machines and these computers consume as much energy as a small city," he explains. "I think I am probably the most polluting person on my street. If I run a supercomputer that takes as much energy as 10 000 households then who am I to tell my children, or other people, they shouldn't shower for 20 minutes?"

As the world grapples with the consequences of climate change, many scientists have begun to face up to the realities of their carbon emissions. Much of the focus is on air travel for academic purposes, where researchers are facing uncomfortable revelations. It turns out, for example, that climate-change researchers fly more frequently than scientists in other fields. According to a 2020 study (*Glob. Environ. Change* **65** 102184)), climate scientists jet off two to three times a year on average, whereas other researchers get on planes just twice during that time. But other scientists also fly a lot. A 2019 study (*Environ. Res. Lett.* **14** 095001) found that professors at the University of Montreal in Canada had twice the annual carbon footprint of the average Canadian, with most of the difference linked to professional travel.

Trips to academic conferences in particular are a huge part of the problem. When the Fall Meeting of the American Geophysical Union took place in California in 2019 the 28 000 delegates emitted around 80 000 tonnes of CO_2 equivalent (tCO_2e) travelling there and back home afterward. This was almost three tonnes per scientist, or the average weekly emissions of the city of Edinburgh (*Nature* **583** 356).

Furthermore, another recent Canadian study, done at the University of British Columbia, showed that air travel for academia has little to no positive impact on productivity or professional success (*J. Cleaner Prod*. **226** 959). And of course, in light of the global COVID-19 pandemic, most academics have been forced to adopt and embrace online conferences and workshops. Online events have allowed a more diverse range of delegates to attend, but there have been environmental benefits too. A 2021 study found that 7000 virtual delegates at three large scientific meetings, held online in 2020, had the same carbon footprint as a single in-person attendee to the same events in 2019 (*Nat. Sustain.* 10.1038/s41893-021-00823-2).

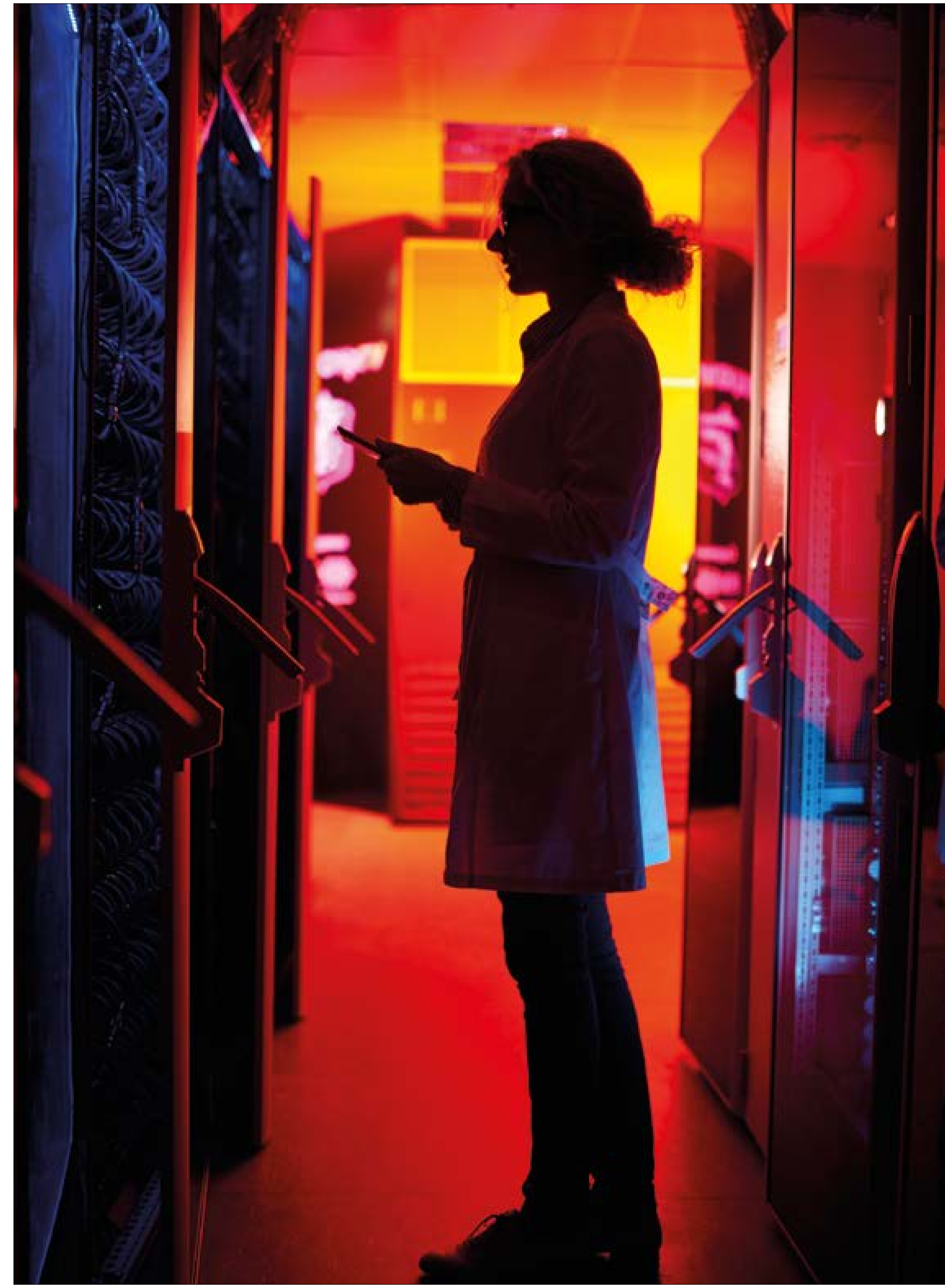
Researchers working in physics have found that their computer usage can make up a huge part of their carbon footprint – sometimes even more than air travel

Cosmic computing costs

While the impact of academic travel on climate change is indisputable, over the last few years a number of physicists have found that their computer usage can make up a huge part of their carbon footprint – sometimes even more than air travel.

Just ask Adam Stevens, an astrophysicist at the University of Western Australia. Together with colleagues, he has analysed Australian astronomers' total greenhouse-gas emissions over 2018–2019 from "regular activities" such as travelling, using supercomputers and working at large observatories. The study found that the average Australian astronomer produces around 37 tCO_2e per year (*Nat. Astron*. **4** 843). That's 40% more than the average Australian and five times the global average. The biggest contribution to this was the use of supercomputers to process the enormous amounts of data collected by telescopes and carry out cosmological simulations. At around 15 tonnes per astronomer, it ran to almost four times their annual emissions from flights (figure 1).

In another example, the upcoming Giant Array for Neutrino Detection (GRAND) project will use



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physicsworld
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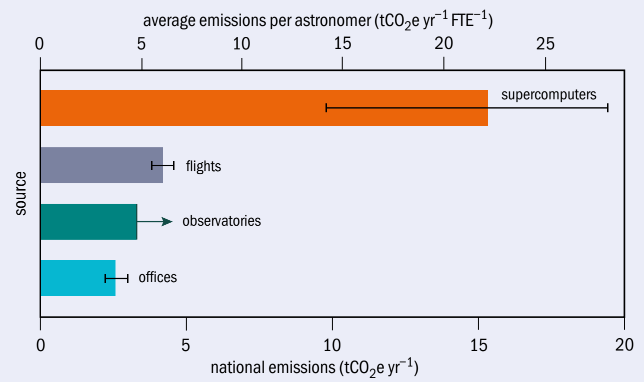
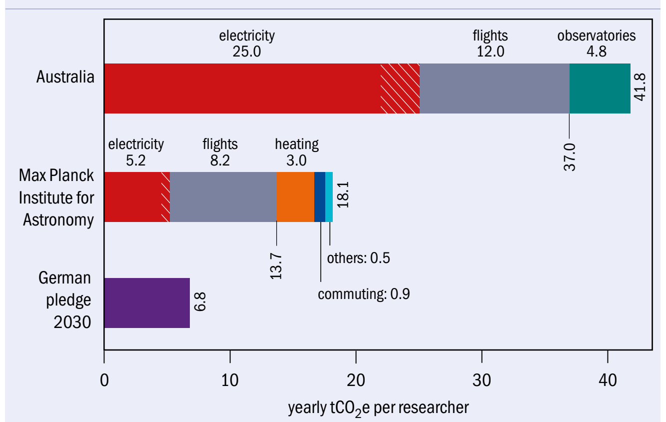
1 Astronomy in Australia: the green cost



Breakdown of the four sources of Australian astronomers' emissions considered in *Nat. Astron.* **4** 843, measured in tonnes (t) of carbon dioxide (CO_2) equivalent (e) per year per person or "full-time equivalent" (FTE). Error bars are shown but note that the value for observatories is a lower limit. © 2020 Springer Nature Limited. Reused with permission.

2 Stacking up emissions



Average annual emissions in 2018 for an Australian astronomer and a German researcher at the Max Planck Institute for Astronomy, broken down by sources, both compared to Germany's target emissions for 2030, according to the Paris Agreement. The electricity-related emissions include both computing and non-computing consumption, a vast majority of which is due to computing, both in Germany and Australia. Taken from *Nat. Astron.* **4** 812. © 2020 Springer Nature Limited. Reused with permission.

200 000 antennas spread across mountainous regions around the world to detect ultrahigh-energy neutrinos originating from deep space. Last year, the team behind the project estimated the greenhouse gas emissions for the three different stages of experiment: the prototype, the mid-scale stage and the full-scale experiment, which will start in the 2030s. What they call "digital technologies" – simulations and data analysis, data transfer and storage, and computers and other electronic devices – will account for a huge proportion of the project's carbon footprint (*Astroparticle Physics* **131** 102587).

In the prototype stage 69% of emissions are expected to be from digital technologies, compared with 27% from travel and 4% from "hardware equipment", such as manufacturing the radio antennas. In the mid-stage, digital technologies will account for 40% of emissions, with the rest split equally between travel and hardware. Once the full experiment is up and running most of the emissions will be shared between hardware (48%) and digital technologies (45%).

What's interesting is that the environmental cost of supercomputing can depend hugely on where the energy to power the devices comes from. In 2020 the Dutch Astronomy Council asked Portegies Zwart and a group of other researchers to analyse the carbon footprint of its six member institutes (*Nat. Astron.* **5** 1195). They estimated that in 2019, the average astronomer in the Netherlands emitted 4.7 tCO_2e – far less than in Australia – with just 4% of that coming from supercomputing.

Floris van der Tak, an astrophysicist from the Netherlands Institute for Space Research who led the study, sees no reason why Dutch astronomers would be using supercomputers less than their Australian colleagues. The differences are therefore likely due to differences in energy supply. In particular, the Dutch national supercomputing facility SURF does not produce any carbon emissions because it uses 100% renewable power produced by wind or solar in the Netherlands. The few emissions that are released come from using international facilities and smaller Dutch supercomputers. In fact, Portegies Zwart now always checks to see whether a supercomputer he uses runs on green energy and, if it not, he considers using a different facility. Similarly, van der Tak's advice is "before you ask for time on a facility, first check what kind of power they are using".

Source of the problem

Greenhouse-gas emissions at the Max Planck Institute for Astronomy in Heidelberg, Germany, highlight similar intercountry differences. In 2018 each researcher at the institute emitted around 18 tCO_2e (*Nat. Astron.* **4** 812) – more than astronomers in the Netherlands, but half that of their Australian counterparts (figure 2). These emissions were also 60% higher than the average German resident and three times the German target for 2030, which is in line with the Paris Climate Accords.

Around 29% of the Max Planck Institute's emissions in 2018 were from electricity consumption, with computing, particularly supercomputing, accounting for 75–90% of that. The key difference between Germany and Australia was where the power came from. In 2018 around half of Germany's electricity was from solar and wind, whereas in Australia the vast majority was produced from fossil fuels, mainly coal. This meant that in Australia, electricity for computing produced 0.905 kg of CO_2 per kilowatt hour, while the Max Planck Institute emitted 0.23 kg of CO_2 per kilowatt hour.

Van der Tak does point out that much of this work was conducted a few years ago, and that the world has moved on. More offices now use renewable power, for example. As the Dutch study found, just under a third (29%) of Dutch astronomy's carbon footprint in 2019 came from its use of electricity, including powering local computing at the six

research institutes. Back then, half of the institutes were running on green electricity. But since then, two more have moved to 100% renewable power and van der Tak expects the sixth to make the switch in the next two years.

Indeed, things have also changed in Australia. Since July 2020 one of the country's three national high-performance computing facilities, the OzSTAR supercomputer, has switched to 100% renewable energy purchased from a nearby wind farm. Swinburne University of Technology, which hosts the supercomputer, claims this will dramatically cut its carbon footprint, as electricity represented more than 70% of emissions.

Location, location, location

But how can you work out the emissions from the supercomputer you happen to be using? When mathematician and physicist Loïc Lannelongue found there was no easy answer, he developed Green Algorithms (green-algorithms.org). It's an online tool that enables researchers to estimate the carbon footprint of their computing.

Lannelongue, who is based at the University of Cambridge, UK, reiterates that location is key. Running the same task on the same hardware in Australia, for example, would emit around 70 times more carbon than in Switzerland, which gets much of its electricity from hydropower. The research behind the algorithm (*Adv. Sci.* **8** 2100707) shows that a more efficient computing centre can quickly lose its green advantage if it uses less renewable energy than an alternative less efficient supercomputer. While estimating the carbon footprint of any algorithm is based on key factors such as hardware, how long the task takes and the location of the data centre or supercomputer, Green Algorithms also has a "pragmatic scaling factor" (PSF) that estimates the number of times a computation is performed in practice – which has a direct impact on emissions.

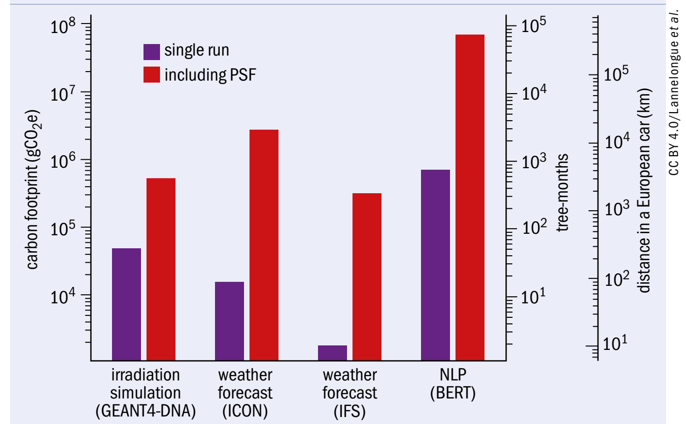
Indeed, most algorithms are run multiple times – sometimes even many hundreds of times with different parameters – and the number can vary greatly depending on the task and the research field (figure 3). The research also found that the emissions of computing in South Africa, as well as some states in the US, are similar to Australia. On the other hand, the carbon intensity of electricity in Iceland, Norway and Sweden is particularly low.

With cloud computing it is now much easier for researchers to choose which supercomputer they use. But if they are unable to switch to a different machine, there are still other ways they can reduce their emissions. Lannelongue says that simply using the latest version of your software can make a massive difference. "Updating versions and using optimized software is maybe the next big step if you can't act on location because it will impact everything, as it will reduce the computing requirements," he explains.

Better coding

Efficient coding is also vital for making computing greener. "I see a lot of people around me coding extremely inefficiently," says Portegies Zwart. But as

3 Quantifying computing's carbon footprint



Green Algorithms is a free tool to estimate the carbon footprint of an algorithm. It uses a number of factors, including the hardware requirements of the tool, the runtime and the location of the data centre. Users can evaluate their computations or estimate the carbon savings or costs of redeploying them on other architectures. This graph compares the carbon footprints of a number of algorithms from a variety of scientific fields – from particle physics simulations and DNA irradiation to atmospheric sciences and machine learning – and compares each algorithm being run only once, to repeated computations for the same task (PSF). The result in grams (g) of carbon dioxide (CO_2) equivalent (e) is compared to the amount of carbon sequestered by trees and the emissions of common activities, such as driving a car. Taken from *Adv. Sci.* **8** 2100707.

he explains, if you take a bit more time and optimize your code, it will run faster, and so produce fewer emissions. Switching coding languages could also be a good idea.

To test this, Portegies Zwart conducted an experiment where he took an algorithm and ran it using about a dozen different coding languages (*Nat. Astron.* **4** 819). He says that none of the codes were particularly optimized, and each took a similar amount of time to write. But Python, the most popular coding language among physicists, takes a lot longer to run and so produces more emissions than other languages, such as C++ or Fortran. The issue, according to Portegies Zwart, is that Python is extremely easy to use, but hard to optimize, while other languages are harder to code, but easier to optimize.

Simply shifting away from Python, however, is not necessarily the answer. In response to Portegies Zwart's paper, CNRS researcher Pierre Augier argued that better education and the use of Python compilers could be just as effective. Augier, an expert in fluid dynamics and turbulence at the University of Grenoble Alpes in France, used better optimized code and five different implementations of Python to run a similar experiment. He found that four of the implementations were faster and produced fewer emissions than C++ and Fortran, adding that they are also simpler to understand and use (*Nat. Astron.* **5** 334).

"I don't think it is easier to move to a different language, because it is not very difficult to learn how to correctly use Python," Augier explains. Instead of focusing on what coding language to use, he argues that computing and programming should be a bigger

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IOP Publishing

CERN

An accelerator's footprint
As part of reducing its overall carbon emissions, CERN brought in an environmental engineer to oversee the civil engineering of future construction projects.

part of physics education. "We should learn it when we are students, as soon as we specialize in physics." Portegies Zwart agrees that Python can be efficient, but he says that does not reflect reality. "I'm not bashing Python, I'm using Python the way most astronomers do, and that is not very highly optimized," he explains. He thinks that instead of teaching physicists more computing, perhaps physics research institutes should employ more computer experts. "We are great at physics, but a computer scientist spent all the time we learned about physics learning how to communicate with a computer," he says. "There is no doubt that [they] will be better at programming."

Hidden emissions

But it is not just simulations on supercomputers that can be carbon intensive. Kumiko Kotera, from Sorbonne University in France, who co-founded the GRAND neutrino project, says that when you look at the experiment's predicted emissions "you can see that what is really costly is data storage and data transfer". Kotera and her colleagues found that data storage and transfer will account for roughly half of total annual emissions in the prototype stage of the experiment, a quarter in the mid-stage and more than a third during the full-scale experiment (*Astroparticle Phys*. **131** 102587). By comparison, data analysis and simulations will produce around 16%, 13% and 7% of emissions, during the three stages, respectively.

The carbon footprint of data storage and transfer comes from the energy demands of data centres. As with supercomputers, data storage can be tackled to an extent by using data centres with lower emissions. Kotera says that the GRAND project will also be looking at strategies to reduce the volume of data. She explains that this will probably involve being mindful about what is archived – "we don't need to keep everything" – and finding ways to efficiently clean data.

"If we can clean up the data quite quickly, we can probably reduce a lot of the volume and emissions," she explains. "For data transfer it is tricky because it is a global network." But cleaning and reducing data volumes can still help, and scientists can also be careful about what they transfer. Multiple people repeatedly transferring the same pieces of data around the world can quickly add up.

The team calculated that data transfer during GRAND's five-year prototype stage will emit 470 tCO_2e – similar to around 270 flights from Paris to Dunhuang airport, near the prototype's experimental site in China. In fact, the researchers found that sending hard drives by plane four times a year would be many orders of magnitude less carbon-emitting than transferring the data online.

Due to the distributed, global nature of data centres, calculating emissions from data storage and transfer can be tricky. Kotera cautions that their figures are not precise as there are many unknowns, while van der Tak is unsure how much data storage and transfer is covered by the carbon footprint analysis of Dutch astronomy, adding that it might be something they need to look at.

Particle physicists need to do their bit too. CERN, for example, produces around 100 petabytes of data every year. This is stored, distributed and analysed using the Worldwide LHC Computing Grid (WLCG), a global collaboration of around 170 computing centres in more than 40 countries. CERN now publishes environment reports, with the second – published last year – describing the energy-efficiency improvements implemented at the LHC, specifically its ability to gather more data per unit of energy used. Over the 20-year lifespan of the upgraded machine, it will be 10 times more energy efficient than when CERN's flagship facility was originally switched on. But the report also acknowledges that it doesn't really cover the emissions of the WLCG. Energy consumption is only detailed for WLCG facilities owned or operated by CERN.

Change your mindset

Lannelongue would like it if researchers just started thinking more about the emissions of their computing, factoring it into their decisions. A good example is running inefficient code and software overnight because you have the computer resources and you are going to be at home in bed, so it does not matter if it takes ages. "That is fine until you say if I make it more efficient, I will save greenhouse-gas emissions and I will reduce my carbon footprint – so suddenly there is an incentive to do so," he explains.

When it comes to the GRAND project, Kotera says the plan is for the experiment to have simulation libraries that allow people to reuse commonly run simulations instead of producing their own, thereby preventing the same data from being reproduced again and again. According to Kotera this is common practice, even on large collaborations: different people repeatedly running identical simulations, because there is no central store. "It is so easy nowadays to just push a button and run a one-week simulation, get the result and then say 'oh, I didn't really need it'," she says. "Our goal is to really encourage people to think ahead of running simulations whether this is something that they really need."

Reviews

Technology with characters

Andrew Robinson reviews *Kingdom of Characters: a Tale of Language, Obsession and Genius in Modern China* by Jing Tsu

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Key issue
There are tens of thousands of Chinese characters, which creates a challenge for technologies developed based on Western alphabets.

Kingdom of Characters: a Tale of Language, Obsession, and Genius in Modern China
Jing Tsu
2022 Allen Lane 336pp £20.00hb

Chinese characters, in use by the second millennium BCE or even earlier, have functioned longer than any other script, including Egyptian hieroglyphs. Yet they have tended to isolate China, including its science, from other cultures because of their baffling complexity, especially compared to alphabets. To quote a celebrated early 20th-century Chinese writer, Lu Xun: "If the Chinese script does not go, China will certainly perish!"

This quote opens *Kingdom of Characters: a Tale of Language, Obsession and Genius in Modern China* by Jing Tsu, a sinologist at Yale University who was born in Taiwan and educated in the US. Her pioneering, fascinating, if often demanding book tells the story of China's unique transformation over the past century or so. As its clever title suggests, Tsu discusses not only written characters but also many characterful people from the Chinese worlds of computing, librarianship, politics, science and technology behind the transformation – most of whom are relatively unknown outside specialist circles.

They include Zhi Bingyi, who earned a PhD in physics from Leipzig University, returned to China in 1946 and led a distinguished career as an engineer, before being thrown into prison during the 1960s Cultural Revolution as a supposedly "reactionary academic authority". Living in a cowshed, deprived of even toilet paper, with only a stolen pen and the lid of a ceramic teacup as a wipeable writing surface, he invented a way of inputting Chinese characters into computers by mapping them onto an alphabetic code. This he did while contemplating eight characters on the cowshed's wall meaning "Leniency to those who confess, severity to those who refuse." After his eventual release, and a period as a floor-sweeper, toolmaker in a factory and warehouse guard, his breakthrough was hailed in 1978 on the front page of a Shanghai newspaper with the comment: "The Chinese script has entered the computing machine."

The technologies discussed in the book include the typewriter, telegraph, librarian's catalogue and digital computer, each of which receives a chapter. As Tsu sums up: "Every technology that has ever confronted the Chinese script, or challenged it, also had to bow before it. Ideographic characters have pushed to the brink every universalist claim of Western technology, from telegraphy to Unicode [a standard international system for encoding various languages' scripts in computers]. Having bent over backward many times to accommodate the technologies of the Western alphabet, the Chinese script, however, has not been altered in a fundamental way. Having survived, its presence has only been strengthened by those trials."

A century ago, it was by no means clear that this triumph would occur. In 1936, in his first interview with a Western journalist, the leader of the Communist rebels in China, Mao Tse-Tung (as he was then spelt in English), said: "We believe Latinization is a good instrument with which to overcome illiteracy. Chinese characters are so difficult to learn that even the best system of rudimentary characters, or simplified teaching, does not equip the people with a really efficient and rich vocabulary. *Sooner or later, we believe, we will have to abandon the Chinese character altogether if we are to create a new social culture in which the masses fully participate* [emphasis as per original source]."

In practice, Mao – himself a lifelong calligrapher – encountered so much opposition from Chinese intellectuals that he compromised. In 1955, six years after the People's Republic was founded, Chinese characters were officially simplified by eliminating certain variants and reducing the number of strokes in many of those remaining – a process that continues to this day. And in 1958, the government introduced romanized Chinese script, known as Pinyin ("spell sound"), as the official system for writing Chinese sounds (including tones) and for transcribing characters, so that non-Chinese

Having bent over backward many times to accommodate the technologies of the Western alphabet, the Chinese script, however, has not been altered in a fundamental way

"The Chinese Script Has Entered the Computing Machine" Wenhui Bao, 19 July 1978

Compatible code In the 1960s and 1970s physicist and engineer Zhi Bingyi mapped Chinese characters to an alphabetic code for use in computing.

speakers could roughly pronounce the language. In the Pinyin spelling of names (which does not indicate tones), Mao Tse-Tung became Mao Zedong, Peking turned into Beijing and Canton into Guangzhou.

Although Pinyin was opposed during the Cultural Revolution, when xenophobic Red Guards tore down street signs in Pinyin as evidence of China kow-towing to foreigners, it caught on. In today's China, the world's second largest economy, many millions of Chinese computers and smartphones, and the Chinese app WeChat – founded in 2011 and now with over one billion monthly active users – use both characters and Pinyin. As global users type in Pinyin, an array of characters appears on screen, anticipating the sentence or phrase they are composing. Indeed, Pinyin is so popular that some younger Chinese people no longer bother to learn characters the hard way; they have, to some extent, become "Latinized", in Mao's sense.

The issue of making Chinese script compatible with technology predates today's computers. Consider Morse-code telegraphy, which was introduced into China by various foreign companies. In 1870, at the request of the Great Northern Telegraph Company, Danish astronomer Hans Schjellerup, who had taught himself Chinese, started work on a telegraphic code for Chinese. He compiled a proto-list of 260 characters, but then had to return to his observatory work.

A French harbour captain in Shanghai, Septime Viguier, carried on Schjellerup's work without, apparently, much knowledge of Chinese. Soon he produced tables of characters in 20 rows and 10 columns, with each character assigned a four-digit code from 0001 to 9999, leaving empty spaces for perhaps 3000 further codes. However, the link between character and code number was completely arbitrary. Viguier's code offered no information about the character's shape, meaning or sound, to the irritation of native speakers.

Moreover, the Morse-code transmission of numerical digits (rather than the 26 alphabetic letters) was slow and expensive for the customer because numerals required more dots and dashes than letters. For example, you need one dot to send an "e", the commonest English letter, but six dots to transmit the number "6". This caused much resentment in China, not to speak of unreasonable profits for foreign companies, over the next half-century.

Only in 1929 was Chinese telegraphy made more rational by Chinese government approval of a scheme created by scientifically educated Wang Jingchun, managing director of an important railway. He devised a phonetic code for each character – three decades before Pinyin – consisting of four alphabetic letters: one letter for its sound, another for its tone and two more for the spelling of the character's component known as its "radical". Now Chinese could be telegraphed without using numerals, more efficiently and cheaply. Nevertheless, notes Tsu, Viguier's four-digit format "remained in use internationally and within China well into the 1980s".

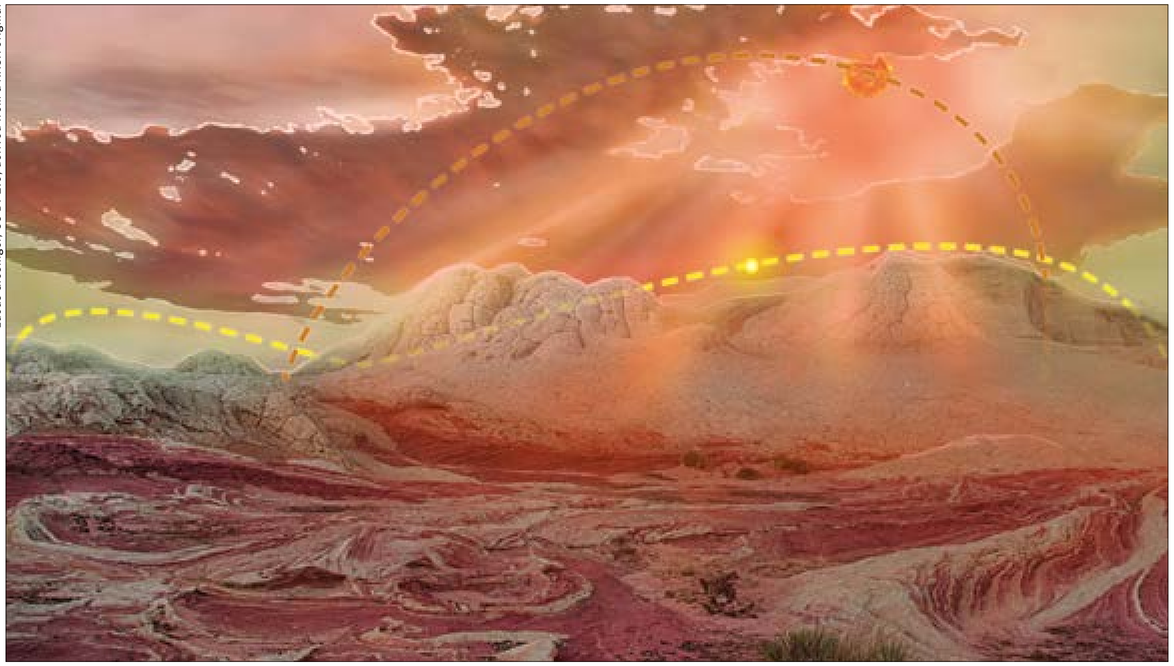
Such historic international struggles encouraged China's newly confident 21st-century government to advance in computing without relying overmuch on foreign – especially American – technology. This determination has led to long-running international arguments about the Chinese characters in Unicode, especially with Taiwan's computer scientists, who are generally opposed to China's character simplification.

By 2020 there were 92 856 Han Chinese characters listed in Unicode (version 13.0). This total could yet increase dramatically, given that several hundred thousand unlisted characters are being extracted and collected from old records – depending on whether China can persuade the Unicode Consortium, based in California. What an astonishing contrast with the character-doubting China of less than a century ago.

Andrew Robinson is the author of *Writing and Script: a Very Short Introduction*, published by Oxford University Press

Putting the physics into science fiction

Kate Gardner reviews *The EXODUS Incident* by Peter Schattschneider



Lucas Giesinger, CC BY 2.0, derived from a NASA original

Star trails This science-fiction novel includes technical details of an exoplanet, such as the path of its nearest star in its sky (orange line), compared with the trajectory of the Sun if Earth were tidally locked (yellow line).

The EXODUS Incident
Peter Schattschneider
2021 Springer
182pp £22.99pb

Science fiction has always explored scientific possibilities, both current technology and the furthest reaches of what could still be described as science. The most interesting SF uses science as a means to explore society, psychology and other aspects of being human, which often means any physics involved isn't explored in depth. Even "hard science fiction" – depicting science that is possible and central to its plot – rarely goes into great scientific detail.

In that regard, *The EXODUS Incident* by Peter Schattschneider is an exception to the rule, not only including lengthy discussions of physics (and indeed other sciences) within its pages, but also featuring a bulky appendix with abundant background detail to the physics explored. It's also a lively crime thriller set in the future.

Schattschneider is a physicist based at TU Wien who has spent much of his career both writing science fiction and using classic SF in his lectures. So he is well placed to blend complex physics into storytelling.

The novel opens with an academic-paper-style abstract followed by social-media messages (Schattschneider wisely doesn't specify what platform they're being posted on), which tell us that the Earth is suffering from catastrophic climate change, a series of pandemics and of course war. In what might be the last chance to save humanity, Europe is sending a spaceship called *Exodus* to establish a colony in the Proxima Centauri system, on a planet identified as habitable by the Breakthrough Starshot project initiated by Yuri Milner and Stephen Hawking (the novel doesn't mention the real-life project's third partner Mark Zuckerberg).

After that set-up, I was a little confused to find the narrative is not initially set on a spaceship, but instead follows two police detectives in Austria investigating a serial murderer. They are living in a future where Vienna is unbearably hot, meat consumption has been outlawed by the EU and the population is declining fast, but otherwise their police work is familiar from any police procedural you might read or watch on TV. Until, that is, lead investigator Oliver Storm is given access to AI virtual-reality tools to help him explore crime scenes.

Schattschneider's depiction of Europe in the future is scarily believable. As well as climate catastrophe, there are frequent military check points, border wars (including between the UK and Ireland – an interesting, albeit unnerving, detail) and resource scarcity. Everyone who can is moving further from the equator to temperate climes. One of the fundamentalist groups we encounter call themselves "Thunberg adepts", who are still struggling to be heard in their call for real action to help the planet.

The hero, Storm, is a smug, misogynistic character yearning for a past when he could own a car, travel freely and eat as much meat as he wanted to. In a nod to classic fictional detectives, he's a loner with a shady past and manages to have sex with every woman he takes a shine to, despite being generally rude to them. He is also, importantly, curious about everything he encounters so that over the course of the novel various specialists can explain complex science and technology to him, as a cypher for us readers.

Sadly, Storm does reflect a certain old-fashioned patriarchal tone to the

novel as a whole. The small number of women characters have no identifying characteristics beyond their appearance; there are no gay, trans or non-binary characters; men are known by their surname, women by forename; and men appear to be in charge of everything (though perhaps this is a deliberate part of the dystopia that Schattschneider has created).

I decided after a few chapters that it's best not to worry too much about the minimal character building, as this is not Schattschneider's strong suit. When he tries to add character detail it's clumsy and stands out from what is otherwise a strange but enjoyable murder mystery with a futuristic SF backdrop, which develops into fully embraced SF with the crime investigation as the backdrop. And while individual characters are lacking in depth, Schattschneider's explorations of wider psychological themes are handled well, particularly isolation and conspiracy theories.

The plot goes to some (for me) unexpected places that explore a range of ideas social, political and psychological. Schattschneider's influences are clear, from *The Matrix* to Arthur C Clarke, and many of these are acknowledged in fictional conversations between characters.

> Schattschneider's depiction of Europe in the future is scarily believable. As well as climate catastrophe, there are border wars and resource scarcity

This novel is part of Springer's Science And Fiction series, a collection of both hard science fiction and analysis of SF by scientists. It's an interesting idea for an academic publisher to pursue, but I couldn't help noticing that the series' large roster of editors are all men, and of the 46 books published in the series since 2014, only three are written by women. SF has historically been a tough market to break into for authors who aren't cis white men, but in recent years that has changed significantly and it's a shame for a major publisher not to follow that trend.

Despite its flaws *The EXODUS Incident* is gripping and thought-provoking. The technical details of the *Exodus* spaceship are particularly thorough. It is propelled by a Bussard ramjet engine and last year Schattschneider co-authored a paper on the feasibility of such a system (*Acta Astronautica* **191** 227) – concluding that the engine could be made to work but would achieve much lower speeds than previous studies suggested (February p3).

For physics fans, the appendix is the real treasure trove, as here Schattschneider produces a fictional mission report with all the technical details, from the ramjet engine to the type of vegetation that might survive on the exoplanet and its weather systems. But don't skip ahead to the back of the book as it is full of spoilers.

Kate Gardner is the content and production manager of *Physics World*

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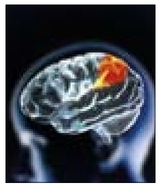
Between the lines



Shutterstock/RealCG Animation Studio

Mind or matter? In *Youniverse*, Elsie Burch Donald looks at the science behind the questions "What are you?", "Who are you?" and "Where are you going?".

The science of self

What are you? Who are you? Where are you going? These are three deceptively simple-sounding questions. But, from the Ship of Theseus to the "hard problem of consciousness", thousands of years of thinking have shown that they have anything but simple answers. And perhaps nothing could have complicated matters more than the past century of scientific discoveries. It is the relatively recent insights into these three profound questions that are the subject of *Youniverse: a Short Guide to Modern Science* by novelist and "lifelong learner" Elsie Burch Donald.

Physicists might first think of the shock revelations of quantum mechanics (that matter, including what we are made of, appears to be fundamentally probabilistic, not deterministic) and of general relativity (that the fabric of space–time can be distorted). These topics are covered in the first, material-focused, section of the book, in answer to the question "What are you?".

But, as Donald shows, physics is not the only discipline that has been thoroughly shaken up in the last 100 years. In the second section, which asks "Who are you?", the book discusses our current understanding of genetics, neuroscience and psychology, while placing it in the context of longer-held knowledge about Darwinian evolution. Often taking a storytelling approach, the writing is engaging, and occasionally accompanied by useful illustrations, such as anatomical diagrams of the brain and a nerve cell.

The third question "Where are you going?" is addressed in the final section, where Donald follows the recent trajectory of progress to speculate about humanity's possible next steps. She opines that "the future is set to become a contest between two scientific disciplines: genetic engineering and computer technology in the form of artificial intelligence".

The book's content is accessible throughout, and would suit any interested person in the early stages of their scientific education, whether at school or learning independently. But, from CRISPR to quantum computers, the breadth of topics covered means that most readers would probably learn something new from it, while enjoying a comprehensive summary of today's science.

- 2021 Duckworth Books 240pp £9.99hb

Laura Hiscott

The sky is (not) the limit

Shortly before the turn of the millennium, a NASA spacecraft called Lunar Prospector plunged into a crater near the Moon's south pole. For its controllers, the crash was the end of a successful mission to find water ice on the lunar surface. In the view of science writer Andrew May, though, it also heralded the dawn of a new era in space exploration. We are now in a world in which commercial concerns (like finding valuable resources) outweigh purely scientific or political interests, while tight cost controls (at $63m, Lunar Prospector was a snip by NASA standards) have gradually replaced the bloated fixed-fee contracts of the Apollo era.

For readers with an interest in how this new era came into being, and how it might evolve in the future, May's book *The Space Business: From Hotels in Orbit to Mining the Moon – How Private Enterprise is Transforming Space* makes an entertaining and drily humorous guide. While it opens with the headline-grabbing space-tourism activities of SpaceX, Blue Origin and Virgin Galactic (the brainchildren/vanity projects of multibillionaires Elon Musk, Jeff Bezos and Richard Branson, respectively), later chapters have a welcome focus on less-heralded firms.

Examples include the New Zealand launch firm Rocket Lab, which uses an electric rather than a mechanical pump to compress its fuel. Then there is the UK-based firm Reaction Engines, which is developing an engine that could power the first true "single-stage-to-orbit" vehicle (if it ever gets built).

While May is somewhat too enthusiastic about space billionaires for my taste, describing them unironically as "people who have a genuine concern for humanity's long-term future" (as opposed to, say, "egomaniacs on a giant tax-avoiding power trip"), he is right to say that they are not thinking small. It will be fascinating to see where the trend that began with Lunar Prospector leads in the future.

- 2021 Icon Books 176pp £8.99/$16.95pb

Margaret Harris

Covert ops with added science

A comic book about teenage scientists joining a secret society with the goal of boosting women in science, and occasionally saving the world, *The Curie Society* sounds in equal measure brilliant and twee. Thankfully, its large creative team and roster of science advisers mean it's both highly entertaining and packed with interesting science.

Co-creators Heather Einhorn and Adam Staffaroni, along with writer Janet Harvey and artist Sonia Liao, have come up with a world that could easily be our own, albeit in brighter colours. We meet our lead characters on their first day at Edmonds University. The three young women share a dorm room and initially do not get on with each other at all. Though each brilliant in her own way, they do not seem destined to become fast friends.

Maya is a mathematics major, Simone is a biology specialist and Taj is a computer scientist. Via a series of puzzles and tasks resembling an extra hard escape room, they are introduced to the Curie Society, which hopes to recruit them. The scientific explanations behind their problem-solving are accurate and clear, though they do occasionally feel more "info dump" than seamless storytelling.

The second half of the comic deals with a specific mission, centred around biotechnology that could be of great benefit to humanity, but in the wrong hands could be dangerous. There is some hubris to the Curie Society deciding that its hands are the "right" ones and this is touched on but dismissed. What we get instead is an action-packed spy-thriller at a tech conference. Which is a lot of fun and gives all the characters their moment to shine.

Not all of the plot threads are tied up, and it's clear there are plans for sequels. Hopefully that will give the lead characters a chance to develop beyond their initially sketched characteristics.

- 2021 MIT Press 168pp $18.95pb

Kate Gardner

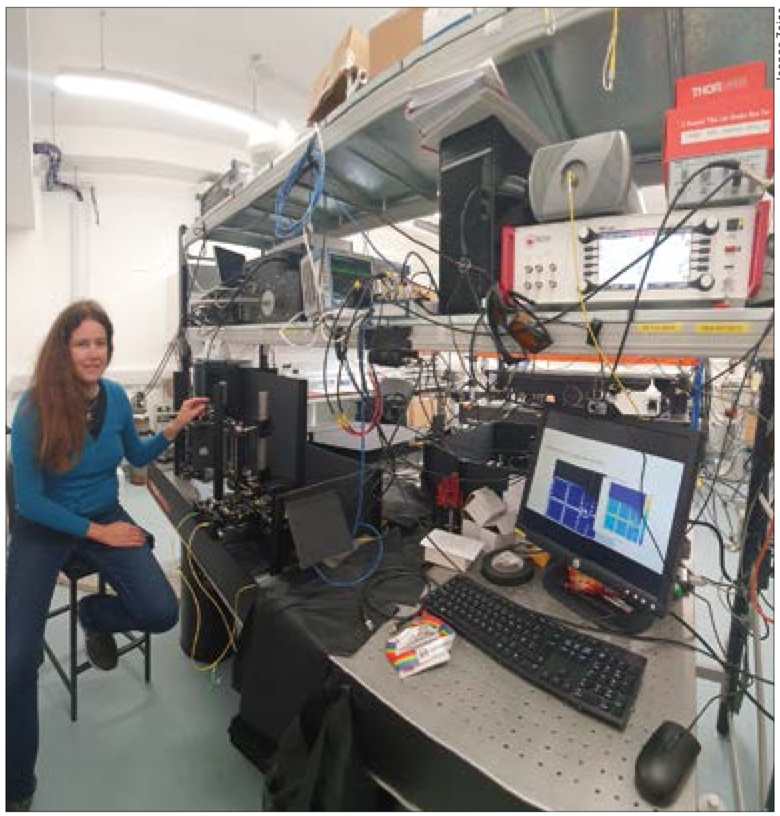
Industry or academia? How to choose your path

After doing a PhD and postdoc in quantum technology, in the UK, **Joanna Zajac** spent three years in industry before returning to fundamental research. She now works as a quantum scientist at Brookhaven National Laboratory. So how do academia and industry differ and which one is right for you?

The fundamental conundrum for junior scientists after graduating is whether to move into industry or continue in academia. I have worked on both sides of this divide. After completing my Master's degree in physics at Southampton University, I went to Cardiff University to do a PhD on novel types of vertical-cavity surface-emitting lasers. I then did a postdoc at Heriot-Watt University in Edinburgh, and at the University of St Andrews, where I worked on single-photon laser diodes and how they can be applied to quantum information technologies.

In 2017 I switched to industry and became a quantitative analyst at Moody's Analytics, a financial-services and risk-assessment company that does research and creates tools for corporate clients. While there, I used my strong mathematical and programming skills to do research in applied finance. After working in industry for three years, I then went back to fundamental science, becoming a senior researcher in quantum computing at the University of Oxford. Last year I moved to Brookhaven National Laboratory in the US, where I currently work as a quantum scientist.

So what are the main differences between academia and industry? In my experience they centre on four major aspects of working life: preferred working style, management, balance between work and family life, and the actual tasks involved in a job. Any career decision is ultimately your own, but I hope my perspective helps you to make a well-informed choice for your career.



Joanna Zajac

Academic endeavours While at the University of Oxford, Joanna Zajac developed a low-temperature confocal imaging system.

Preferred style of work: individual or teamwork

If you are more team-oriented, industry might be a better choice for you. It depends on the company culture, but in industry you are likely to be part of a team collaborating on a project. If you are involved in interdisciplinary projects, as I was, you will be working with colleagues who have expertise in a broad range of areas.

During my time in finance, it was a bare-minimum requirement to have an economist, a physicist and programmers on a team when tackling complex problems in modelling financial markets. A huge benefit for me was that I learned from all these professionals with different backgrounds, who each brought unique skills to the table. For instance, I learned how to do risk modelling while working in teams like this.

In academia, in contrast, group dynamics vary depending on the principal investigator, but in physics and maths there is usually a strong emphasis on individual work. This means you are driving your own research, hopefully given the space and resources you need to grow. I did my PhD and postdoc very much independently and my achievements reflect my determination and hard work. However, this emphasis on individual work creates a highly competitive environment, which I do not think is beneficial for the development of young researchers.

I feel that close collaborations and interactions with colleagues are hugely beneficial, especially during the early stages of your career. That's when it's important to learn not only practical knowledge but also soft skills like communication and management. Consequently, the higher level of guidance and feedback that you get in industry makes it easier for you to learn and improve on the job.

The main differences between academia and industry include preferred working style, management, balance between work and family, and the actual tasks involved in the job

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Management

Another feature of industry is that there is more structure and risk mitigation, with product managers ensuring that solutions are delivered to clients on schedule. In my case, I was responsible for developing and implementing financial modelling tools, among other tasks. My projects had specific resources assigned to them and concrete deadlines that needed to be met. Although the work was clearly structured, it was not always easy, and there were times when extended team efforts were required.

Working in academia tends to be much more ad-hoc, with flexibility to choose what you work on and when. This arrangement can be great, especially for people with strong focus and time-management skills, and it suits me. However, it might not be ideal for everyone, and it takes time to adapt. You might find yourself overwhelmed by passing time with scarce results.

Although some risks are considered and mitigation measures taken in academic research, this is not done as rigorously as in industry. The chances of bottlenecks, especially for collaborative projects, are therefore higher in academia.

Balance of work and family life

One big benefit of industry is that the working environment is more accommodating for employees with families than it is in academia. With companies offering generous benefits to attract top talent, it is easier to find the stability and resources required to support family life. There also tends to be more social interaction with colleagues from various backgrounds who often happily share their own experiences and advice. More generally, there is usually much more going on outside of work too, such as charity events or after-work get-togethers, all of which contribute to a healthy work environment.

Academia lags behind when it comes to supporting employees with families. There are various initiatives aiming to address this. Athena Swan, for example, is a charter and accreditation scheme that makes recommendations on how academic departments can improve gender equality and gives awards to recognize and encourage efforts in this area.

I was a member of the Athena Swan committee at both Heriot-Watt and Oxford, and our efforts were aimed at introducing more benefits for working parents, such as adopting shared parental leave. However, in my opinion, these initiatives do not reach far enough and are slow to keep up with evolving needs.

This is especially visible in science, technology, engineering and maths (STEM) departments where it is very rare to hear of a colleague taking maternity leave. I believe that the limited support available for parents and the prevalence of short-term contracts in academia contribute to the low retention rate of female academics in STEM fields.

Tasks involved

The final major point to consider when deciding whether to move into industry or stay in academia is the actual work you will be doing. Industry is product-oriented, so you will see your idea develop from the whiteboard through to implementation, and even receive feedback from users. While working at Moody's Analytics, for example, I was involved in projects developing client-oriented software solutions for use by financial institutions. My colleagues and I did write reports and papers about our research, just as we would in academia, but these documents were for internal purposes only to protect the company's intellectual property.

This product-development cycle is rarely present in academia, where the projects are usually on prototype-stage ideas or even completely blue-skies research. The focus on very detailed tasks can certainly be intellectually stimulating, but it can also leave you longing to work on something more applied and immediately useful. Having said that, current graduates have much broader career options compared with what was available to me and my peers when I graduated almost 15 years ago. This is because quantum research has become much more mature and product-driven in recent years.

In the end, the choice of which path to take depends on what type of work and professional environment you will personally find satisfying. What is most important is that you make yourself aware of these differences, so you can find a job and workplace that is right for you.

Joanna Zajac is a quantum scientist at Brookhaven National Laboratory, US

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Ask me anything: Maksym Sich


AEGIQ

Maksym Sich is co-founder and chief executive of Aegiq, a quantum-photonics spin-out company working on the development of secure quantum data communications and quantum photonics. Sich did a PhD and postdoc in semiconductor and quantum science at the University of Sheffield before moving into industry. In 2021 Aegiq won a Business Start-Up Award from the Institute of Physics.

What skills do you use every day in your job?
I use multiple skills every day. Some of them are people skills, but others are about understanding the physics, so you get an interesting synergy there. You need to understand the subject matter of what you're doing, but to develop a business you also need to be able to translate that into solving real-world problems and figure out how it applies to everybody's lives. As a chief executive, you are responsible for getting your team together, ensuring good dynamics and, of course, business growth, so that's something else I do every day.

What do you like best and least about your job?
What I like most is the scope and the fact that the quantum-technology sector is very new and there's a lot to be discovered, not just in terms of science but also in terms of business and how the company can grow. That's something that drives you and can get you through any difficulty. In academic research you tend to have a particular direction, but when you run a business you release yourself from those boundaries. You're free to do whatever works best. It can be a curse and a blessing, but I focus on the latter.

What I like least is the quantity of tasks that need to be done, and the challenge of balancing the management work with the actual thinking and creative work. There is always a lot happening at the same time and I find that multitasking can be quite taxing.

> Ask yourself why you are doing what you're doing, and be clear with yourself about the reasons. This allows you to make better decisions about what to pursue and how to build your career

What do you know today, that you wish you knew when you were starting out in your career?
This is the most difficult question, because there is a lot, but that's probably a good sign because it means you have developed. It's important to ask yourself why you are doing what you're doing, and to really understand and be clear with yourself about the reasons. That allows you to make better decisions about what to pursue and how to build your career more efficiently. The more incoming opportunities you have, the more critical this question becomes. You should also ensure you are careful with your time.

For people who have just graduated, I would advise them to explore topics outside physics too. Degrees are typically very technical and scientific, but they largely neglect the aspects of why you do physics and how it is applicable in the context of society, because there are not many people to teach that. It's not easy to put that in a curriculum. It's nearly common sense, but you need a professor who has worked in a lot of different settings to teach this, and there are very few out there. So it's really important for students to start thinking about these questions. A lot of people tend to be quite narrowly focused and neglect other possibilities, but the opportunities are there if you can think outside the purely technical skillset. If you focus completely on physics and think that whatever else is happening is probably not as great, then you're going to miss out.

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Conceptual juggling

I remember once while I was at school being asked to fill in a questionnaire in class to discover my personal learning style: visual, auditory or kinaesthetic. That last one sounded exotic, but the teacher told us that it meant you learned best by being physically involved in activities, rather than absorbing information through listening to explanations or watching demonstrations.

Although categories like this can offer useful insights, they have their limitations when it comes to real life. Most students in the class, myself included, turned out to be a little bit of each type of learner. Each academic subject lends itself more to one learning style than another, too. Physics, with its emphasis on what we observe physically happening in the 3D world, probably has more scope for kinaesthetic learning than most subjects.

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After all, children are learning kinaesthetically about gravity every time they drop something (or fall over); about friction every time they go down a slide with their shoes on instead of just socks; about circular motion when they feel themselves being pulled to the outside of a spinning roundabout. This is how we first learn about cause and effect, and develop a physical intuition about how objects interact.

Using playful exploration to introduce scientific principles is the thinking behind a series of workshops on the physics of circus skills, developed by a Bristol-based theatre group last year. The Oddly Moving Theatre Company teamed up with the Institute of Physics, and the physics-education charity The Ogden Trust, to deliver the workshops to local schoolchildren between the ages of 10 and 14, focusing on three tricks: juggling, spinning plates and diabolo.

Oddly Moving was founded in 2016 by circus and theatre performer Grania Pickard, and creates circus-theatre shows, which combine both art forms. Although circus entertainment has historically involved tamed animals doing various stunts, Oddly Moving takes the more modern approach of showcasing the agility and ingenuity of human performers.

These kinds of circus tricks are a great entry point for sparking curiosity and unlocking new ideas. After all, the tricks are surprising and impressive because they defy our expectations. We know from a young age, perhaps from building towers out of blocks, that it's very hard to put a larger object on top of a narrow platform without toppling it. This might be described as an intuitive understanding of centre of mass. So it's surprising to find wide plates balancing with ease atop beanpoles, at least the first time you see it. But, as any physicist will tell you, having your expectations defied is a sign that you're about to learn something new.

The workshops begin with a member of the theatre group demonstrating one of the circus tricks and teaching the technique, after which a volunteer physicist describes the physical principles behind how it works. For example, they explain how conservation of momentum leads to gyroscopic effects, which stabilize the spinning plates and stop them from falling off the sticks, as you would expect them to do if they were still. The physicist also explores the concept of friction and how the plates gradually lose energy, so need to be sped up occasionally to maintain their balance. After these explanations, the children have the chance to try the trick themselves, getting direct experience of these principles in action.

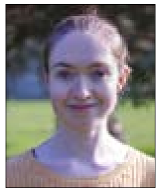
Children are learning kinaesthetically about gravity every time they drop something (or fall over)

Sam, a student from the University of Bristol who volunteered to help out with the workshops, says that the children find it harder to grasp some concepts than others. When learning to juggle, they might quickly understand the idea that the force from your hand throws the ball up, but they are often confused by the idea of kinetic energy being converted into gravitational potential energy. Perhaps this is to be expected; potential energy is a much more abstract and less tangible concept, and doesn't lend itself to being directly experienced, unlike the angular momentum of spinning plates.

After having a go at spinning plates and juggling, the children get to try their hand at diabolo, but this time the physicist doesn't go through the principles underpinning it first. Instead, after attempting various diabolo tricks, the children are asked to explain the physics involved in this new context. Stability due to the conservation of angular momentum is a key aspect here, as are friction, transfer of energy and centre of mass. Wave motion also crops up, since generating a wave along the string transfers energy to the diabolo to set it spinning.

Sam found that, in general, the children who are most keen on mastering the circus skills tend to also be the ones who are most interested in the physics. Perhaps this is because the more you want to get good at something, the more motivated you are to learn how it works, so you can apply that knowledge when you practise it.

That said, it's perfectly possible to be a pro at the theory while struggling with the practical side, or vice versa. Sam also noted that he found it both amusing and slightly embarrassing that many of the children were better at – and quicker to learn – the circus skills than he and the other student volunteers were. He found this surprising because he thought his more sophisticated understanding would be a big advantage. Having the theoretical knowledge might give you a leg up in figuring out how to improve your technique, but it's no guarantee that you'll pull something off in practice.



Laura Hiscott is reviews and careers editor of *Physics World*

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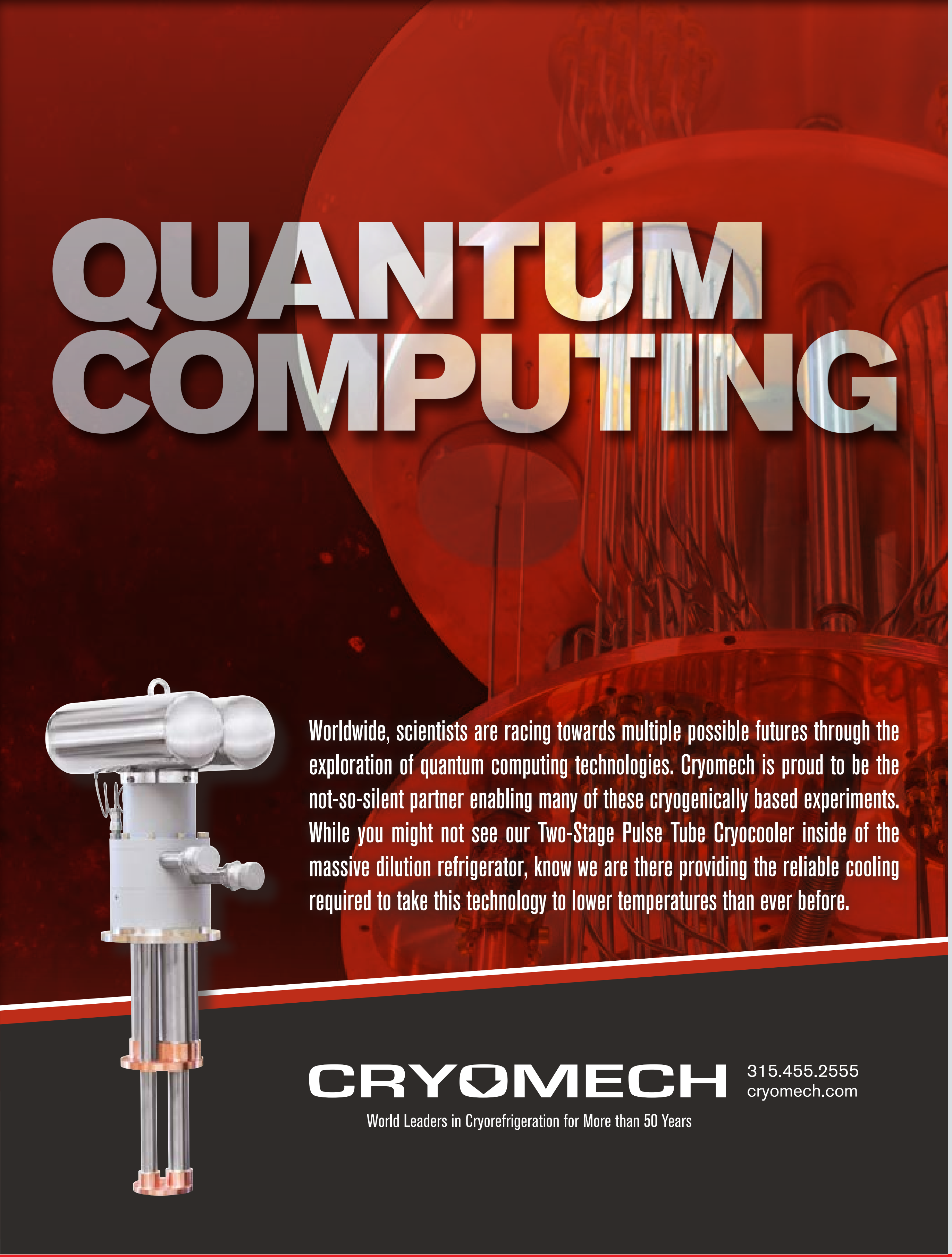
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