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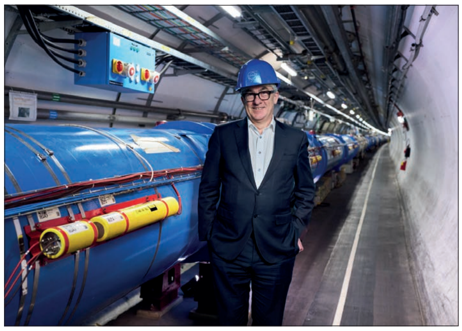

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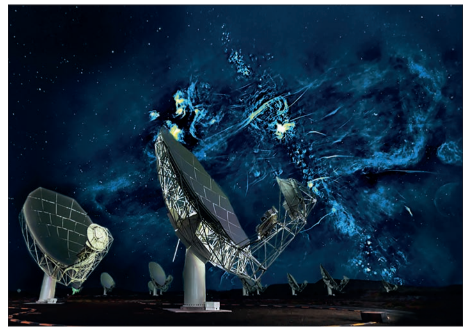

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News & Analysis

Trump turmoil hits US science

The administration of US president Donald Trump is continuing to cause upheaval to US science, but demonstrators are fighting back, as **Peter Gwynne** reports

A few months into Donald Trump's second presidency and many parts of US science – across government, academia and industry – continue to be hit hard by the new administration's policies. Science-related government agencies are seeing budgets and staff cut, especially in programmes linked to climate change and diversity, equity and inclusion (DEI). Elon Musk's Department of Government Efficiency (DOGE) is also causing havoc as it seeks to slash spending.

In mid-February, DOGE fired more than 300 employees at the National Nuclear Safety Administration, which is part of the US Department of Energy, many of whom were responsible for reassembling nuclear warheads at the Pantex plant in Texas. A day later, the agency was forced to rescind all but 28 of the sackings amid concerns that their absence could jeopardise national security.

A judge has also reinstated workers who were laid off at the National Science Foundation (NSF) as well as at the Centers for Disease Control and Prevention. The judge said the government's Office of Personnel Management, which sacked the staff, did not have the authority to do so. However, the NSF rehiring applies mainly to military veterans and staff with disabilities, with the overall workforce down by about 140 people – or roughly 10%.

The NSF has also announced a reduction, the size of which is unknown, in its Research Experiences for Undergraduates programme. For almost 40 years, the initiative has given thousands of college students – many with backgrounds that are under-represented in science – the opportunity to carry out original research at institutions during the summer holidays. NSF staff are reviewing thousands of grants containing words such as "women" and "diversity".

United States government work

Cracking down Policies introduced by the administration of Donald Trump are leading to reduced budgets and staff cuts.

NSF staff are reviewing thousands of grants containing words such as "women" and "diversity"

NASA, meanwhile, is to shut its office of technology, policy and strategy, along with its chief-scientist office, and the DEI and accessibility branch of its diversity and equal opportunity office. "I know this news is difficult and may affect us all differently," admitted acting administrator Janet Petro in an all-staff e-mail. Affecting about 20 staff, the move is on top of plans to reduce NASA's overall workforce. Reports also suggest that NASA's science budget could be slashed by as much as 50%.

Hundreds of "probationary employees" have been sacked by the National Oceanic and Atmospheric Administration (NOAA), which provides weather forecasts that are vital for farmers and people in areas threatened by tornadoes and hurricanes. "If there were to be large staffing reductions at NOAA there will be people who die in extreme weather events and weather-related disasters who would not have otherwise," warns climate scientist Daniel Swain from the University of California, Los Angeles.

Climate concerns

In his first cabinet meeting on 26 February, Trump suggested that officials "use scalpels" when trimming their departments' spending and personnel – rather than Musk's figurative chainsaw. But bosses at the Environmental Protection Agency (EPA) still plan to cut its budget by about two-thirds. "[W]e fear that such cuts would render the agency incapable of protecting Americans from grave threats in our air, water and land," wrote former EPA administrators William Reilly, Christine Todd Whitman and Gina McCarthy in the *New York Times*.

The White House's attack on climate science goes beyond just the EPA. In January the US Department of Agriculture removed almost all data on climate change from its website. The action resulted in a lawsuit in March from the Northeast Organic Farming Association of New York and two non-profit organizations – the Natural Resources Defense Council and the Environmental Working Group. They say that the removal hinders research and "agricultural decisions".

The Trump administration has also barred NASA's now former chief scientist Katherine Calvin and members of the State Department from travelling to China for a planning meeting of the Intergovernmental Panel on Climate Change. Meanwhile, in a speech to African energy ministers in Washington on 7 March, US energy secretary Chris Wright claimed that coal has "transformed our world and made it better", adding that climate change, while real, is not on his list of the world's top 10 problems. "We've had years of Western countries shamelessly saying 'don't develop coal'," he said. "That's just nonsense."

At the National Institutes of Health (NIH), staff are being told to cancel hundreds of research grants that involve DEI and transgender issues. The Trump administration also wants to cut the allowance for indirect costs of NIH's and other agencies' research grants to 15% of research contracts, although a district court judge has put that move on hold pending further legal arguments. On 8 March the Trump administration threatened to cancel $400m in funding to Columbia purportedly due to its failure to tackle antisemitism on the campus.

A Trump policy of removing "undocumented aliens" also continues to alarm universities that have overseas students. Some institutions have already advised those students against travelling abroad during holidays, in case immigration officers do not let them back in when they return. Others warn that their international students should carry their immigration documents with them at all times. Universities have also started to rein in spending, with Harvard and the Massachusetts Institute of Technology, for example, implementing a hiring freeze.

Falling behind

Amid the turmoil, the US scientific community is beginning to fight back. Individual scientists have supported court cases that have overturned sackings at government agencies, while a letter to Congress signed by the Union of Concerned Scientists and 48 scientific societies asserts that the administration has "already caused significant harm to American science". On 7 March more than 30 US cities hosted Stand Up for Science rallies attended by thousands of demonstrators.

Elsewhere, a group of government, academic and industry leaders – known collectively as Vision for American Science and Technology – released a report warning that the US could fall behind China and other competitors in science and technology. Entitled *Unleashing American Potential*, it calls for increased public and private investment in science to maintain US leadership. "The more dollars we put in from the feds, the more investment comes in from industry, and we get job growth, we get economic success, and we get national security out of it," notes Sudip Parikh, chief executive of the American Association for the Advancement of Science, who was involved in the report.

Marcia McNutt, president of the National Academy of Sciences, meanwhile, has called on the community to continue to highlight the benefit of science. "We need to underscore the fact that stable federal funding of research is the main mode by which radical new discoveries have come to light – discoveries that have enabled the age of quantum computing and AI and new materials science," she said. "These are areas that I am sure are very important to this administration as well."

Peter Gwynne is *Physics World*'s North America correspondent

Demonstrators rally for science across the US

All images courtesy: Robert P Crease

Thousands of demonstrators attended Stand Up for Science rallies in more than 30 cities across the US on 7 March to protest the Trump administration's planned cuts to research funding and to scientific agencies. The main rally took place on the steps of the Lincoln Memorial in Washington DC, where speakers included the physicist Bill Foster, a Democratic Congressional representative from Illinois. Other protests were held everywhere from New York City (see photos) and San Francisco to Chicago and Denver. The grass-roots protest movement has three main aims, which are to "end censorship and political interference in science"; "secure and expand scientific funding"; and "defend diversity, equity, inclusion and accessibility in science". It is calling on "leaders at every level, regardless of political affiliation, to champion and protect scientific research, education and communication – for the progress, prosperity and well-being of all".

● Visit tinyurl.com/39y48wxv to read Robert P Crease's account of the rally at Washington Square in New York

Publishing

Study reveals growing trend of 'stealth corrections'

The integrity of science could be threatened by publishers changing scientific papers after they have been published – but without making any formal public notification. That's the verdict of a new study by an international team of researchers, who coin such changes "stealth corrections". They want publishers to publicly log all changes that are made to published scientific research (*Learned Publishing* 38 e1660).

When corrections are made to a paper after publication, a notice is usually added to the article explaining what has been changed and why. This transparent record-keeping is designed to retain trust in the scientific record. But last year, René Aquarius, a neurosurgery researcher at Radboud University Medical Center in the Netherlands, spotted an issue with an image in a published paper. After raising his concerns with the authors, they stated that they were "checking the original data to figure out the problem" and would keep him updated. However, Aquarius was surprised to see that the figure had been updated a month later, but without a correction notice stating that the changes had been made.

iStock/Yuliya-Taba

Changing habits The researchers say that clearer guidelines are required about what constitutes a correction in scientific articles.

Aquarius and his colleagues began to record other instances of stealth corrections, which they define as at least one post-publication change being made to a scientific article that does not provide a correction note or any other indicator that the publication has been temporarily or permanently altered. The researchers identified 131 stealth corrections spread across 10 scientific publishers and in different fields of research. In 92 of the cases, the stealth correction involved a change in the content of the article, such as to figures, data or text.

The remaining unrecorded changes covered three categories: "author information" such as the addition of authors or changes in affiliation; "additional information", including edits to ethics and conflict of interest statements; and "the record of editorial process", for instance alterations to editor details and publication dates.

After the authors began drawing attention to the stealth corrections, five of the papers received an official correction notice, nine were given expressions of concern, 17 reverted to the original version and 11 were retracted. Aquarius says he believes it is "important" that readers know what has happened to a paper "so they can make up their own mind whether they want to trust [it] or not".

The researchers would now like to see publishers implementing online correction logs so that changes are transparently reported. They also say that clearer definitions and guidelines are required concerning what constitutes a correction and needs a correction notice. "We need to have sustained vigilance in the scientific community to spot these stealth corrections and also register them publicly," Aquarius says.

Michael Allen

Space

NASA launches $488m SPHEREx observatory

NASA has launched a $488m infrared mission to map the distribution of galaxies and study cosmic inflation. The Spectro-Photometer for the History of the Universe, Epoch of Reionization and Ices Explorer (SPHEREx) mission took off last month from Vandenberg Space Force Base in California.

Set to operate for two years in a polar orbit about 650 km from the Earth's surface, SPHEREx will collect data from 450 million galaxies as well as more than 100 million stars to create a 3D map of the cosmos, providing an insight into cosmic inflation – the rapid expansion of the universe following the Big Bang. The mission will also search the Milky Way for hidden reservoirs of water, carbon dioxide and other ingredients critical for life as well as study the cosmic glow of light from the space between galaxies.

NASA/JPL-Caltech

Light cone SPHEREx features three concentric shields that surround the telescope to protect it from light and heat.

The craft features three concentric shields that surround the telescope to protect it from light and heat. Three mirrors, including a 20 cm primary mirror, collect light before feeding it into filters and detectors, allowing it to resolve 102 different wavelengths of light. SPHEREx has been launched together with another NASA mission dubbed Polarimeter to Unify the Corona and Heliosphere (PUNCH). Via a constellation of four satellites in a low-Earth orbit, PUNCH will make 3D observations of the Sun's corona to learn how the mass and energy become solar wind. It will also explore the formation and evolution of space weather events such as coronal mass ejections, which can create storms of energetic particle radiation that can be damaging to spacecraft.

"Congratulations to both mission teams as they explore the cosmos from far-out galaxies to our neighbourhood star," noted Nicky Fox, associate administrator for NASA's science mission directorate. "I am excited to see the data returned in the years to come."

Michael Banks


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Planning the future of particle physics

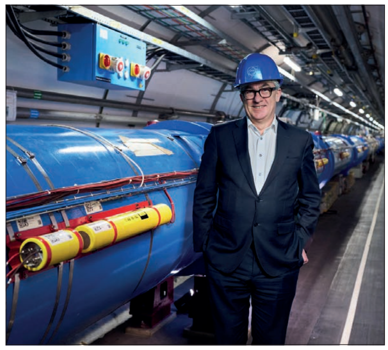
Mark Thomson, who will take over from Fabiola Gianotti as director-general of CERN next year, talks to Michael Banks about his plans in the hot seat and the challenges ahead for high-energy physics

How did you get interested in particle physics?
I completed a DPhil at the University of Oxford in 1991 studying cosmic rays and neutrinos. In 1992 I moved to University College London as a research fellow. That was the first time I went to CERN and two years later I began working on the Large Electron-Positron Collider, which was the predecessor of the Large Hadron Collider. I was fortunate enough to work on some of the really big measurements of the W and Z bosons and electroweak unification, so it was a great time in my life. In 2000 I worked at the University of Cambridge where I set up a neutrino group. It was then that I began working at Fermilab – the US's premier particle-physics lab.

So you flipped from collider physics to neutrino physics?
Over the past 20 years, I have oscillated between them and sometimes have done both in parallel. Probably the biggest step forward was in 2013 when I became spokesperson for the Deep Underground Neutrino Experiment – a really fascinating, challenging and ambitious project. In 2018 I was appointed executive chair of the Science and Technology Facilities Council (STFC) – one of the main UK funding agencies. The STFC funds particle physics and astronomy in the UK and maintains relationships with organizations such as CERN and the Square Kilometre Array Observatory, as well as operating some of the UK's biggest national infrastructures such as the Rutherford Appleton Laboratory and the Daresbury Laboratory.

What did that role involve?
It covered strategic funding of particle physics and astronomy in the UK and also involved running a large scientific organization with about 2800 scientific, technical and engineering staff. It was very good preparation for the role as CERN director-general.

What attracted you to become CERN director-general?



CERN

Looking ahead
Mark Thomson will take up the position as CERN director-general on 1 January 2026.

AUDIO
Listen to an extended version of this interview

CERN is such an important part of the global particle-physics landscape. But I don't think there was ever a moment where I just thought "Oh, I must do this." I've spent six years on the CERN Council, so I know the organization well. I realized I had all of the tools to do the job – a combination of the science, knowing the organization and then my experience in previous roles. CERN has been a large part of my life for many years, so it's a fantastic opportunity for me.

What were your first thoughts when you heard you had got the role?
It was quite a surreal moment. My first thoughts were "Well, OK, that's fun" – it didn't really sink in until the evening. I'm obviously very happy and it was fantastic news, but it was almost a feeling of "What happens now?".

What happens now as CERN director-general designate?
There will be a little bit of shadowing, but you can't shadow someone for the whole year, that doesn't make very much sense. So what I really have to do is understand the organization, how it works from the inside and, of course, get to know the fantastic CERN staff, which I've already started doing. A lot of my time at the moment is meeting people and understanding how things work.

Might you do things differently?
I don't think I will do anything too radical. I will have a look at where we can make things work better. But my priority for now is putting in place the team that will work with me from January. That's quite a big chunk of work.

What do you think your leadership style will be?
I like to put around me a strong leadership team and then delegate and trust the leadership team to deliver. I'm there to set the strategic direction but also to empower them to deliver. That means I can take an outward focus and engage with the member states to promote CERN. I think my leadership style is to put in place a culture where the staff can thrive and operate in a very open and transparent way. That's very important to me because it builds trust both within the organization and with CERN's partners. The final thing is that I'm 100% behind CERN being an inclusive organization.

So diversity is an important aspect for you?
I am deeply committed to diversity and CERN is deeply committed to it in all its forms, and that will not change. This is a common value across Europe: our member states absolutely see diversity as being critical, and it means a lot to our scientific communities as well. From a scientific point of view, if we're not supporting diversity, we're losing people who are no different from others who come from more privileged backgrounds. Also, diversity at CERN has a special meaning: it means all the normal protected characteristics, but also national diversity. CERN is a community of 24 member states and quite a few associate member states, and ensuring nations are represented is incredibly important. It's the way you do the best science, ultimately, and it's the right thing to do.

The LHC is undergoing a £1bn upgrade towards a High Luminosity-LHC (HL-LHC), what will that entail?
The HL-LHC is a big step up in terms of capability and the goal will be to increase the luminosity

of the machine (see box below). We are also upgrading the detectors to make them even more precise. The HL-LHC will run from about 2030 to the early 2040s. So by the end of LHC operations, we would have only taken about 10% of the overall data set once you add what the HL-LHC is expected to produce.

Beyond the HL-LHC, you will also be involved in planning what comes next. What are the options?
We have a decision to make on what comes after the HL-LHC in the mid-2040s. It seems a long way off but these projects need a 20-year lead-in. I think the consensus among the scientific community for a number of years has been that the next machine must explore the Higgs boson. The motivation for a Higgs factory is incredibly strong.

Yet there has not been much consensus whether that should be a linear or circular machine?
My personal view is that a circular collider is the way forward. One option is the Future Circular Collider (FCC) – a 91 km circumference collider that would be built at CERN.

I'm 100% behind CERN being an inclusive organization

What benefits would the FCC have?
We know how to build circular colliders and it gives you significantly more capability than a linear machine by producing more Higgs bosons. It is also a piece of research infrastructure that will be there for many years beyond the electron–positron collider. The other aspect is that at some point in the future, we are going to want a high-energy hadron collider to explore the unknown.

But it won't come cheap, with estimates being about £12–15bn for the electron–positron version, dubbed FCC-ee?
While the price tag for the FCC-ee is significant, that is spread over 24 member states for 15 years and contributions can also come from elsewhere. I'm not saying it's going to be easy to actually secure that jigsaw puzzle of resources, because money will need to come from outside Europe as well.

What would happen to the FCC if China builds the Circular Electron Positron Collider (CEPC), as it hopes to do by the 2030s?
I think that will be part of the European Strategy for Particle Physics, which will happen throughout this year, to think about the ifs and buts. Of course, nothing has really been decided in China. It's a big project and it might not go ahead. It's quite easy to put down aggressive timescales on paper but actually delivering them is always harder. The big advantage of CERN is that we have the scientific and engineering heritage in building colliders and operating them. There is only one CERN in the world.

Michael Banks is news editor of *Physics World*

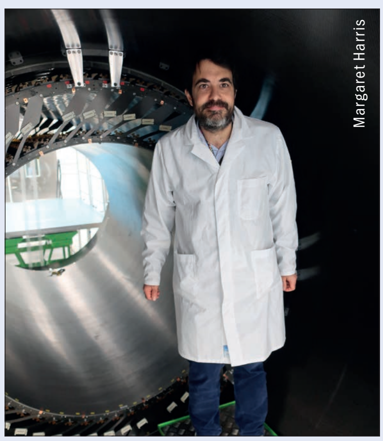
High energy, meet High Lumi

While CERN's leaders discuss proposals for new particle colliders (see main text), rank-and-file scientists at Europe's flagship particle-physics lab are gearing up to improve the machine they already have. The Large Hadron Collider (LHC) is now nearly 17 years old, and between 2026 and 2030 it will receive its final major upgrade, which is designed keep it churning out data until the early 2040s.

Unlike a previous big upgrade, which raised the LHC's maximum collision energy from 7 TeV to 14 TeV, this one will increase its luminosity – the collision rate divided by the probability that a collision will take place (the cross section). The goal of the High Luminosity LHC (known informally as "High Lumi") is to boost collision rates at the LHC's two biggest particle detectors, CMS and ATLAS.

Doing this will require a multi-pronged approach, with more powerful focusing magnets, better collimators, improved beam optics and upgraded power lines all playing a role. One of the most eye-catching modifications involves changing the geometry of the LHC's beams at the points where they cross. These beams are not continuous streams of protons. Instead, they are made up of bunches that contain around 100 billion protons each. In the LHC's current form, these bunches cross at an angle, and collisions can only occur in the area where they overlap. Increasing this area by flattening the crossing angle is thus a conceptually simple way of increasing the number of collisions per crossing.

To achieve this in practice, teams are constructing superconducting radio-frequency cavities that can push bunches of protons sideways, like a crab walks. These so-called "crab" cavities have been installed in other particle accelerators, but never in a high-energy hadron collider like the LHC. The High Lumi upgrade includes 16 such cavities, several of which have already arrived at CERN for testing.


Margaret Harris

On track Physicist Karolos Potamianos with the carbon-fibre barrel that will house a new Inner Tracker for the high-luminosity upgrade at the Large Hadron Collider.

AUDIO Listen to an extended version of this story

Another focus of the upgrade is the detectors themselves. For example, the innermost part of the ATLAS detector, which is the first to "see" the decay products of particle collisions and therefore receives high amounts of radiation, will be removed and replaced with a new Inner Tracker (ITk). The ITk's design calls for hundreds of strip-like silicon-based sensors to be slotted into a carbon-fibre barrel. When *Physics World* visited in late January, this barrel was sitting on a platform in the ATLAS integration hall, watched over somewhat anxiously by members of the ITk team. Once the ITk is assembled, the team will experience further anxious moments as the 6 m long, 2 m high barrel and its intricate innards are lowered into place through a hole in the ceiling of the 100 m-deep ATLAS chamber.

As for the science of the High-Lumi era, CERN's current director-general, Fabiola Gianotti, told *Physics World* that one key focus will be studying how the Higgs boson interacts with itself. This interaction, she explains, is a portal to events that took place in the early universe, when the Higgs field became established and initially massless elementary particles interacted with it to become the massive electrons and quarks we know today. "I cannot promise we will discover new particles or new forces – I have no idea because it is in the hands of nature," Gianotti says. "But for sure we will make progress, progress in understanding how the laws of nature work at the most fundamental level."

Margaret Harris, Geneva

People

Physicist Ian Chapman picked to head UKRI

The fusion physicist Ian Chapman is to be the next head of UK Research and Innovation (UKRI) – the UK's biggest public research funder. He will take up the role in June, replacing the geneticist Ottoline Leyser who has held the position since 2020.

Having studied mathematics and physics at Durham University and done a PhD in fusion science at Imperial College London, in 2014 Chapman became head of tokamak science at Culham and then fusion programme manager a year later. In 2016, aged just 34, he was named chief executive of the UK Atomic Energy Authority (UKAEA), which saw him lead the UK's magnetic confinement fusion research programme at Culham.

With an annual budget of £9bn, UKRI is the umbrella organization of the UK's nine research councils. Chapman, who currently sits on UKRI's board, says that he is "excited" to take over as head of UKRI. "Research and innovation must be central to the prosperity of our society and our economy, so UKRI can shape the future of the country," he notes. "I was tremendously fortunate to represent UKAEA, an organization at the forefront of global research and innovation of fusion energy, and I look forward to building on those experiences to enable the wider UK research and innovation sector."

The UKAEA has announced that Tim Bestwick, who is currently UKAEA's deputy chief executive, will take over as interim UKAEA head until a permanent replacement is found.

Steve Cowley, director of the Princeton Plasma Physics Laboratory in the US and a former chief executive of UKAEA, told *Physics World* that UKRI is in "excellent hands". "[Chapman] has set a direction for UK fusion research that is bold and inspired," adds Cowley. "It will be a hard act to follow but UK fusion development will go ahead with great energy."

Michael Banks

Policy

Serbian physicists go on strike

Physicists in Serbia went on strike last month in response to what they say is government corruption and social injustice. The one-day strike on 7 March, called by the country's official union for researchers, saw thousands of scientists joining students who have already been demonstrating for months over conditions in the country.

The student protests, which began in November, were triggered by a railway station canopy collapse that killed 15 people. Since then, it has grown into an ongoing mass protest seen by many as indirectly seeking to change the government, currently led by president Aleksandar Vučić. The Serbian government, however, claims it has met all student demands such as transparent publication of all documents related to the accident and the prosecution of individuals who have disrupted the protests. The government has also accepted the resignation of prime minister Miloš Vučević as well as transport minister Goran Vesić and trade minister Tomislav Momirović, who previously held the transport role during the station's reconstruction.

Many university faculties in Serbia have been blockaded by protesting students, who have been using them as a base for their demonstrations. Amid the continuing disruptions, the Serbian national science foundation has twice delayed a deadline for the award of €24m of research grants, citing "circumstances that adversely affect the collection of project documentation". The foundation adds that 96% of its survey participants requested an extension.

The researchers' union has also called on the government to freeze the work status of PhD students employed as research assistants or interns to accommodate the months' long pause to their work. The government has promised to look into it.

Mićo Tatalović and Nenad Jarić Daunhauer

Bojan Džodan

Taking to the streets
Anti-government protests were held in Niš on 1 March.

Space

Firefly Aerospace achieves lunar landing

The US firm Firefly Aerospace has claimed to be the first commercial company to achieve "a fully successful soft landing on the Moon". On 2 March the company's Blue Ghost lunar lander touched down on the Moon's surface in an "upright, stable configuration". It then operated for 14 days drilling into the lunar soil and imaging a total eclipse from the Moon where the Earth blocks the Sun.

Blue Ghost launched on 15 January from NASA's Kennedy Space Center in Florida via a SpaceX Falcon 9 rocket. Following a 45-day trip, the craft landed in Mare Crisium, touching down within its 100 m landing target next to a volcanic feature called Mons Latreille. The mission carries 10 NASA instruments, including a lunar subsurface drill, sample collector, X-ray imager and dust-mitigation experiments. Firefly's next lunar mission is expected to launch next year, and will aim to land on the far side of the Moon.

Firefly Aerospace

Perfect landing
Firefly Aerospace's Blue Ghost landed on the Moon on 2 March.

Meanwhile, the Houston-based company Intuitive Machines announced that its Athena lander, which launched to the Moon in late February, performed a soft landing on 6 March but landed on its side about 250 m away from the intended landing spot. Given that the lander was then unable to recharge its batteries, the firm declared the mission over, with the team accessing the data that has been collected. In February 2024 Intuitive Machines' first lunar lander – Odysseus – also made a soft landing, but did so at a 30-degree angle, which affected radio-transmission rates.

Michael Banks

Research updates

Microsoft qubit claim scrutinized

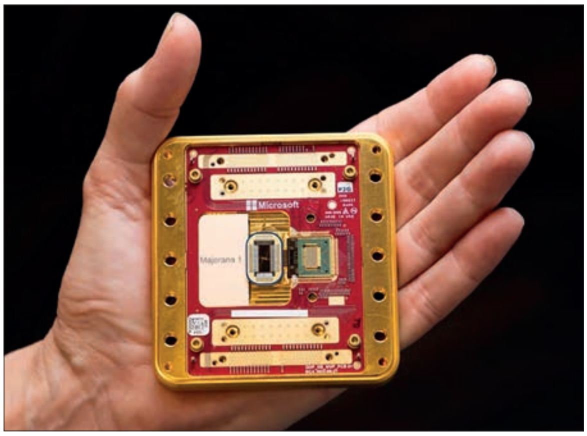
Tech giant Microsoft says it has made the first topological qubit, but some experts say the peer-reviewed research does not back it up, as **Philip Ball** explains

Researchers at Microsoft in the US claim to have made the first topological quantum bit (qubit) – a potentially transformative device that could make quantum computing robust against the errors that currently restrict what it can achieve (*Nature* **638** 651). The claim, however, has proven controversial because evidence supporting it has not yet been presented in a peer-reviewed paper. It was made in a press release from Microsoft accompanying the paper, which itself stops short of claiming a topological qubit but instead reports some of the key device characterization underpinning it.

Central to the controversy is the existence (or not) of Majorana zero modes (MZMs) – qubits that would be able to encode superpositions of the two readout states (representing a 1 or 0). An MZM is a quasiparticle (a particle-like collective electronic state) that can act as a topological qubit. By quantum-entangling such qubits, information could be manipulated in ways not possible for classical computers, greatly speeding up certain kinds of computation. In MZMs, the two states are distinguished by "parity": whether the quasiparticles contain even or odd numbers of electrons.

As MZMs are "topological" states, their settings cannot easily be flipped by random fluctuations to introduce errors into the calculation. Rather, the states are like a twist in a buckled belt that cannot be smoothed out unless the buckle is undone. Topological qubits would therefore suffer far less from the errors that afflict current quantum computers.

Writing in a peer-review file accompanying the paper, which has been written by more than 160 researchers from Microsoft's Azure Quantum team, the *Nature* editorial team says that it sought additional input from two of the article's reviewers to "establish its technical correctness", concluding that "the results in this manuscript do not represent evidence for the presence of Majorana zero modes in the reported devices". Chetan Nayak, leader of Microsoft Azure Quantum, which is based in Redmond, Washington, says that the evidence for a topological qubit was obtained in the period between submission of the paper in March 2024 and its publication.



John Brecher/Microsoft

Bold claims Microsoft has unveiled a quantum processor called Majorana 1 that, it says, features a "topological core".

Yet Winfried Hensinger, a physicist at the University of Sussex who works on quantum computing using trapped ions, is concerned that "the press release doesn't make it clear what the paper does and doesn't contain". He worries that some might conclude that the strong claim of having made a topological qubit is now supported by a paper in *Nature* and could lead to unrealistic expectations about what quantum computers can do. "We don't need to make these claims – that is just unhealthy and will really hurt the field," he says.

Catching up

It has long been thought that MZMs might be produced at the ends of nanoscale wires made of a superconducting material. Indeed, Microsoft researchers have been trying for several years to fabricate such structures and look for the characteristic signature of MZMs at their tips. But it can be hard to distinguish this signature from those of other electronic states that can form in these structures. In 2018 researchers at labs in the US and the Netherlands (including the Delft University of Technology and Microsoft), claimed to have evidence of an MZM in such devices. However, they then had to retract the work after others raised problems with the data. "That history is making some experts cautious about the new claim," says Scott Aaronson, a computer scientist at the University of Texas at Austin. "If the claim stands, [however,] it would be a scientific milestone for the field of topological quantum computing and physics beyond."

For now, though, it seems that Nayak and colleagues have cracked the technical challenges. In the *Nature* paper, they report measurements in a nanowire heterostructure made of superconducting aluminium and semiconducting indium arsenide that are consistent with, but not definitive proof of, MZMs forming at the two ends. The crucial advance is an ability to accurately measure the parity of the electronic states. "The paper shows that we can do these measurements fast and accurately," says Nayak. In the press release, the Microsoft team claims now to have put eight MZM topological qubits on a chip called Majorana 1, which is designed to house a million of them.

Even if the Microsoft claim stands up, a lot will still need to be done to get from a single MZM to a quantum computer, says Hensinger. Topological quantum computing is "probably 20–30 years behind the other platforms", he says. Yet researchers are supportive of the efforts "I'm grateful that at least one player stuck with the topological approach even when it ended up being a long, painful slog," says Aaronson.

Astronomy

Record-breaking ultra-high-energy neutrino spotted

The most energetic cosmic neutrino with an energy greater than 100 PeV – has been seen by researchers working on the KM3NeT neutrino observatory, located deep beneath the Mediterranean Sea. The team says that such detections could enhance our understanding of cosmic neutrino sources or reveal new physics (*Nature* 638 376).

Neutrinos are subatomic particles with masses less than a millionth of that of electrons. They are electrically neutral and interact rarely with matter via the weak force. As a result, neutrinos can travel vast cosmic distances without being deflected by magnetic fields or absorbed by interstellar material. Scientists expect high-energy neutrinos to come from powerful astrophysical accelerators such as active galactic nuclei powered by supermassive black holes, gamma-ray bursts, and other extreme cosmic events. However, pinpointing such accelerators remains challenging because their cosmic rays are deflected by magnetic fields as they travel to Earth, while their gamma rays can be absorbed on their journey.

Marco Kraan/Nikhef

Spectacular find The KM3NeT observatory, which is situated on the Mediterranean seabed, has spotted a neutrino with an energy about 30 times higher than the previous record.

Neutrinos, however, move in straight lines and this makes them unique messengers that could point back to astrophysical accelerators. The KM3NeT observatory is situated on the Mediterranean seabed, with detectors more than 2000 m below the surface. Occasionally, a high-energy neutrino will collide with a water molecule, producing a secondary charged particle. This particle moves faster than the speed of light in water, creating a faint flash of Cherenkov radiation. The detector's array of optical sensors capture these flashes, allowing researchers to reconstruct the neutrino's direction and energy.

KM3NeT has already identified many high-energy neutrinos, but in 2023 it detected a neutrino with an energy far in excess of any previously detected cosmic neutrino. Now, analysis by Paul de Jong from the University of Amsterdam, who is spokesperson for the KM3NeT collaboration, and colleagues put the neutrino's energy at about 30 times higher than that of the previous record-holder, which was spotted by the IceCube observatory at the South Pole. "It is a surprising and unexpected event," he says.

Scientists suspect that such a neutrino could originate from the most powerful cosmic accelerators, such as blazars. The neutrino could also be cosmogenic, being produced when ultra-high-energy cosmic rays interact with the cosmic microwave background radiation. While this single neutrino has not been traced back to a specific source, it opens the possibility of studying ultra-high-energy neutrinos as a new class of astrophysical messengers. "Regardless of what the source is, our event is spectacular: it tells us that either there are cosmic accelerators that result in these extreme energies, or this could be the first cosmogenic neutrino detected," adds de Jong.

Andrey Feldman

Biophysics

Here's how polar bears get their fur free of ice

Researchers in Ireland and Norway claim to have discovered why polar bear fur always remains free of ice. Having traced the fur's ice-shedding properties to a substance called sebum that is produced by glands near the root of each hair, the researchers suggest that the work could result in new environmentally-friendly anti-icing surfaces and lubricants (*Sci. Adv.* **11** eads7321).

The team obtained these results by comparing polar bear hairs naturally coated with sebum to hairs where the sebum had been removed using a surfactant. Their experiment involved forming a 2 × 2 × 2 cm block of ice on the samples and placing them in a cold chamber. They then used a force gauge on a track to push it off. By measuring the maximum force needed to remove the ice and dividing this by the area of the sample, they obtained ice adhesion strengths for the washed and unwashed fur.

Jenny E Ross

Bear necessities The work on polar bear fur could lead to new environmentally-friendly anti-icing surfaces and lubricants.

The experiment showed that the ice adhesion of unwashed polar bear fur is as little as 50 kPa. In contrast, the ice adhesion of washed (sebum-free) fur is at least 100 kPa greater than the unwashed fur. To determine the sebum's exact composition, the researchers used a range of experimental techniques as well as density functional theory methods to calculate the adsorption energy of the major components of the sebum. "In this way, we were able to identify which elements were responsible for the low ice adhesion," Carolan tells *Physics World*.

They found that sebum in the bear's fur contains three major components: cholesterol, diacylglycerols and anteisomethyl-branched fatty acids. These chemicals have a similar ice adsorption profile to that of perfluoroalkyl (PFAS) polymers, which are commonly employed in anti-icing applications. "While PFAS are very effective, they can be damaging to the environment," explains Julian Carolan from Trinity College Dublin. "Our results suggest that we could replace these with sebum components."

Isabelle Dumé

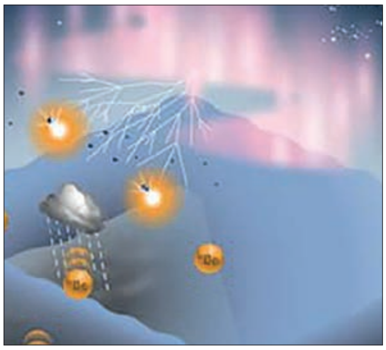
Environment

Curious radioactive anomaly appears in the oceans

An unknown event on Earth around 10 million years ago resulted in a "signature" of radioactive beryllium-10, according to studies of rocks located deep beneath the ocean. The finding could be evidence for a previously-unknown cosmic event or major changes in ocean circulation. With further study, the newly-discovered beryllium anomaly could also become an independent time marker for the geological record (*Nature Communications* **16** 866).

Most of the beryllium-10 found on Earth originates in the upper atmosphere where it forms when cosmic rays interact with oxygen and nitrogen molecules. The beryllium then attaches to aerosols, falls to the ground and is transported into the oceans. Eventually, it reaches the seabed and accumulates, becoming part of one of the most pristine geological archives on Earth. As beryllium-10 has a half-life of 1.4 million years, its abundance can be used to pin down the dates of geological samples that are more than 10 million years old.

In the new work, physicists in Germany and Australia measured the amount of beryllium-10 in geological samples taken from the Pacific Ocean. The samples are primarily made up of iron and manganese and formed slowly over millions of years. To date them, the team used a technique called accelerator mass spectrometry to distinguish beryllium-10 from its decay product, boron-10, which has the same mass, and from other beryllium isotopes.



HZDR / blrck.de

Cosmic mystery Around 10 million years ago, the amount of beryllium-10 deposited into ferromanganese crusts in the deep ocean increased substantially, for reasons still unexplained.

The researchers found that the samples dated to around 10 million years ago, a period known as the late Miocene, and contained almost twice as much beryllium-10 as they expected to see. The source of this overabundance is a mystery, says TU Dresden researcher Dominik Koll, but he offers three possible explanations. The first is that changes to the ocean circulation near the Antarctic, which scientists recently identified as occurring between 10 and 12 million years ago, could have distributed beryllium-10 unevenly across the Earth. "Beryllium-10 might thus have become particularly concentrated in the Pacific Ocean," says Koll.

The second possibility is that a supernova exploded in our galactic neighbourhood 10 million years ago, producing a temporary increase in cosmic radiation. The third option is that the Sun's magnetic shield, which deflects cosmic rays away from the Earth, became weaker through a collision with an interstellar cloud, making our planet more vulnerable to cosmic rays. The second and third scenarios would have increased the amount of beryllium-10 that fell to Earth without affecting its geographic distribution.

Isabelle Dumé

Biophysics

'Phononic shield' protects mantis shrimp from its own shock waves

Researchers at Northwestern University in the US have identified a structure in the shrimp's dactyl club that protects it when it strikes prey. Their findings, which they obtained by using ultrasonic techniques to investigate surface and bulk wave propagation in the dactyl club, could lead to novel advanced protective materials for military and civilian applications (*Science* 387 659).

Dactyl clubs are hammer-like structures located on each side of a mantis shrimp's body. They store energy in elastic structures similar to springs that are latched in place by tendons. When the shrimp contracts its muscles, the latch releases propelling the club forward with a peak force of up to 1500 N. The club's punch also creates bubbles that rapidly collapse to produce shockwaves in the megahertz range. "This secondary shockwave effect makes the shrimp's strike even more devastating," explains Northwestern biomechanical engineer Horacio Dante Espinosa.

Andy Law

Packing a punch A mantis shrimp's dactyl clubs can be propelled forward with a peak force of up to 1500 Newtons.

To answer how the shrimp's own soft tissues escape damage, Espinosa and colleagues studied the animal's armour by characterizing its microstructure and using ultrasonic techniques to analyse how stress waves propagate through it. The team identified three distinct regions in the shrimp's dactyl club.

The outermost layer consists of a hard hydroxyapatite coating approximately 70 μm thick, which is durable and resists damage. Beneath this, an approximately 500 μm-thick layer of mineralized chitin fibres arranged in a herringbone pattern enhances the club's fracture resistance. Deeper still, is a region that features twisted fibre bundles organized in a corkscrew-like arrangement known as a Bouligand structure. Within this structure, each successive layer is rotated relative to its neighbours, giving it a unique and crucial role in controlling how stress waves propagate through the shrimp.

"Our key finding was the existence of phononic bandgaps – through which waves within a specific frequency range cannot travel – in the Bouligand structure," Espinosa explains. "These bandgaps filter out harmful stress waves so that they do not propagate back into the shrimp's club and body.

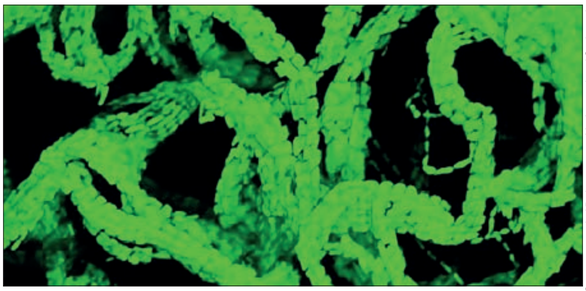
Isabelle Dumé

Biophysics

Bacteria make cables to form a 'living gel'

Researchers have found that bacterial cells in solutions of polymers such as mucus grow into long cable-like structures that buckle and twist on each other forming a "living gel" made of intertwined cells. This behaviour is very different from what occurs in polymer-free liquids and could lead to new treatments for bacterial infections in patients with cystic fibrosis. The finding could also help scientists understand how cells organize themselves into polymer-secreting conglomerations of bacteria called biofilms that can foul medical and industrial equipment (*Sci. Adv.* 11 *eadq7797*).

Interactions between bacteria and polymers are ubiquitous in nature. For example, many bacteria live as multicellular colonies in polymeric fluids, including host-secreted mucus, exopolymers in the ocean and the extracellular polymeric substance that encapsulates biofilms. Often, these growing colonies can become infectious, including in cystic fibrosis patients, whose mucus is more concentrated than it is in healthy individuals. Laboratory studies of bacteria, however, typically focus on cells in polymer-free fluids.



Sebastian Gonzalez La Corte *et al.*/Princeton University/Caltech

Green goo Research into bacterial cables could lead to new treatments for patients with cystic fibrosis.

In their work, a team at the California Institute of Technology (Caltech) and Princeton University, used a confocal microscope to monitor how different species of bacteria grew in purified samples of mucus. Normally, when bacterial cells divide, the resulting "daughter" cells diffuse away from each other. However, in polymeric mucus solutions, the team observed that the cells instead remain stuck together and begin to form long cable-like structures. These cables can contain thousands of cells, and eventually they start bending and folding on top of each other to form an entangled network.

The team's work reveals that polymers, far from being a passive medium, play a pivotal role in supporting bacterial life by shaping how cells grow in colonies. The morphology of these colonies is known to influence cell–cell interactions and is important for maintaining their genetic diversity. It also helps determine how resilient a colony is to external stressors. "By revealing this previously-unknown morphology of bacterial colonies in concentrated mucus, our finding could help inform ways to treat bacterial infections in patients with cystic fibrosis," Caltech biophysicist Sujit Datta told *Physics World*.

Datta is not yet sure why bacteria form large cables but it could be because they become more resilient against the body's immune system, making them more infectious. Another possibility is that the reverse is true – cable formation could in fact leave bacteria more exposed to the host's defence mechanisms. These include "mucociliary clearance", which is the process by which tiny hairs on the surface of the lungs constantly sweep up mucus and propel it upwards.

Isabelle Dumé

Medical physics

Cancer patients treated for first time ever with proton arc therapy

A team at the Trento Proton Therapy Centre in Italy has delivered the first clinical treatments using an emerging proton delivery technique called proton arc therapy (PAT). Following successful dosimetric comparisons with clinically delivered proton plans, the researchers confirmed the feasibility of PAT and used it to treat nine cancer patients (*Medical Physics* doi.org/10.1002/mp.17669).

Proton therapy is mostly delivered using pencil-beam scanning (PBS). While this provides "conformal" dose distributions, delivery can be compromised by the small number of possible beam angles. PAT overcomes this limitation by moving to an arc trajectory, which provides a large number of beam angles. It also optimizes the number of energies used for each beam direction, which improves delivery time (from the start of the first beam to the end of the last).

The Trento researchers – working with colleagues from RaySearch Laboratories – compared the dosimetric parameters of PAT plans with those of state-of-the-art PBS plans for 10 patients with head-and-neck cancer. They focused on this site due to the high number of organs close to the target that may be spared using the new technique.

The PAT plans dramatically improved dose conformality compared with previous treatments. While target coverage was of equal quality, PAT decreased the mean doses to other organs for all patients. The biggest impact was in the brainstem, where PAT reduced maximum and mean doses by 19.6 and 9.5 Gy(RBE), respectively. Doses to other primary organs did not differ significantly between plans, but PAT achieved an impressive reduction in mean dose to secondary organs not directly adjacent to the target.

UO Fisica Sanitaria and UO Protonterapia, APSS, Trento

On target Nine patients have received or are undergoing proton arc therapy at the Trento Proton Therapy Centre in Italy.

To verify the feasibility of clinical PAT, the researchers found that delivery times were similar for PAT compared to other techniques, at around 36 minutes for PAT with 30 beam directions. Reducing the number of beam directions to 20 reduced the delivery time to 25 minutes, while maintaining near-identical dosimetric data. This success prompted the team to begin clinical treatments and to date, nine patients have received or are undergoing PAT treatment: five with head-and-neck tumours, three with brain tumours and one thorax cancer. The researchers are now analysing acute toxicity data from the patients to determine whether PAT reduces toxicity. They are also looking to further reduce the delivery times.

Tami Freeman

Opinion

physicsworld

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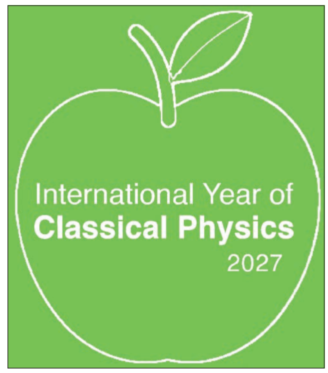
Beyond a joke

Why it can be disconcertingly hard to tell fact from fiction

Physicists in the UK are drawing up plans for an International Year of Classical Physics in 2027 – exactly three centuries after the death of Isaac Newton. Following successful international years devoted to astronomy (2009), light (2015) and quantum science (2025), they want more recognition to be given to a branch of physics that underpins much of modern life. An apple, naturally, will be the official logo for the year.



Before going any further, I should admit I'm not being serious. The above was in fact the start of our April Fool's joke for 2025, which appeared on the *Physics World* website earlier this month. We've been running April Fool's gags for quite a few years, penned by our fictitious columnist Ken Heartly-Wright. The best by far was the year we revealed that Brian Cox was to star in the TV soap *Coronation Street*, which had many of you fooled.

Over time, however, it's been getting harder to come up with good April Fool's jokes. The Internet these days is awash with so much fake news that's it's tricky to know what's genuine and what's nonsense – and what's clearly a joke. Artificial intelligence (AI) is also a threat, allowing words to be put – literally – into people's mouths. Worryingly, it allows scammers to use AI to clone the voices of, say, your family or friends.

Donald Trump's re-election as US president is blurring the line between fact and fiction still further. When I heard Trump say he wanted the US to take over Greenland, I assumed he was joking – until I discovered that a US politician really is putting a bill through Congress to rename it "Red, White, and Blueland". More seriously, some of his planned budget cuts and sackings at scientific agencies, while seemingly bizarre, are not fake at all (see pp3–4).

There are also chilling reports from the US of articles being edited to remove references to activities that contradict Trump's executive orders denouncing diversity initiatives. The Rubin Observatory, for example, is said to have altered text on its website about the astronomer Vera Rubin, who pioneered the notion of dark matter by studying the anomalous motion of galaxies. It has apparently cut information about her efforts to open up science to women.

When you hear stories like that, maybe we really should have an International Year of Classical Physics. After all, with Newton's laws – at least in the everyday world – you know exactly where you stand.

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

Critical Point Stop making sense

People often respond to scientific findings by invoking "stories" of dubious truth. **Robert P Crease** wonders if anything can be done about it

iStock/Laurence Dutton

Sense making Humans understand the world by taking information and fitting it into pre-existing stories that might be right or might be wrong.

If aliens came to Earth and tried to work out how we earthlings make sense of our world, they'd surely conclude that we take information and slot it into pre-existing stories – some true, some false, some bizarre. Ominously, these aliens would be correct. You don't need to ask earthling philosophers, just look around.

Many politicians and influencers, for instance, are convinced that scientific evidence does not tell the reality about, for instance, autism or AIDS, the state of the atmosphere or the legitimacy of elections, or even about aliens. Truth comes to light only when you "know the full story", which will eventually reveal the scientific data to be deceptive or irrelevant.

To see how this works in practice, suppose you hear someone say that a nearby lab is leaking *x* picocuries of a radioactive substance, potentially exposing you to *y* millirems of dose. How do you know if you're in danger? Well, you'll instinctively start going through a mental checklist of questions.

Who's speaking – scientist, politician, reporter or activist? If it's a scientist, are they from the government, a university, or an environmental or anti-nuclear group? You might then wonder: how trustworthy are the agencies that regulate the substance? Is the lab a good neighbour, or did it cover up past incidents? How much of the substance is truly harmful?

Your answers to all these questions will shape the story you tell yourself. You might conclude: "The lab is a responsible organization and will protect me". Or perhaps you'll think: "The lab is a thorn in the side of the community and is probably doing weapons-related work. The leak's a sign of something far worse."

Perhaps your story will be: "Those environmentalists are just trying to scare us and the data indicate the leak is harmless". Or maybe it'll be: "I knew it! The lab's sold out, the data are terrifying, and the activists are revealing the real truth". Such stories determine the meaning of the picocuries and millirems for humans, not the other way around.

Acquiring data

Humans gain a sense of what's happening in several ways. Three of them, to use philosophical language, are deferential, civic and melodramatic epistemology.

In "deferential epistemology", citizens habitually take the word of experts and institutions about things like the dangers of *x* picocuries and exposures of *y* millirems. In his 1624 book *New Atlantis*, the philosopher Francis Bacon famously crafted a fictional portrait of an island society where deferential epistemology rules and people instinctively trust the scientific infrastructure.

We may think this is how people ought to behave. But Bacon, who was also a politician, understood that deference to experts is not automatic and requires constantly curating the public face of the scientific infrastructure. Earthlings haven't seen deferential epistemology in a while.

"Civic epistemology", meanwhile, is how people acquire knowledge in the absence of that curation. Such people don't necessarily reject experts but hear their voices alongside many others claiming to know best how to pursue our interests and values. Civic epistemology is when we negotiate daily life not by first consulting scientists but by pursuing our concerns with a mix of habit, trust, experience and friendly advice.

We sometimes don't, in fact, take scientific advice when it collides with how we already behave; we may smoke or drink, for instance, despite warnings not to. Or we might seek guidance from non-scientists about things like the harms of radiation.

Finally, what I call "melodramatic epistemology" draws on the word "melodrama", a genre of theatre involving extreme plots, obvious villains, emotional appeal, sensational language and moral outrage (the 1939 film *Gone with the Wind* comes to mind).

Melodramas were once considered culturally insignificant, but scholars such as Peter Brooks from Yale University have shown that a melodramatic lens can be a powerful and irresistible way for humans to digest difficult and emotionally charged events. The clarity, certainty and passion provided by a melodramatic read on a situ-

A melodramatic lens can be a powerful and irresistible way for humans to digest difficult and emotionally charged events

ation tends to displace the complexities, uncertainties and dispassion of scientific evaluation and evidence.

One example from physics occurred at the Lawrence Berkeley Laboratory in the late 1990s when activists fought, successfully, for the closing of its National Tritium Labeling Facility (NTLF). As I have written before, the NTLF had successfully developed techniques for medical studies while releasing tritium emissions well below federal and state environmental standards.

Activists, however, used melodramatic epistemology to paint the NTLF's scientists as villains spreading breast cancer throughout the area, and denounced them as making "a terrorist attack on the citizens of Berkeley". One activist called the scientists "piano players in a nuclear whorehouse."

The best, and perhaps only, way to challenge melodramatic stories is to write bigger, more encompassing stories that reveal that a different plot is unfolding

The critical point

The aliens studying us would worry most about melodramatic epistemology. Melodramatic epistemology, though dangerous, is nearly impervious to being altered, for any contrary data, studies and expert judgment are considered to spring from the villain's allies and therefore to incite rather than allay fear.

Two US psychologists – William Brady from Northwestern University and Molly Crockett from Princeton University – recently published a study of how and why misinformation spreads (*Science* **386** 991). By analysing data from Facebook and Twitter and by conducting real experiments with participants, they found that sources of misinformation evoke more outrage than trustworthy sources. Worse still, the outrage encourages us to share the misinformation even if we haven't fully read the original source.

This makes it hard to counter misinformation. As the authors tactfully conclude: "Outrage-evoking misinformation may be difficult to mitigate with interventions that assume users want to share accurate information".

In my view, the best, and perhaps only, way to challenge melodramatic stories is to write bigger, more encompassing stories that reveal that a different plot is unfolding. Such a story about the NTLF, for instance, would comprise story lines about the benefits of medical techniques, the testing of byproducts, the origin of regulations of toxins, the perils of our natural environment, the nature of fear and its manipulation, and so forth. In such a big story, those who promote melodramatic epistemology show up as an obvious, and dangerous, subplot.

If the aliens see us telling such bigger stories, they might not give up earthlings for lost.

Robert P Crease is a professor in the Department of Philosophy, Stony Brook University, US; e-mail robert.crease@stonybrook.edu; www.robertpcrease.com; his latest book is *The Leak* (2022 MIT Press)

Transactions Start up to start out

iStock/claffra

Career benefit Working for a small start-up firm that built a product to improve the safety of helicopters was a formative experience for Honor Powrie.

Working for a large corporation can be stable and secure. But **Honor Powrie** explains why you can learn so much more in a start-up business

A few months ago, I attended a presentation and reception at the Houses of Parliament in London for companies that had won Business Awards from the Institute of Physics in 2024. What excited me most at the event was hearing about the smaller start-up companies and their innovations. They are developing everything from metamaterials for sound proofing to instruments that can non-invasively measure pressure in the human brain.

The event also reminded me of my own experience working in the small-business sector. After completing my PhD in high-speed aerodynamics at the University of Southampton, I spent a short spell working for what was then the Defence and Evaluation Research Agency (DERA) in Farnborough. But wanting to stay in Southampton, I decided working permanently at DERA wasn't right for me so started looking for a suitable role closer to home.

I soon found myself working as a development engineer at a small engineering company called Stewart Hughes Limited. It was founded in 1980 by Ron Stewart and Tony Hughes, who had been researchers at the Institute of Sound and Vibration Research (ISVR) at Southampton University. Through numerous research contracts, the pair had spent almost a decade developing techniques for monitoring the condition of mechanical machinery from their vibrations.

By attaching accelerometers or vibration sensors to the machines, they discovered that the resulting signals can be processed to determine the physical condition of the devices. Their particular innovation was to find a way to both capture and process the accelerometer signals in near real time to produce indicators relating to the health of the equipment being monitored. It required a combination of hardware and software that was cutting edge at the time.

Exciting times

Although I did not join the firm until early 1994, it still had all the feel of a start-up. We were located in a single office building (in reality it was a repurposed warehouse) with 50 or so staff, about 40 of whom were electronics, software and mechanical engineers. There was a strong emphasis on "systems engineering" – in other words, integrating different disciplines to design and build an overarching solution to a problem.

In its early years, Stewart Hughes had developed a variety of applications for their vibration health monitoring technique. It was used in all sorts of areas, ranging from conveyor belts carrying coal and Royal Navy ships travelling at sea to supersized trucks working on mines. But when I joined, the company was focused on helicopter drivetrains.

In particular, the company had developed a product called Health and Usage Monitoring System (HUMS). The UK's Civil Aviation Authority required this kind of device to be fitted on all helicopters transporting passengers to and from oil platforms in the North Sea to improve operational safety. Our equipment (and that of rival suppliers – we did not have a monopoly) was used to monitor mechanical parts such as gears, bearings, shafts and rotors.

For someone straight out of university, it was an exciting time. There were lots of technical challenges to be solved, including designing effective ways to process signals in noisy environments and extracting information about critical drivetrain components. We then had to convert the data into indicators that could be monitored to detect and diagnose mechanical issues.

As a physicist, I found myself working closely with the engineers but tended to approach things from a more fundamental angle, helping to explain why certain approaches worked and others didn't. Don't forget that the technology developed by Stewart Hughes wasn't used in the comfort of a physics lab but on a real-life working helicopter. That meant capturing and processing data on the airborne helicopter itself using bespoke electronics to manage high onboard data rates.

iStock/AndreyPopov

Flexible benefits A job in a small hi-tech company can give physicists the chance to learn how to adapt and respond to changes – but cash-flow problems can be an ongoing struggle.

After the data were downloaded, they had to be sent on floppy disks or other portable storage devices to ground stations. There the results would be presented in a form to allow customers and our own staff to interpret and diagnose any mechanical problems. We also had to develop ways to monitor an entire fleet of helicopters, continuously learning and developing from experience.

Stewart Hughes's innovative and successful HUMS technology, which was the first of its kind to be flown on a North Sea helicopter, saw the company win Queen's Awards on two separate occasions. The first was in 1993 for "export achievement" and the second was in 1998 for "technological achievement". By the end of 1998 the company was bought by Smiths Industries, which in turn was acquired by General Electric in 2007.

Stormy days

If it all sounds as if working in a small business is plain sailing, well it rarely is. A few years before I joined, Stewart Hughes had ridden out at least one major storm when it was forced to significantly reduce the workforce because anticipated contracts did not materialize. "Black Friday", as it became known, made the board of directors nervous about taking on additional employees, often relying on existing staff to work overtime instead.

This arrangement actually suited many of the early-career employees, who were keen to quickly expand their work experience and their pay packet. But when I arrived, we were once again up against cash-flow challenges, which is the bane of any small business. Back then there were no digital electronic documents and web portals, which led to some hairy situations.

I can recall several occasions when the company had to book a despatch rider for 2 p.m. on a Friday afternoon to dash a report up the motorway to the Ministry of Defence in London. If we hadn't got an approval signature and contractual payment before the close of business on the same day, the company literally wouldn't have been able to open its doors on Monday morning.

Being part of a small company was undoubtedly a formative part of my early career experience

At some stage, however, the company's bank lost patience with this hand-to-mouth existence and the board of directors was told to put the firm on a more solid financial footing. This edict led to the company structure becoming more formal and the directors being less accessible, with a seasoned professional brought in to help run the business. The resulting change in strategic trajectory eventually led to its sale.

Being part of a small company was undoubtedly a formative part of my early career experience. It was an exciting time and the fact all employees were – literally – under one roof meant that we knew and worked with the decision makers. We always had the opportunity to speak up and influence the future. We got to work on unexpected new projects because there was external funding available. We could be flexible when it came to trying out new software or hardware as part of our product development.

The flip side was that we sometimes had to flex too much, which at times made it hard to stick to a cohesive strategy. We struggled to find cash to try out blue sky or speculative approaches – although there were plenty of good ideas. These advantages come with being part of a larger corporation with bigger budgets and greater overall stability.

That said, I appreciate the diverse and dynamic learning curve I experienced at Stewart Hughes. The founders were innovators, whose vision and products have stood the test of time, still being widely used today. The company benefited many people not just the staff who led successful careers but also the pilots and passengers on helicopters whose lives may potentially have been saved.

Working in a large corporation is undoubtedly a smoother ride than in a small business. But it's rarely seat-of-the-pants stuff and I learned so much from my own days at Stewart Hughes. Attending the IOP's business awards reminded me of the buzz of being in a small firm. It might not be to everyone's taste, but if you get the chance to work in that environment, do give it serious thought.

Honor Powrie is an engineer who is now senior director for data science and analytics at GE in Southampton, UK. She is writing here in a personal capacity

Fostering a sense of community

The International Conference on Women in Physics offers the perfect opportunity for women to come together and share their experiences in physics, as **Chethana Setty** explains

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Support network Events such as the International Conference on Women in Physics offer women around the world a place to discuss their experiences in physics.

International conferences are a great way to meet people from all over the world to share the excitement of physics and discuss the latest developments in the subject. But the International Conference on Women in Physics (ICWIP) offers more by allowing us to listen to the experiences of people from many diverse backgrounds and cultures. At the same time, it highlights the many challenges that women in physics still face.

The ICWIP series is organized by the International Union of Pure and Applied Physics (IUPAP) and the week-long event typically features a mixture of plenaries, workshops and talks. Prior to the COVID-19 pandemic, the conferences were held in various locations across the world, but the last two have been held entirely online. The last such meeting – the 8th ICWIP run from India in 2023 – saw around 300 colleagues from 57 countries attend. I was part of a seven-strong UK contingent – at various stages of our careers – who gave a presentation describing the current situation for women in physics in the UK.

Being held solely online didn't stop delegates fostering a sense of community or discussing their predicaments and challenges. What became evident during the week was the extent and types of issues that women from across the globe still have to contend with. One is the persistence of implicit and explicit gender bias in their institutions or workplaces. This, along with negative stereotyping of women, produces discrepancies between male and female numbers in institutions, particularly at postgraduate level and beyond. Women often end up choosing not to pursue physics later into their careers and being reluctant to take up leadership roles.

Much more needs to be done to ensure women are encouraged in their careers. Indeed, women often face challenging work–life balances, with some expected to play a greater role in family commitments than men, and have little support at their workplaces. One postdoctoral researcher at the 2023 meeting, for example, attempted to discuss her research poster in the virtual conference room while looking after her young children at home – the literal balancing of work and life in action.

To improve their circumstances, delegates suggested enhancing legislation to combat gender bias and improve institutional culture through education to reduce negative stereotypes. More should also be done to improve networks and professional associations for women in physics. Another factor mentioned at the meeting, meanwhile, is the importance of early education and issues related to equity of teaching, whether delivered face-to-face or online. But women can face disadvantages other than their gender, such as socioeconomic status and identity, resulting in a unique set of challenges for them. This is the principle of intersectionality and was widely discussed in the context of problems in career progression.

In the UK, change is starting to happen. The Limit Less campaign by the Institute of Physics (IOP) encourages students post 16 years old to study physics. The annual Conference for Undergraduate Women and Non-binary Physicists provides individuals with support and encouragement in their personal and professional development. There are also other initiatives such as the STEM Returner programme and the Daphne Jackson Trust for those wishing to return to a physics career. WISE Ten Steps contributes to supporting workplace culture positively and the Athena SWAN and the IOP's new Physics Inclusion Award aims to improve women's prospects.

As we now look forward to the next ICWIP there is still a lot more to do. We must ensure that women can continue in their physics careers while recognizing that intersectionality will play an increasingly significant role in shaping future equity, diversity and inclusion policies. It is likely that soon a new team will be sought from academia and industry, comprising of individuals at various career stages to represent the UK at the next ICWIP. Please do get involved if you are interested. Participation is not limited to women.

Women are doing physics in a variety of challenging circumstances. Gaining an international outlook of different cultural perspectives, as is possible at an international conference like the ICWIP, helps to put things in context and highlights the many common issues faced by women in physics. Taking the time to listen and learn from each other is critical, a process that can facilitate collaboration on issues that affect us all. Fundamentally, we all share a passion for physics, and endeavour to be catalysts for positive change for future generations.

● This article was based on discussions with Sally Jordan from the Open University; Holly Campbell, UK Atomic Energy Authority; Josie C, AWE; Wendy Sadler and Nils Rehm, Cardiff University; and Sarah Bakewell and Miriam Dembo, IOP

Chethana Setty is studying for a BSc in physics at the Open University, UK, and was a member of the UK team that attended ICWIP 2023, e-mail chetsetty@yahoo.com

A physicist's guide to ice cream

Ice cream has a simple ingredient list – just cream and sugar, but as anyone who's tried to make it knows, this frozen dessert can easily become a sticky, icy mess. Food scientist **Douglas Goff** explains how lessons from materials science can teach us how to make the perfect scoop

Douglas Goff is an emeritus professor at the University of Guelph, Canada. He is an expert in the science of ice cream and frozen desserts. **Hamish Johnston** is an online editor of *Physics World*

What exactly is ice cream? For most of us, it's a tasty frozen dessert, but to food scientists like Douglas Goff, it's also a marvel of physics and chemistry. Ice cream is a complex multiphase material, containing emulsion, foam, crystals, solutes and solvent. Whether made in a domestic kitchen or on a commercial scale, ice cream requires a finely tuned ratio of ingredients and precision control during mixing, churning and freezing.

Goff is a researcher in food science at the University of Guelph in Canada and an expert in the science of ice cream. In addition to his research studying, among other things, structure and ingredient functionality in ice cream, Goff is also the instructor on the University of Guelph's annual ice-cream course, which, having been taught since 1914, is the longest-running at the university.

In a conversation with *Physics World's* Hamish Johnston, Goff explains the science of ice cream, why it's so hard to make vegan ice cream and how his team performs electron microscopy experiments without their samples melting.

How would you describe the material properties of ice cream to a physicist?

Ice cream is an incredibly complex multiphase system. It starts as an emulsion, where fat droplets are dispersed in a sugary water-based solution. Then we whip the emulsion to incorporate an air phase into it – this is called foaming (see "Phases in ice cream", p24). In a frozen tub of ice cream, about half of the volume is air. That air is present in the form of tiny bubbles that are distributed throughout the product.

Then we partially freeze the aqueous phase, turning at least half of the water into microscopically small ice crystals. The remaining unfrozen phase is what makes the ice cream soft, scoopable and chewable. It remains unfrozen because of all the sugar that's dissolved in it, which depresses the freezing point.

So you end up with fat droplets in the form of an emulsion, air bubbles in the form of a foam, a partially crystalline solvent in the form of ice crystals, and a concentrated sugar solution.

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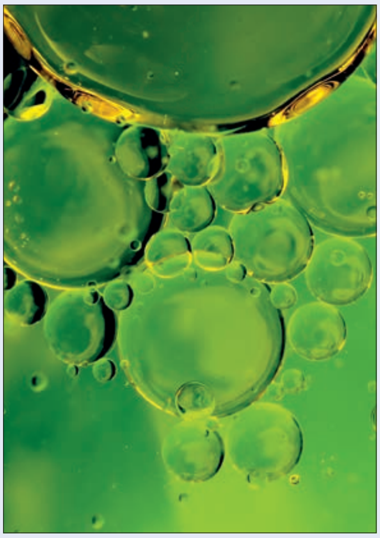
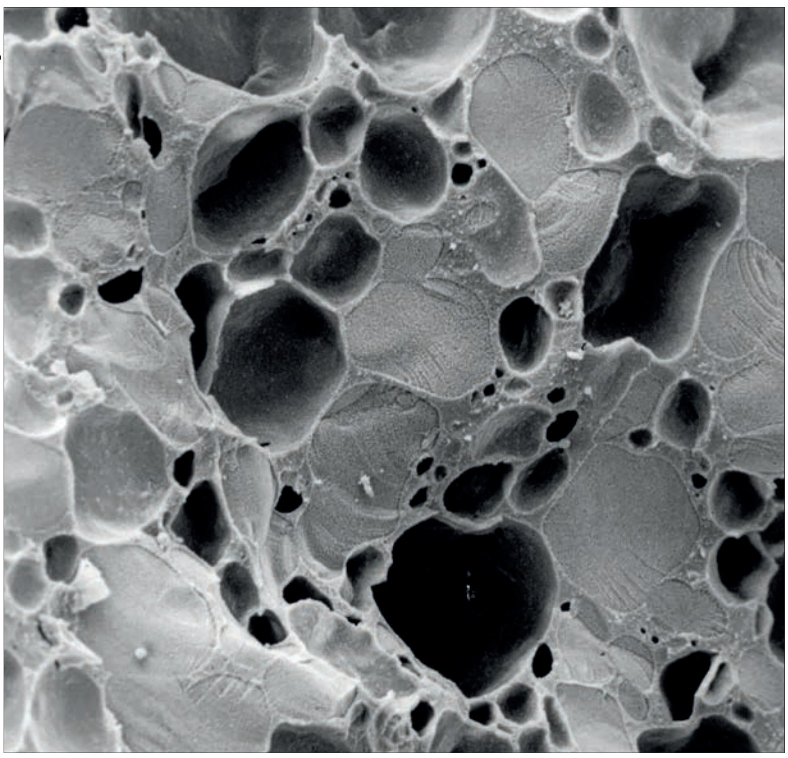
Phases in ice cream



Emulsion Some liquids, such as oil and water, will not mix if droplet of one is added to the other – they are said to be immiscible. If many droplets of one liquid can be stabilized in another without coalescing, the resulting mixture is called an emulsion (left image).

Foam A foam, like an emulsion, consists of two phases where one is dispersed in the other. In the case of foam, many tiny gas bubbles are trapped in a liquid or solid (right image).

Glass When a liquid is cooled below a certain temperature, it generally undergoes a first-order phase transition to a solid crystal. However, if a liquid can be cooled below its freezing point without crystallizing (supercooling) – for example, if it is cooled very quickly, it may form glass – an amorphous solid with a disordered, liquid-like structure but solid-like mechanical properties. The temperature at which the glass forms, marked by a rapid increase in the material's viscosity, is called the glass transition temperature.



Close up Ice cream imaged with an electron microscope. The image shows the air bubbles, ice crystals and fat droplets, each surrounded by a layer of sugary solvent.

What are the length scales of the different phases in the ice cream?

We've done a lot of electron microscopy research studying this in my lab. In fact, our research was some of the very first that utilized electron microscopy techniques for the structure of ice cream. The fat droplets are about one micron in diameter and the air bubbles, depending on the equipment that's used, would be about 20 to 30 microns in diameter. The ice crystals are in the 10 to 20 micron size range.

It really is a beautiful thing to look at under an electron microscope, depending on the technique that you use (see image, above).

What are the big differences between ice cream that's made in a commercial setting versus a domestic kitchen?

The freezing and whipping happen at the same time whether it's an ice cream maker in the kitchen or a commercial operation. The biggest difference between what you do in the kitchen and what they're going to do in the factory is the structure of the ice cream. Homemade ice cream is fine for maybe a day or two, but it starts to get icy pretty quickly, whereas we want a shelf life of months to a year when ice cream is made commercially.

This is because of the way the ice phase evolves over time – a process called recrystallization. If ice cream warms up it starts to melt. When the temperature is lowered again, water is frozen back into the ice phase, but it doesn't create new ice crystals, it just grows onto the existing ice crystals.

This means that if ice cream is subject to lots of temperature fluctuation during storage, it's going to degrade and become icy much quicker than if it was stored at a constant temperature. The warmer the temperature, the faster the rate of recrystallization. Commercial freezing equipment will give you much smaller ice crystal size than homemade ice cream machines. Low and constant temperature storage is what everybody strives for, and so the lower the temperature and the more constant it is, and the smaller the ice crystals are to begin with, the longer your shelf life before changes start occurring.

There's also another structural element that is important for the long-term storage of ice cream. When that unfrozen sugary solvent phase gets concentrated enough, it can undergo a glass transition (see "Phases in ice cream"). Glass is an amorphous solid, so if this happens, there will be no movement of water or solute within the system and it can remain unchanged for years. For ice cream, the glass transition temperature is around –28 to –32° C so if you want long-term storage, you have to get down below that glass transition temperature.

The third thing is the addition of stabilisers. Those are things like locust bean gum, guar gum or cellulose gum and there are some novel ones as well. What those

Elizabeth Calvert Siddon (NOAA/UAF)

Cool customers Specialized proteins that prevent the formation of large ice crystals enable some animals, such as the Arctic cod pictured above, to live in subzero conditions.

do is increase the viscosity in the unfrozen phase. This slows down the rate of ice recrystallization because it slows down the diffusion of water and the growth of ice.

There are also some other novel agents that can prevent ice from recrystallizing into large crystals. One of these is called propylene glycol monostearate, it absorbs onto the surface of an ice crystal and prevents it from growing as the temperature fluctuates. This is also something we see in nature. Some insect, fish and plant species that live in cold environments have proteins that control the growth of ice in their blood and tissues. A lot of fish, for example, swim around with minute ice crystals in their in their body, but the proteins prevent the crystals from getting big enough to cause harm.

How does adding flavourings to ice cream change the manufacturing process?

When you think about ice cream around the world, there are hundreds of different flavours. The important question is whether the flavouring will impact the solution or emulsion.

For example, a chocolate chip will be inert, it's not going to interact at all with the rest of the matrix. Strawberries on the other hand, really impact the system because of the high sugar content in the fruit preparation. We need to add sugar to the fruit to make sure it is softer than the ice cream itself – you don't want to bite into ice cream and find a hard, frozen berry. The problem is that some of that sugar will diffuse into the unfrozen phase and lower its freezing point. This means that if you don't do anything to the formulation, strawberry ice cream will be softer than something like vanilla because of the added sugar.

Another example would be alcohol-based flavours, anything from rum to Baileys Irish Cream or Frangelico, or even wine and beer. They're very popular but the alcohol depresses the freezing point, so if you add enough to give you the flavour intensity that you want, your product won't freeze. In that case, you might need to add less of the alcohol and a little bit more of a de-alcoholized flavouring.

You can try to make ice cream with just about any flavour, but you certainly have to look at what that flavouring is going to do to the structure and things like shelf life and so on.

Shutterstock/Radoxist studio

Spoilt for choice From Jalapeno peppers to blue cheese, ice cream comes in almost every flavour imaginable. However, additional ingredients can change the stability and freezing point, so creating new flavours requires careful consideration of physics and chemistry.

Nowadays one can also buy vegan ice creams. How do the preparation and ingredients differ compared to dairy products?

A lot of it will be similar. We're going to have an emulsified fat source, typically something like coconut oil or palm kernel oil, and then there's the sugar, stabilisers and so on that you would have in a dairy ice cream.

The difference is the protein. Milk protein is both a very good foaming agent and a very good emulsifying agent. [Emulsifying and foaming agents are molecules that stabilize foams and emulsions. The molecules attach to the surface of the liquid droplets or air bubbles and stop them from coalescing with each other.] Plant proteins aren't very good at either. If you look at cashew, almond or soy-based products, you'll find additional ingredients to deliver the functionality that we would otherwise get from the milk protein.

What techniques do you use to study ice cream? And how do you stop the ice cream from melting during an experiment?

The workhorses of instrumentation for research are particle size analysis, electron microscopy and rheology (see "Experimental techniques", overleaf).

So first there's laser light scattering which tells us everything we need to know about the fat globules and

Experimental techniques


Douglas Goff

Rheology Rheology is the study of the flow and deformation of materials. A rheometer is an apparatus used to measure the response of different materials to applied forces.

Dynamic light scattering (DLS) A laser-based technique used to measure the size distribution of dispersed particles. Dispersed particles such as fat globules in ice cream exhibit Brownian motion, with small particles moving faster than larger particles. The interference of laser light scattered from the particles is used to calculate the characteristic timescale of the Brownian motion and the particle size distribution.

Electron microscopy Imaging techniques that use a beam of electrons, rather than photons, to image a sample. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) are two common examples. SEM uses reflected electrons to study the sample surface, whereas TEM uses electrons travelling through a sample to understand its internal structure.

Critical point drying When a sample is dried in preparation for microscopy experiments, the effects of surface tension between the water in the sample and the surrounding air can cause damage. At the critical point, the liquid and gas phases are indistinguishable, if the water in the sample is at its critical point during dehydration, there is no boundary between the water and vapour, and this protects the structure of the sample.

fat structure (see "Experimental techniques"). Then we use a lot of optical microscopy. You either need to put the microscope in a freezer or cold box or have a cold stage where you have the ice cream on a slide inside a chamber that's cooled with liquid nitrogen. On the electron microscopy side (see "Experimental techniques"), we've done a lot of cryo-scanning electron microscopy (SEM), with a low-temperature unit.

We've also done a lot of transmission electron microscopy (TEM), which generally uses a different approach. Instead of performing the experiment in cold conditions, we use a chemical that "fixes" the structure in place and then we dry it, typically using a technique called "critical point drying" (see "Experimental techniques"). It's then sliced into thin samples and studied with the TEM.

After decades of studying ice cream, do you still get excited about it?

Oh, absolutely. I've been fortunate enough to have travelled to many, many interesting countries and I always see what the ice cream market looks like when I'm there. It's not just a professional thing. I also like to know what's going on around the world so I can share that with people. But of course, how can you go wrong with ice cream? It's such a fun product to be associated with.

● Listen to the full interview with Douglas Goff on the *Physics World Weekly* podcast.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Quantum physics comes down to earth

INTERNATIONAL YEAR OF Quantum Science and Technology

Quantum-based gravity sensors promise a sensitive and robust way to locate buried objects, and they've recently taken their first steps out of the laboratory, as **Katherine Skipper** explains

Katherine Skipper is a features editor at *Physics World*

"I could have sworn I put it somewhere safe," is something we've all said when looking for our keys, but the frustration of searching for lost objects is also a common, and very costly, headache for civil engineers. The few metres of earth under our feet are a tangle of pipes and cables that provide water, electricity, broadband and waste disposal. However, once this infrastructure is buried, it's often difficult to locate it again.

"We damage pipes and cables in the ground roughly 60 000 times a year, which costs the country about 2.4 billion pounds," explains Nicole Metje, a civil engineer at the University of Birmingham in the UK. "The ground is such a high risk, but also such a significant opportunity."

The standard procedure for imaging the subsurface is to use electromagnetic waves. This is done either with ground penetrating radar (GPR), where the signal reflects off interfaces between objects in the ground, or with locators that use electromagnetic induction to find objects. Though they are stalwarts of the civil engineering toolbox, the performance of both these techniques is limited by many factors, including the soil type and moisture.

Metje and her team in Birmingham have participated in several research projects improving subsurface mapping. But her career took an unexpected turn in 2009 when one of her colleagues was contacted out of the blue by Kai Bongs – a researcher in the Birmingham school of physics. Bongs, who became the director of the Institute for Quantum Technologies at the German Aerospace Centre (DLR) in 2023, explained that his group was building quantum devices to sense tiny changes in gravity and thought this might be just what the civil engineers needed.

However, there was a problem. The device required a high-stability, low-noise environment – rarely compatible with the location of engineering surveys. But as Bongs spoke to more engineers he became more interested. "I understood why tunnels and sewers are very interesting," he says, and saw an opportunity to "do something really meaningful and impactful".

What lies beneath

Although most physicists are happy to treat g, the acceleration due to gravity, as 9.81 m/s^2, it actually varies across the surface of Earth. Changes in g indicate the presence of buried objects and varying soil composition and can even signal the movement of tectonic plates and oceans. The engineers in Birmingham were well aware of this; classical devices that measure changes in gravity using the extension of springs are already used in engineering surveys, though they aren't as widely adopted as electromagnetic signals. These machines – called gravimeters – don't require holes to be dug and the measurement isn't limited by soil conditions, but changes in the properties of the spring over time cause drift, requiring frequent recalibration.

More sensitive devices have been developed that use a levitating superconducting sphere. These devices have been used for long-term monitoring of geophysical phenomena such as tides, volcanos and seismic activity, but they are less appropriate for engineering surveys where speed and portability are of the essence.

The perfect test mass would be a single atom – it has no moving mechanical parts, can be swapped out for any of the same isotope, and its mass will never change. "Today or tomorrow or in 100 years' time, it'll be exactly the same," says physicist Michael Holynski, the principal investigator of the UK Quantum Technology Hub for Sensors and Timing led by the University of Birmingham.

Falling atoms

The gravity sensing project in Birmingham uses a technique called cold-atom interferometry, first demonstrated in 1991 by Steven Chu and Mark Kasevich at Stanford University in the US (*Phys. Rev. Lett.* **67** 181). In the cold-atom interferometer, two atomic test masses fall from different heights, and g is calculated by comparing their displacement in a given time.

Because it's a quantum object, a single atom can act as both test masses at once. To do this, the interferometer uses three laser pulses that sends the atom on two trajectories. First, a laser pulse puts the atom in a superposition of two states, where one state gets a momentum "kick" and recoils away from the other. This means that when the atom is allowed to freefall, the state nearest the centre of the Earth accelerates faster. Halfway through the freefall, a second laser pulse then switches the state with the momentum kick. The two states start to catch up with each other, both still falling under gravity.

Finally, another laser pulse, identical to the first, is applied. If the acceleration due to gravity were constant everywhere in space, the two states would fall exactly the same distance and overlap at the end of the sequence. In this case, the final pulse would effectively reverse the first, and the atom would end up back in the ground state. However, because in the real world the atom's acceleration changes as it falls through the gravity gradient, the

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Physics at work Damage to underground infrastructure costs millions of pounds a year in the UK alone. That's why there is a need to develop new methods to image the subsurface that don't require holes to be dug or rely on electromagnetic pulses whose penetration depth is highly variable.

two states don't quite find each other at the end. Since the atom is wavelike, this spatial separation is equivalent to a phase difference. Now, the outcome of the final laser pulse is less certain; sometimes it will return the atom to the ground state, but sometimes it will collapse the wavefunction to the excited state instead.

If a cloud of millions of atoms is dropped at once, the proportion that finishes in each state (which is measured by making the atoms fluoresce) can be used to calculate the phase difference, which is proportional to the atom's average gravitational acceleration.

To measure these phase shifts, the thermal noise of the atoms must be minimized. This can be achieved using a magneto-optical trap and laser cooling, a technique pioneered by Chu, in which spatially varying magnetic fields and lasers trap atoms and cool them close to absolute zero. Chu, along with William H Phillips and Claude Cohen-Tannoudji, was awarded the 1997 Nobel Prize in Physics for his work on laser cooling.

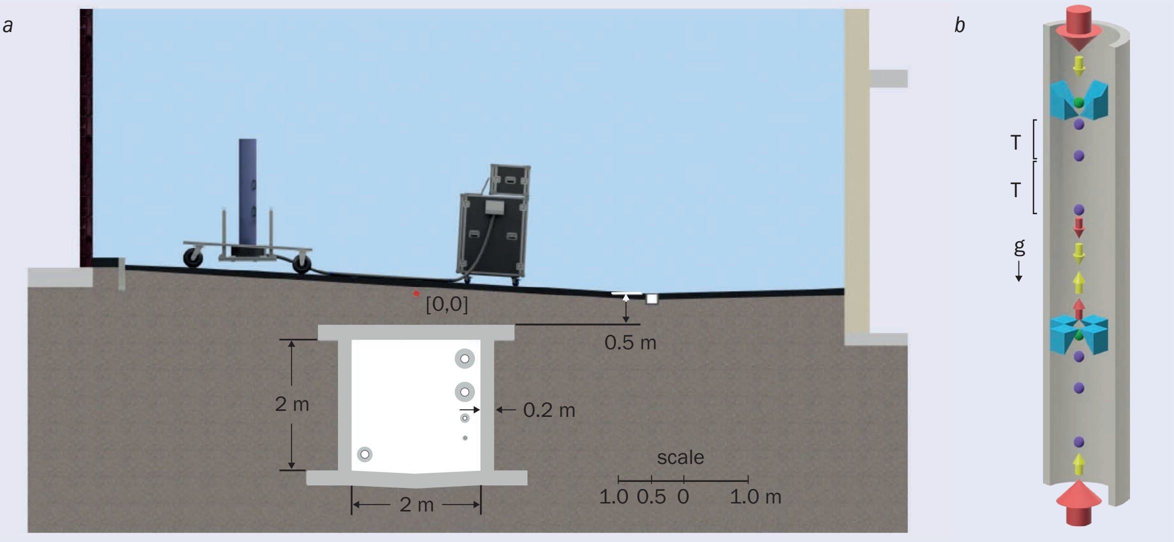
Bad vibrations

Unlike the spring or the superconducting gravimeter, the cold-atom device produces an absolute rather than a relative measurement of g. In their first demonstration, Chu and Kasevich measured the acceleration due to gravity to three parts in 100 million. This was about a million times better than previous attempts with single atoms, but it trailed behind the best absolute measurements, which were made using a macroscopic object in free fall.

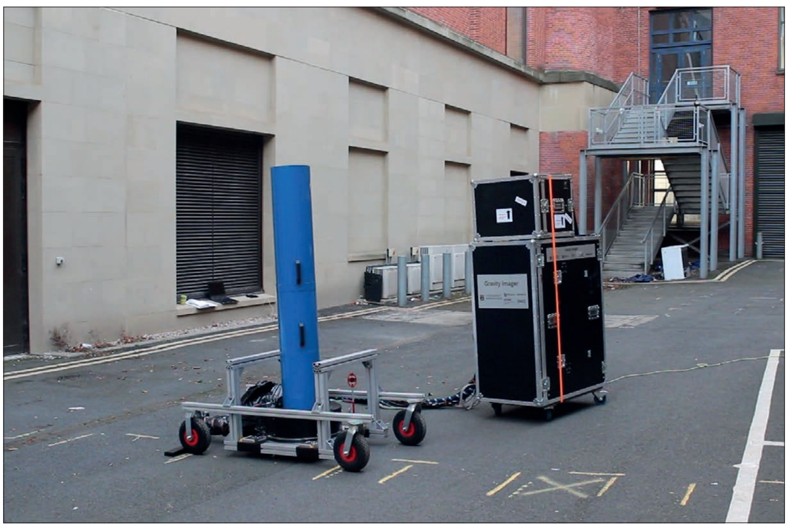
"It's always one thing to do the first demonstration of principle, and then it's a different thing to really get it to a performance level where it actually is useful and competitive," says Achim Peters, who started a PhD with Chu in 1992 and is now a researcher at the Humboldt University of Berlin.

Whether spring or quantum-based, gravimeters share the same major source of noise – vibrations. Although we don't feel it, the ground, which is the test mass's reference frame, is never completely still. According to the Einstein

1 Testing times



(*a*) A schematic of the 2021 test of the gravity gradiometer, with the hollow utility tunnel pictured to scale. (*b*) The hourglass configuration of the quantum gravity gradiometer. The atom clouds (green dots) are laser-cooled (red arrows) in magneto-optical traps formed using mirrors (blue). To measure the gravity gradient the atoms are subject to interferometry laser pulses (yellow arrows) under freefall (purple dots).



Out and about The quantum-based gravity sensor, pictured outside on the University of Birmingham campus. The blue tube houses the two interferometers and the black box houses the lasers and control electronics.

equivalence principle, we can't differentiate the acceleration due to these vibrations from the acceleration of the test mass due to gravity.

When Peters was at Stanford he built a sophisticated vibration isolation system where the extension of mechanical springs was controlled by electronic feedback. This brought the quantum device in line with other state-of-the-art measurement techniques, but such a complex apparatus would be difficult to operate outside a laboratory.

However, if a cold-atom gravity sensor could operate outside without being hampered by vibrations it would have an instant advantage over spring devices, where vibrations have to be averaged out by taking longer measurements. "If we want to measure several hectares, you're talking about three weeks or plus [with spring gravimeters]," explains Metje. "That takes a lot of time and therefore also a lot of cost."

Enter the gravity gradiometer

A few years after Chu and Kasevich published the first cold-atom interferometer result, the US Navy declassified a technology that had been developed by Bell Aerospace (later acquired by Lockheed Martin) for submarines and which transformed the field of geophysics. This device – called a gravity gradiometer – calculated the gravity gradient by measuring the acceleration of several spinning discs. As well as finding objects, gravity can identify a geographical location, meaning that gravity sensors have applications in GPS-free navigation. Compared to gravimeters, a gradiometer is more sensitive to nearby objects and when the gravity gradiometer was declassified it was seized upon for use in oil and gas exploration. The Lockheed Martin device remains the industry standard – it measures gravity gradient in three dimensions and its sophisticated vibration-isolation system means it can be used in the field, including in airborne surveys – but it is prohibitively costly for most researchers.

In 1998 Kasevich's group demonstrated a gradiometer built from two cold-atom interferometers stacked one above the other, where the difference between the phases on the atom clouds was used to calculate the gravity gradient (*Phys. Rev. Lett.* **81** 971). In this configuration, the interferometry pulses illuminating the two clouds come from the same laser beams, which means that the vibrations that had previously required a complex damping system are cancelled out. In the laboratory, cold-atom gravity gradiometers have many applications in fundamental physics – they have been used to test the Einstein equivalence principle to one part in a trillion, and a 100 m tall interferometer is currently under construction at Fermilab, where it will be used to hunt for gravitational waves.

It was around this time, in 2000, when Bongs first encountered cold-atom interferometry, as a postdoc with Kasevich, then at Yale. He explains that the goal was to "get one of the lab-based systems, which were essentially the standard at the time, out into the field". Even without the problem of vibrational noise, this was a significant challenge. Temperature fluctuations, external magnetic fields and laser stability will all limit the performance of the gradiometer. The portability of the system must also be balanced against the fact that a taller device will allow longer freefall and more sensitive measurements. What's more, the interferometers will rarely be perfectly directed towards the centre of the Earth, which means the atoms fall slightly sideways relative to the laser beams.

In the summer of 2008, by which time Bongs was in Birmingham, Kasevich's group, now back at Stanford, mounted a cold-atom gradiometer in a truck and measured the gravity gradient as they drove in and out of a loading bay on the Stanford campus. They measured a peak that coincided with the building's outer wall, but this demonstration took place with a levelling platform and temperature control inside the truck. The demonstration of the first truly free-standing, outdoor cold-atom gradiometer was still up for grabs.

Ears to the ground

The portable cold-atom gravity sensor project in Birmingham began in earnest in 2011, as a collaboration between the engineers and the physicists. The team knew that building a device that was robust enough to operate outside would be only half the challenge. They also needed to make something cost-effective and easy to operate. "If you can manage to make the laser system small and compact and cheap and robust, then you more or less own quantum technologies," says Bongs.

When lasers propagate in free space, small knocks and bumps easily misalign the optical components. To make their device portable, the researchers made an early decision to instead use optical fibres, which direct light to the right place even if the device is jolted during transportation or operation.

However, they quickly realized that this was easier said than done. In a standard magneto-optical trap, atoms are cooled by three orthogonal pairs of laser beams that cool and trap them in three dimensions. In the team's original configuration, this light came from three fibres that were split from a single laser. Bending and temperature fluctuations exert stresses on the optical fibre that alter the polarization of the light as it propagates. Unstable polarizations in the beams meant that the atom clouds were moving around in the optical traps. "It wasn't very robust," says Holynski, "we needed a different approach".

To solve this problem, they adopted a new solution in which light enters the chamber from the top and bottom, where it bounces off a configuration of mirrors to create the two atom traps. Because the beams can't be individually adjusted, this sacrifices some efficiency, but if it fixed the laser polarization problem, the team decided it was worth a try.

In the world of quantum technologies, 1550 is something of a magic number. This is the most common wavelength of telecoms lasers because light of this wavelength propagates furthest in optical fibres. The telecoms industry has therefore invested significant time and money into developing robust lasers operating close to 1550 nm.

Courtesy: University of Birmingham © Crown Copyright

Below the surface The University of Birmingham's quantum-based gravity sensor during an underground test at Poole's cavern, a cave in the Peak District in the UK.

By lucky chance, 1550 nm is also almost twice the main resonant frequency of rubidium-87 (780 nm), an alkali metal that is well-suited to atom interferometry. Conveniently close to rubidium-87's resonant frequency are hyperfine transitions that can be used to cool the atoms, measure their final state and put them into a superposition for interferometry. Frequency doubling using non-linear crystals is a well-established optical technique, so combining a rubidium interferometer with a telecoms laser was an ideal solution.

By 2018, as part of the hub and under contract with the UK Ministry of Defence, the team had assembled a freestanding gradiometer – a 2 m tall tube containing the two interferometers, attached to a box of electronics and the lasers, both mounted on wheels. The researchers performed outdoor trials in 2018 and 2019, including a trip to an underground cave in the Peak District, but they still weren't getting the performance they wanted. "People get their hopes up," says Holynski. "This was quite a big journey."

The researchers worked out that another gamble they had made, this time to reduce the cost of the magnetic shield, wasn't performing as well as hoped. External magnetic fields shift the atom's energy levels, but unlike the phase shift due to gravity, this source of error is the same whether the momentum kick is directed up or down. By taking two successive measurements with a downwards and upwards kick, they thought they could remove magnetic noise, enabling them to reduce the cost of the expensive alloy they were using to shield the interferometers.

This worked as expected, but because they were operating outside a controlled laboratory environment, the large variation of the magnetic fields in space and time introduced other errors. It was back to the lab, where the team disassembled the sensor and rebuilt it again with full magnetic shielding.

By 2020 the researchers were ready to take the new device outside. However, the COVID-19 pandemic ground work to a halt and they had to wait until the following year.

Quantum tunnelling

"One of the things that changes about you when you work on gravity gradiometers is you start looking around for


Courtesy: University of Birmingham © Crown Copyright

Making waves Part of the UK Quantum Technology Hub for Sensors and Timing team pictured with the gravity gradiometer on a ship in the North Sea.

potential targets everywhere you go," says Holynski. In March 2021 a team of physicists and engineers that included Bongs, Metje and Holynski took the newly rebuilt gradiometer for its first outside trial, where they trundled it repeatedly over a road on the University of Birmingham campus. They knew that running under the road was a two-by-two-metre hollow tunnel, built to carry utility lines. They also knew approximately where it was, but wanted to see if the gradiometer could find it.

The first time they did this, they noticed a dip in the gravity gradient that seemed to have the right dimensions for the tunnel, and when they repeated the measurements, they saw it again. Because of their previous unsuccessful attempts, Holynski remained trepidatious. "People get quite excited. And then you have to say to them, 'Sorry, I don't think that's quite conclusive enough yet'."

Elsewhere on campus, another team was busy analysing the data. The results, when they were done, were consistent with a hollow object, about two-by-two metres across, and about a metre below the surface. Millions of people will have walked over that road without thinking once about what's beneath it, but to the researchers, this was the culmination of a decade of work, and proof that cold-atom gradiometers can operate outside the lab (*Nature* **602** 590).

The valley of death

"It's one more step in the direction of making quantum sensors available for real-world everyday use," says Holger Müller, a physicist at the University of California, Berkeley. In 2019 Müller's group published the results of a gravity survey it had taken with a cold-atom interferometer during a drive through the California hills (*Sci. Adv.* **5** 10.1126/sciadv.aax0800). He is also involved in a NASA project that aims to perform atom interferometry on the International Space Station (*Nature Communications* **15** 6414). Müller thinks that for researchers especially, cold-atom gradiometers could make gravity gradient surveys more accessible than with the Lockheed Martin device.

By now, the Birmingham gravity gradiometer is well travelled. As well as land-based trials, it has been on two ship voyages, one lasting several weeks, to test its performance in different environments and its potential for use in navigation. The project has also become a flagship of the UK's national quantum technologies programme, garnering industry partners including Network Rail and RSK and spinning out into start-up DeltaG (of which Holynski is a co-founder). Another project in France led by the company iXblue has also built a prototype gravity gradiometer that has been demonstrated inside (*Phys. Rev. A* **105** 022801).

However, if cold-atom gravity gradiometers are to become an alternative to electromagnetic surveys or spring gravimeters, they must escape the "Valley of Death" – the critical phase in a technology journey when it has been demonstrated but not yet been commercialized.

This won't be easy. The team has estimated that the gravity gradiometer currently performs about 1.5 times better than the industry-leading spring gravimeter. Spring gravimeters are small, easy to operate and significantly cheaper than the quantum alternative. The cost of the lasers in the quantum gradiometer alone are several hundreds of thousands of pounds, compared to about £100 000 for a spring-based instrument.

The quantum device is also large, requires a team of scientists to operate and maintain it, and consumes much more power than a spring gravimeter. As well as saving time compared to spring gravimeters, a potential advantage of the quantum gravity gradiometer is that because it has no machined moving parts it could be used for passive, long-term environmental monitoring. However, unless the power consumption is reduced it will be tricky to operate it in remote conditions.

In the years since the first test, the team has built another prototype that is about half the size, consumes significantly less power, and delivers the cooling, detection and interferometry using a single laser, which will significantly reduce the total cost. Holynski explains that this system is a "work in progress" that is currently being tested in the laboratory.

A large focus of the group's efforts has been bringing down the cost of the lasers. "We've taken available components from the telecom community and found ways to make them work in our system," says Holynski. "Now we're starting to work with the telecom community, the academic and industry community, to think 'how can we twist their technology and make it cheaper to fit what we need?' "

When Chu and Kasevich demonstrated it for the first time, the idea of atom interferometry was already three decades old, having been proposed by David Bohm and later Eugene Wigner (*Am. J. Phys*. **31** 6). Rather than lasers, this theoretical device was based on the Stern–Gerlach effect, in which an atom is in a superposition of spin states, deflected in opposite directions in a magnetic field. Atoms have a much smaller characteristic wavelength than photons, so a practical interferometer requires exquisite control over the atomic wavefronts. In the decades after it was proposed, several theorists, including Julian Schwinger, investigated the idea but found that a useful interferometer would require an extraordinarily controlled low-noise environment that then seemed inaccessible (*Found. Phys*. **18** 1045).

Decades in the making, the mobile cold-atom interferometer is a triumph of practical problem-solving and even if the commercial applications have yet to be realized, one thing is clear: when it comes to pushing the boundaries of quantum physics, sometimes it pays to think like an engineer. ■

Paving the way for the SKA

When it starts taking scientific data in 2028, the Square Kilometre Array Observatory promises to be the world's largest and most sensitive radio telescope. But as **Sarah Wild** discovers, its development has been shaped by a suite of smaller experiments that are already resetting the agenda – and flagging problems that the giant telescope could face

Sarah Wild is a freelance writer based in the UK

From its sites in South Africa and Australia, the Square Kilometre Array (SKA) Observatory last year achieved "first light" – producing its first-ever images. When its planned 197 dishes and 131 072 antennas are fully operational, the SKA will be the largest and most sensitive radio telescope in the world.

Under the umbrella of a single observatory, the telescopes at the two sites will work together to survey the cosmos. The Australian side, known as SKA-Low, will focus on low-frequencies, while South Africa's SKA-Mid will observe middle-range frequencies. The £1bn telescopes, which are projected to begin making science observations in 2028, were built to shed light on some of the most intractable problems in astronomy, such as how galaxies form, the nature of dark matter, and whether life exists on other planets.

Three decades in the making, the SKA will stand on the shoulders of many smaller experiments and telescopes – a suite of so-called "precursors" and "pathfinders" that have trialled new technologies and shaped the instrument's trajectory. The 15 pathfinder experiments dotted around the planet are exploring different aspects of SKA science. Meanwhile on the SKA sites in Australia and South Africa, there are four precursor telescopes – MeerKAT and HERA in South Africa and Australian SKA Pathfinder (ASKAP) and the Murchison Widefield Array (MWA) in Australia. These precursors are weathering the arid local conditions and are already broadening scientists' understanding of the universe.

"The SKA was the big, ambitious end game that was going to take decades," says Steven Tingay, director of the MWA based in Bentley, Australia. "Underneath that umbrella, a huge number of already fantastic things have been done with the precursors, and they've all been investments that have been motivated by the path to the SKA."

Even as technology and science testbeds, "they have far surpassed what anyone reasonably expected of them", adds Emma Chapman, a radio astronomer at the University of Nottingham, UK.

MeerKAT: glimpsing the heart of the Milky Way

In 2018, radio astronomers in South Africa were scrambling to pull together an image for the inauguration of the 64-dish MeerKAT radio telescope. MeerKAT will eventually form the heart of SKA-Mid, picking up frequencies between 350 megahertz and 15.4 gigahertz, and the researchers wanted to show what it was capable of.

Like all the SKA precursors, MeerKAT is an interferometer, with many dishes acting like a single giant instrument. MeerKAT's dishes stand about three storeys high, with a diameter of 13.5 m, and the largest distance between dishes being about 8 km. This is part of what gives the interferometer its sensitivity: large baselines between dishes increase the telescope's angular resolution and thus its sensitivity.

Additional dishes will be integrated into the interferometer to form SKA-Mid. The new dishes will be larger (with diameters of 15 m) and further apart (with baselines of up to 150 km), making it much more sensitive than MeerKAT on its own. Nevertheless, using just the provisional data from MeerKAT, the researchers were able to mark the unveiling of the telescope with the clearest radio image yet of our galactic centre.

Four years later, an international team used the MeerKAT data to produce an even more detailed image of the centre of the Milky Way (*ApJL* **949** L31). The image

(overleaf) shows long radio-emitting filaments up to 150 light–years long unspooling from the heart of the galaxy. These structures, whose origin remains unknown, were first observed in 1984, but the new image revealed 10 times more than had ever been seen before.

"We have studied individual filaments for a long time with a myopic view," Farhad Yusef-Zadeh, an astronomer at Northwestern University in the US and an author on the image paper, said at the time. "Now, we finally see the big picture – a panoramic view filled with an abundance of filaments. This is a watershed in furthering our understanding of these structures."

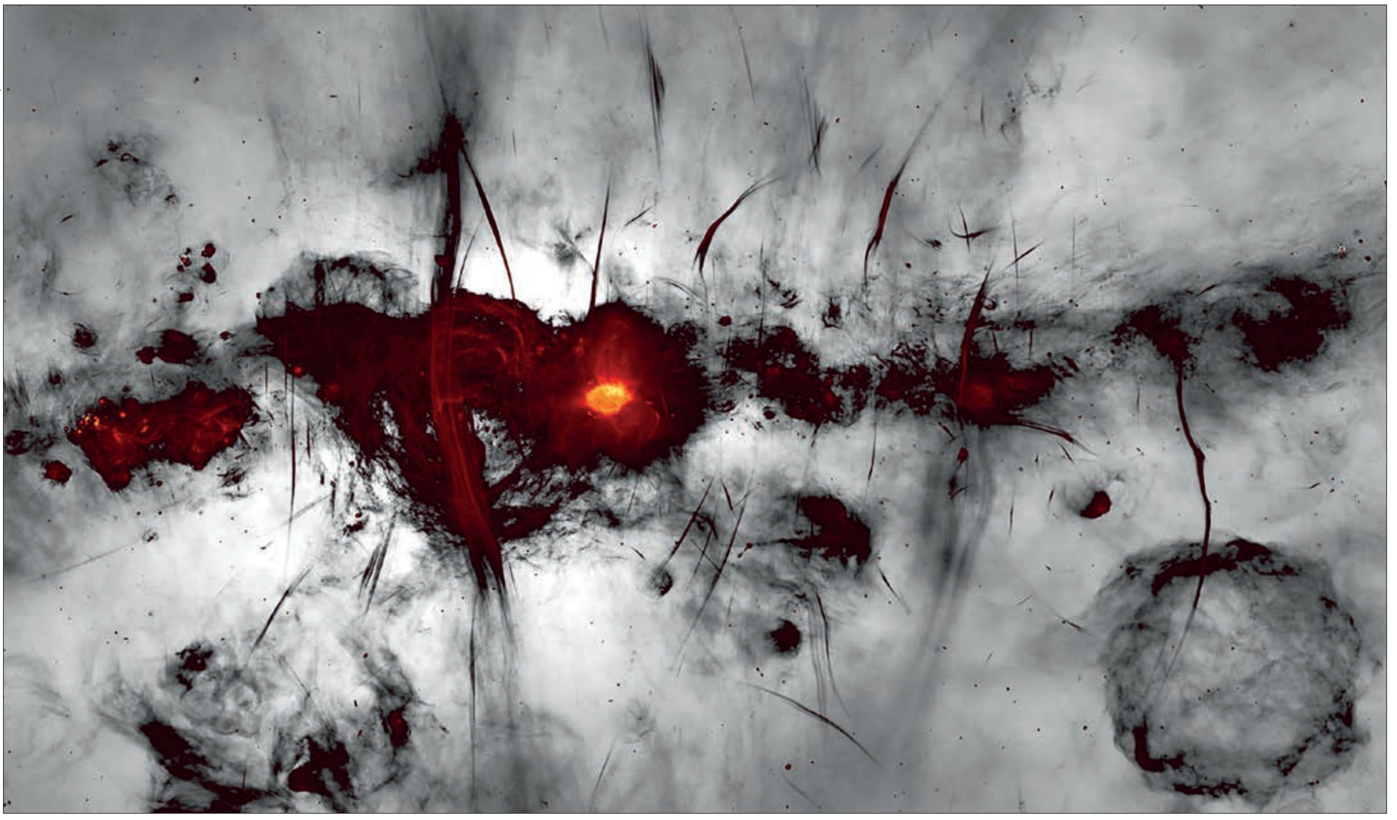
The image resembles a "glorious artwork, conveying how bright black holes are in radio waves, but with the busyness of the galaxy going on around it", says Chapman. "Runaway pulsars, supernovae remnant bubbles, magnetic field lines – it has it all."

In a different area of astronomy, MeerKAT "has been a surprising new contender in the field of pulsar timing", says Natasha Hurley-Walker, an astronomer at the Curtin University node of the International Centre for Radio Astronomy Research in Bentley. Pulsars are rotating neutron stars that produce periodic pulses of radiation hundreds of times a second. MeerKAT's sensitivity,

Eyes on the skies A composite image with South Africa's MeerKAT telescope in the foreground. The backdrop shows a visible night sky on the left, with MeerKAT's radio view of the centre of the Milky Way on the right.

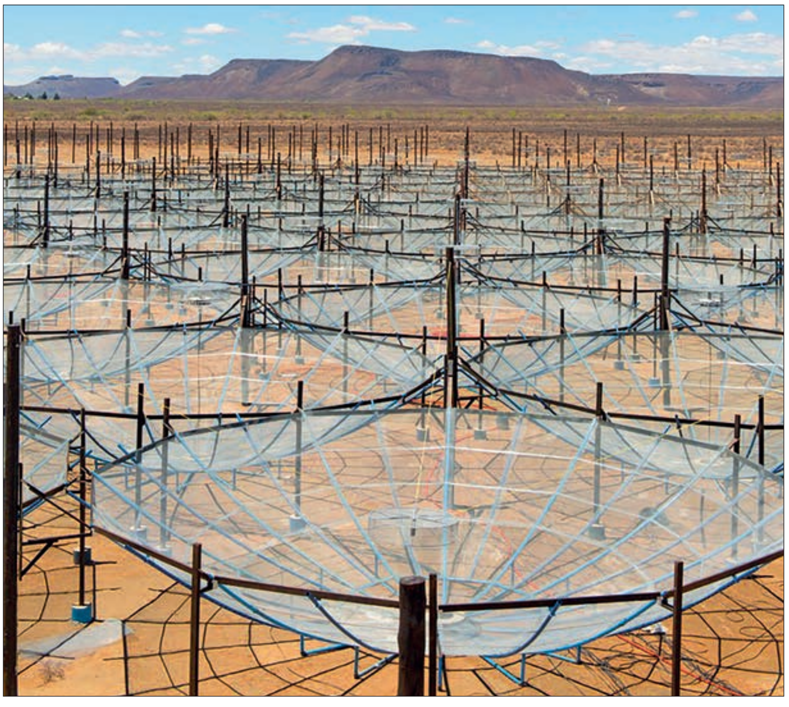
I. Heywood, SARAO

I. Heywood, SARAO



As you've never seen it before A radio image of the centre of the Milky Way taken by the MeerKAT telescope. The elongated radio filaments visible emanating from the heart of the galaxy are 10 times more numerous than in any previous image.

SARAO



Echoes of the early universe The HERA telescope is listening for faint signals from the first primordial hydrogen that formed after the Big Bang.

combined with its precise time-stamping, allows it to accurately map these powerful radio sources.

An experiment called the MeerKAT Pulsar Timing Array has been observing a group of 80 pulsars once a fortnight since 2019 and is using them as "cosmic clocks" to create a map of gravitational-wave sources. "If we see pulsars in the same direction in the sky lose time in a connected way, we start suspecting that it is not the pulsars that are acting funny but rather a gravitational wave background that has interfered," says Marisa Geyer, an astronomer at the University of Cape Town and a co-author on several papers about the array published last year.

HERA: the first stars and galaxies

When astronomers dreamed up the idea for the SKA about 30 years ago, they wanted an instrument that could not only capture a wide view of the universe but was also sensitive enough to look far back in time.

In the first billion years after the Big Bang, the universe cooled enough for hydrogen and helium to form, eventually clumping into stars and galaxies. When these early stars began to shine, their light stripped electrons from the primordial hydrogen that still populated most of the cosmos – a period of cosmic history known as the Epoch of Reionization. The reionized hydrogen gave off a faint signal and catching glimpses of this ancient radiation remains one of the major science goals of the SKA.

Developing methods to identify primordial hydrogen signals will be the Hydrogen Epoch of Reionization Array (HERA) – a collection of hundreds of 14 m dishes, packed closely together as they watch the sky, like bowls made of wire mesh (see image, left). They have been specifically designed to observe fluctuations in primordial hydrogen in the low-frequency range of 100 MHz to 200 MHz.

Understanding this mysterious epoch sheds light on how young cosmic objects influenced the formation of larger ones and later seeded other objects in the universe.


Marianne Annereau, 2015 Murchison Widefield Array (MWA)

Sharp eyes With its wide field of view and low-noise signal amplifiers, the MWA telescope in Australia is poised to spot brief and rare cosmic events, and it has already discovered a new class of mysterious radio transients.


CSIRO

Down under The ASKAP telescope array in Australia was used to demonstrate Australia's capability to host the SKA. Able to rapidly take wide surveys of the sky, it is also a valuable scientific instrument in its own right, and has made significant discoveries in the study of fast radio bursts.

Scientists using HERA data have already reported the most sensitive power limits on the reionization signal (*ApJ* **945** 124), bringing us closer to pinning down what the early universe looked like and how it evolved, and will eventually guide SKA observations. "It always helps to be able to target things better before you begin to build and operate a telescope," explains HERA project manager David de Boer, an astronomer at the University of California, Berkeley in the US.

MWA: "unexpected" new objects

Over in Australia, meanwhile, the MWA's 4096 antennas crouch on the red desert sand like spiders (see image above, left). This interferometer has a particularly wide-field view because, unlike its mid-frequency precursor cousins, it has no moving parts, allowing it to view large parts of the sky at the same time. Each antenna also contains a low-noise amplifier in its centre, boosting the relatively weak low-frequency signals from space. "In a single observation, you cover an enormous fraction of the sky", says Tingay. "That's when you can start to pick up rare events and rare objects."

Hurley-Walker and colleagues discovered one such object a few years ago – repeated, powerful blasts of radio waves that occurred every 18 minutes and lasted about a minute. These signals were an example of a "radio transient" – an astrophysical phenomena that last for milliseconds to years, and may repeat or occur just once. Radio transients have been attributed to many sources including pulsars, but the period of this event was much longer than had ever been observed before.

After the researchers first noticed this signal, they followed up with other telescopes and searched archival data from other observatories going back 30 years to confirm the peculiar time scale. "This has spurred observers around the world to look through their archival data in a new way, and now many new similar sources are being discovered," Hurley-Walker says.

The discovery of new transients, including this one, are "challenging our current models of stellar evolution", according to Cathryn Trott, a radio astronomer at the Curtin Institute of Radio Astronomy in Bentley, Australia. "No one knows what they are, how they are powered, how they generate radio waves, or even whether they are all the same type of object," she adds.

This is something that the SKA – both SKA-Mid and SKA-Low – will investigate. The Australian SKA-Low antennas detect frequencies between 50 MHz and 350 MHz. They build on some of the techniques trialled by the MWA, such as the efficacy of using low-frequency antennas and how to combine their received signals into a digital beam. SKA-Low, with its similarly wide field of view, will offer a powerful new perspective on this developing area of astronomy.

ASKAP: giant sky surveys

The 36-dish ASKAP saw first light in 2012, the same year it was decided to split the SKA between Australia and South Africa. ASKAP was part of Australia's efforts to prove that it could host the massive telescope, but it has since become an important instrument in its own right. These dishes use a technology called a phased

iStock/yucelyilmaz

The wild, wild west Satellites constellations are causing interference with ground-based observatories.

array feed which allows the telescope to view different parts of the sky simultaneously.

Each dish contains one of these phased array feeds, which consists of 188 receivers arranged like a chessboard. With this technology, ASKAP can produce 36 concurrent beams looking at 30 degrees of sky. This means it has a wide field of view, says de Boer, who was ASKAP's inaugural director in 2010. In its first large-area survey, published in 2020, astronomers stitched together 903 images and identified more than 3 million sources of radio emissions in the southern sky, many of which were new (*PASA* **37** e048).

Because it can quickly survey large areas of the sky, the telescope has shown itself to be particularly adept at identifying and studying new fast radio bursts (FRBs). Discovered in 2007, FRBs are another kind of radio transient. They have been observed in many galaxies, and though some have been observed to repeat, most are detected only once.

This work is also helping scientists to understand one of the universe's biggest mysteries. For decades, researchers have puzzled over the fact that the detectable mass of the universe is about half the mass that we know existed after the Big Bang. The dispersion of FRBs by this "missing matter" allows us to weigh all of the normal matter between us and the distant galaxies hosting the FRB.

By combing through ASKAP data, researchers in 2020 also discovered a new class of radio sources, which they dubbed "odd radio circles" (*PASA* **38** e003). These are giant rings of radiation that are observed only in radio waves. Five years later their origins remain a mystery, but some scientists maintain they are flashes from ancient star formation.

While the SKA has many concrete goals, it is these unexpected discoveries that Philippa Hartley, a scientist at the SKAO, based near Manchester, is most excited about. "We've got so many huge questions that we're going to use the SKA to try and answer, but then you switch on these new telescopes, you're like, 'Whoa! We didn't expect that.'" That is why the precursors are so important. "They've given us new questions. And it's incredibly exciting," she adds.

Trouble on the horizon

As well as pushing the boundaries of astronomy and shaping the design of the SKA, the precursors have made a discovery much closer to home – one that could be a significant issue for the telescope. In a development that the SKA's founders will not have foreseen, the race to fill the skies with constellations of satellites is a problem both for the precursors and also for the SKA itself.

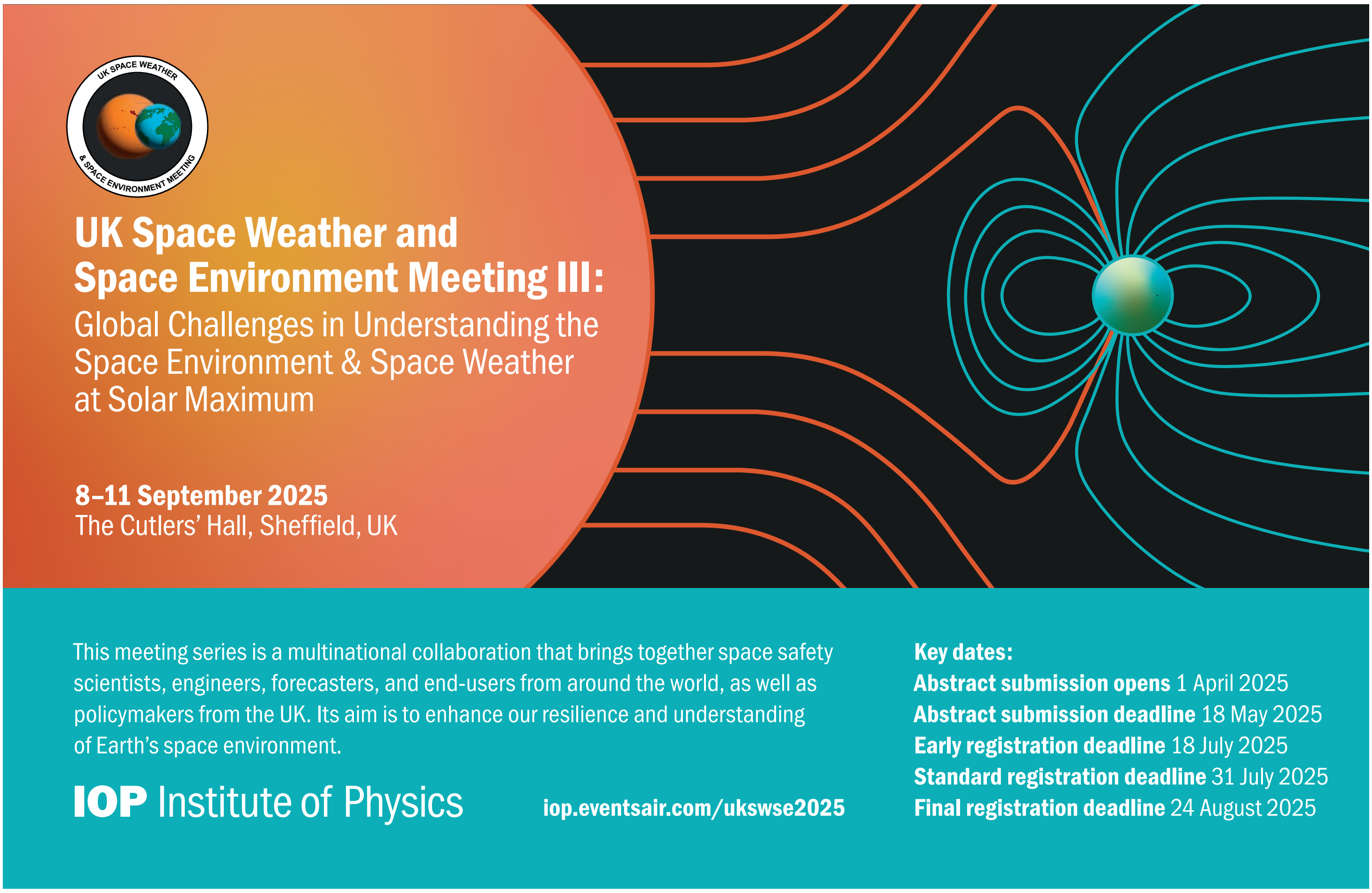
Large corporations, including SpaceX in Hawthorne, California, OneWeb in London, UK, and Amazon's Project Kuiper in Seattle, Washington, have launched more than 6000 communications satellites into space. Many others are also planned, including more than 12 000 from the Shanghai Spacecom Satellite Technology's G60 Starlink based in Shanghai. These satellites, as well as global positioning satellites, are "photobombing" astronomy observatories and affecting observations across the electromagnetic spectrum.

ASKAP, MeerKAT and the MWA have all flagged the impact of satellites on their observations. "The likelihood of a beam of a satellite being within the beam of our telescopes is vanishingly small and is easily avoided," says Robert Braun, SKAO director of science. However, because they are everywhere, these satellites still introduce background radio interference that contaminates observations, he says.

In 2022, the International Astronomical Union (IAU) launched its Centre for the Protection of the Dark and Quiet Sky from Satellite Constellation Interference. The SKA Observatory and the US National Science Foundation's centre for ground-based optical astronomy NOIRLab co-host the facility, which aims to reduce the impact of these satellite constellations.

Although the SKA Observatory is engaging with individual companies to devise engineering solutions, "we really can't be in a situation where we have bespoke solutions with all of these companies", SKAO director-general Phil Diamond told a side event at the IAU general assembly in Cape Town last year. "That's why we're pursuing the regulatory and policy approach so that there are systems in place," he said. "At the moment, it's a bit like the wild, wild west and we do need a sheriff to stride into town to help put that required protection in place."

In this, too, SKA precursors are charting a path forwards, identifying ways to observe even with mega satellite constellations staring down at them. When the full SKA telescopes finally come online in 2028, the discoveries it makes will, in large part, be thanks to the telescopes that came before it. ■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Reviews

How physics raised the roof

Sharon Ann Holgate reviews *Pistols in St Paul's: Science, Music and Architecture in the Twentieth Century* by Fiona Smyth

Courtesy: Fiona Smyth. From the collection of Professor Peter Parkin

Echo chamber
A pistol is fired to test the acoustics at the Royal Festival Hall in London in 1951. A similar acoustic experiment was also performed in the same year at St Paul's Cathedral.

Pistols in St Paul's: Science, Music and Architecture in the Twentieth Century
Fiona Smyth
2024 Manchester University Press
328pp
£25.00/$36.95

Sometimes an attention-grabbing title is the best thing about a book, but not in this case. *Pistols in St Paul's: Science, Music and Architecture in the Twentieth Century* by historian Fiona Smyth, is an intriguing journey charting the development of acoustics in architecture during the first half of the 20th century.

The story begins with the startling event that gives the book its unusual moniker: the firing of a Colt revolver in the famous London cathedral in 1951. A similar experiment was also performed in the Royal Festival Hall in the same year (see above photo). Fortunately, this was simply a demonstration for journalists of an experiment to understand and improve the listening experience in a space notorious for its echo and other problematic acoustic features.

St Paul's was completed in 1711 and Smyth, a historian of architecture, science and construction at the University of Cambridge in the UK, explains that until the turn of the last century, the only way to evaluate the quality of sound in such a building was by ear. The book then reveals how this changed. Over five decades of innovative experiments, scientists and architects built a quantitative understanding of how a building's shape, size and interior furnishings determine the quality of speech and music through reflection and absorption of sound waves.

We are first taken back to the dawn of the 20th century and shown how the evolution of architectural acoustics as a scientific field was driven by a small group of dedicated researchers. This includes architect and pioneering acoustician Hope Bagenal, along with several physicists, notably Harvard-based US physicist Wallace Clement Sabine.

Details of Sabine's career, alongside those of Bagenal, whose personal story forms the backbone for much of the book, deftly put a human face on the research that transformed these public spaces. Perhaps Sabine's most significant contribution was the derivation of a formula to predict the time taken for sound to fade away in a room. Known as the "reverberation time", this became a foundation of architectural acoustics, and his mathematical work still forms the basis for the field today.

The presence of people, objects and reflective or absorbing surfaces all affect a room's acoustics. Smyth describes how materials ranging from rugs and timber panelling to specially developed acoustic plaster and tiles have all been investigated for their acoustic properties. She also vividly details the venues where acoustics interventions were added – such as the reflective teak flooring and vast murals painted on absorbent felt in the Henry Jarvis Memorial Hall of the Royal Institute of British Architects in London.

Other locations featured include the Royal Albert Hall, Abbey Road Studios, White Rock Pavilion at Hastings, and the Assembly Chamber of the Legislative Building in New Delhi, India. Temporary structures and spaces for musical performance are highlighted too. These include the National Gallery while it was cleared of paintings during the Second World War and the triumph of acoustic design that was the Glasgow Empire Exhibition concert hall – built for the 1938 event and sadly dismantled that same year.

Unsurprisingly, much of this acoustic work was either punctuated or heavily influenced by the two world wars. While in the trenches during the First World War, Bagenal wrote a journal paper on cathedral acoustics that detailed his pre-war work at St Paul's Cathedral, Westminster Cathedral and Westminster Abbey. His paper discussed timbre, resonant frequency "and the effects of interference and delay on clarity and harmony".

In 1916, back in England recovering from a shellfire injury, Bagenal started what would become a long-standing research collaboration with the commandant of the hospital where he was recuperating – who happened to be Alex Wood, a physics lecturer at Cambridge. Equally fascinating is hearing about the push in the wake of the First World War for good speech acoustics in public spaces used for legislative and diplomatic purposes.

Smyth also relates tales of the wrangling that sometimes took place over funding for acoustic experiments on public buildings, and how, as the 20th century progressed, companies specializing in acoustic materials sprang up – and in some cases made dubious claims about the merits of their products. Meanwhile, new technologies such as tape recorders and microphones helped bring a more scientific approach to architectural acoustics research.

The author concludes by describing how the acoustic research from the preceding decades influenced the auditorium design of the Royal Festival Hall on the South Bank in London, which, as Smyth states, was "the first building to have been designed from the outset as a manifestation of acoustic science".

> The evolution of architectural acoustics as a scientific field was driven by a small group of dedicated researchers

As evidenced by the copious notes, the wealth of contemporary quotes, and the captivating historical photos and excerpts from archive documents, this book is well-researched. But while I enjoyed the pace and found myself hooked into the story, I found the text repetitive in places, and felt that more details about the physics of acoustics would have enhanced the narrative.

But these are minor grumbles. Overall Smyth paints an evocative picture, transporting us into these legendary auditoria. I have always found it a rather magical experience attending concerts at the Royal Albert Hall. Now, thanks to this book, the next time I have that pleasure I will do so with a far greater understanding of the role physics and physicists played in shaping the music I hear. For me at least, listening will never be quite the same again.

Sharon Ann Holgate is a freelance science writer and broadcaster. Her latest book is *Communicating Science Clearly: a Self-Help Guide For Students and Researchers*. www.sharonannholgate.com

Careers

Preparing the next generation for a quantum future

INTERNATIONAL YEAR OF Quantum Science and Technology

Emily Edwards, co-leader of the National Q-12 Education Partnership in the US, and **Claudia Fracchiolla**, head of public engagement at the American Physical Society, talk to Tushna Commissariat about the challenges and opportunities in quantum education, highlighting the efforts of various organizations to foster a skilled and diverse quantum workforce

Lloyd DeGrane/ University of Illinois Urbana-Champaign/ Chicago Quantum Exchange

Inspirational impact Students learn about the excitement of quantum science from postdoctoral fellow Yujie Zhang at the Public Quantum Network launch at the University of Illinois Urbana-Champaign in 2023.

Quantum technologies are flourishing world over, with advances across the board researching practical applications such as quantum computing, communication, cryptography and sensors. Indeed, the quantum industry is booming – an estimated \$42bn was invested in the sector in 2023, and this amount is projected to rise to \$106bn by 2040.

With academia, industry and government all looking for professionals to join the future quantum workforce, it's crucial to have people with the right skills, and from all educational levels. With this in mind, efforts are being made across the US to focus on quantum education and training; with educators working to introduce quantum concepts from the elementary-school level, all the way to tailored programmes at PhD and postgraduate level that meet the needs of potential employers in the area. Efforts are being made to ensure that graduates and early-career physicists are aware of the many roles available in the quantum sphere.

"There are a lot of layers to what has to be done in quantum education," says Emily Edwards, associate research professor of electrical and computer engineering at Duke University and co-leader of the National Q-12 Education Partnership. "I like to think of quantum education along different dimensions. One way is to think about what most learners may need in terms of foundational public literacy or student literacy in the space. Towards the top, we have people who are very specialized. Essentially, we have to think about many different learners at different stages – they might need specific tools or might need different barriers removed for them. And so different parts of the economy – from government to industry to academia and professional institutions – will play a role in how to address the needs of a certain group."

Engaging young minds

To ensure that the US remains a key global player in quantum information science and technology (QIST), the National Q-12 Education Partnership – launched by the White House Office of Science and Technology Policy and the National Science Foundation (NSF) – is focused on ways to engage young minds in quantum, building the necessary tools and strategies to help improve early (K-12) education and outreach. To achieve this, Q-12 is looking at outreach and education in middle school and high school, by introducing QIST concepts and providing access to learning materials and to inspire the next generation of quantum leaders. Over the next decade, Q-12 also aims to provide quantum-related curricula – developed by professionals in the field – beyond university labs and classrooms, to community colleges and online courses.

Edwards explains that while Q-12 mainly focuses on the K-12 level, there is also an overlap with early undergraduate, two-year colleges – meaning that there is a wide range of requirements, issues and unique challenges to contend with. Such a big space also means that different companies and institutions have varying levels of funding and interests in quantum education research and development.

"Academic organizations, for example, tend to work on educational research or to provide professional development, especially because it's nascent," says Edwards. "There is a lot of the activity in the academic space, within professional societies. We also work with a number of private companies, some of which are developing curricula, or providing free access to different tools and simulations for learning experiences."

The American Physical Society (APS) is strongly involved in quantum education – by making sure that teachers have access to tools and resources for quantum education as well as connecting quantum professionals with K-12 classrooms to discuss careers in quantum. "The APS has been really active in engaging with teachers and connecting them with the vast network of APS members, stakeholders and professionals, to talk about careers," says Edwards. APS and Q-12 have a number of initiatives – such as Quantum To-Go and QuanTime – that help connect quantum professionals with classrooms and provide teachers with ready-to-use quantum activities.

Claudia Fracchiolla, who is the APS's head of public engagement, points out that while there is growing interest in quantum education, there is a lack of explicit support for high-school teachers who need to be having conversations about a possible career in quantum with students that will soon be choosing a major.

"We know from our research that while teachers might want to engage in this professional development, they don't always have the necessary support from their institution and it is not regulated," explains Fracchiolla. She adds that while there are a "few stellar people in the field who are creating materials for teachers", there is not a clear standard on how they can be used, or what can be taught at a school level.

Quantum resources

To help tackle these issues, the APS and Q-12 launched the Quantum To-Go programme, which pairs educators with quantum-science professionals, who speak to students about quantum concepts and careers. The programme covers students from the first year of school through to undergraduate level, with scientists visiting in person or virtually.

"I think it's a really great way for quantum professionals in different sectors to visit classrooms and talk about their experiences," says Edwards. She adds that this kind of collaboration can be especially useful "because we know that students – particularly young women, or students of colour or those from any marginalized background – self-select out of these areas while they're still in the K-12 environment." Edwards puts this down to a lack of role models in the workplace. "Not only do they not hear about quantum in the classroom or in their curriculum, but they also can't see themselves working in the field," says Edwards. "So there's no hope of achieving a diverse workforce if you don't connect a diverse set of professionals with the classroom. So we are really proud to be a part of Quantum To-Go."

APS

Role model The Quantum To-Go programme matches scientists, engineers and professionals in QIST with classrooms across the country to inspire students to enter the quantum workforce.

House Science Committee

National Quantum Initiative Testifying before the House Science Committee on 7 June 2023, were (from left to right) National Quantum Coordination Office director Charles Tahan, former Department of Education under secretary for science Paul Dabbar, NASA quantum scientist Eleanor Rieffel, Quantum Economic Development Consortium executive director Celia Merzbacher, and University of Illinois quantum scientist Emily Edwards (now at Duke University).

With 2025 being celebrated as the International Year of Quantum Science and Technology (IYQ), both Q-12 and the APS hope to see and host many community-driven activities and events focused on young learners and their families. An example of this is Q-12's QuanTime initiative, which seeks to help teachers curate informal quantum activities across the US all year round. "Education is local in the US, and so it's most successful if we can work with locals to help develop their own community resources," explains Edwards.

A key event in the APS's annual calendar of activities celebrating IYQ is the Quantum Education and Policy Summit, held in partnership with the Q-SEnSE institute. It aims to bring together key experts in physics education, policymakers and quantum industry leaders, to develop quantum educational resources and policies.

Another popular resource produced by the APS is its PhysicsQuest kits, which are aimed at middle-school students to help them explore specific physics topics. "We engaged with different APS members who work in quantum to design activities for middle-school students," says Fracchiolla. "We then worked with some teachers to pilot and test those activities, before finalizing our kits, which are freely available to teachers. Normally, each year we do four activities, but thanks to IYQ, we decided to double that to eight activities that are all related to topics in quantum science and technology."

To help distribute these kits to teachers, as well as provide them with guidance on how to use all the included materials, the APS will host workshops for teachers during the Teachers' Days at the APS Global Physics Summit in March. Workshops will also be held at the APS Division of Atomic, Molecular and Optical Physics (DAMOP) annual meeting in June.

"A key part of IYQ is creating an awareness of what quantum science and technology entails, because it is also about the people that work in the field," says Fracchiolla. She adds that "Something that was really important when we were writing the proposal to send to the UN for the IYQ was to demonstrate how quantum technologies will supports the UN's sustainable development goals. I hope this also inspires students to pursue careers in quantum, as they realize that it goes beyond quantum computing."

Fracchiolla is also keen to highlight the fact that having a diverse range of people in the quantum workforce will ensure that these technologies will help to tackle societal and environmental issues, and vice versa. "If we are focusing on quantum technologies to address sustainable development goals, we need to make sure that they are accessible to everyone. And that's not going to happen if diverse minds are not involved in the process of developing these technologies," she says, while acknowledging that this is currently not the case.

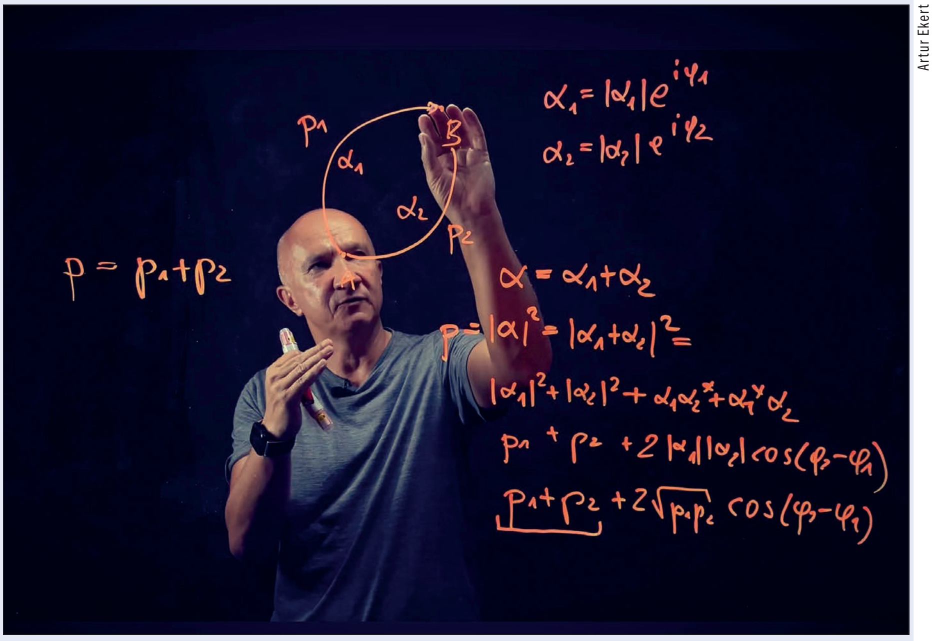
It is Fracchiolla's ultimate hope that the IYQ and the APS's activities taken together will help all students feel empowered that there is a place for them in the field. "Quantum is still a nascent field and we have the opportunity to not repeat the errors of the past, that have made many areas of science exclusive. We need to make the field diverse from the get go."

- First published in *APS Careers 2025*

Tushna Commissariat is the features editor of *Physics World*

Ask me anything: Artur Ekert

Artur Ekert is a professor of quantum physics and cryptography at the University of Oxford, UK, whose work on information processing in quantum mechanical systems has wide-ranging applications in cryptography and quantum computing. In 2024 he received the Royal Society's Milner Award for outstanding achievement in computer science by a European researcher.



Artur Ekert

Joining the dots Artur Ekert stresses the importance of thinking outside of the normal science "silos" in order to connect ideas.

What skills do you use every day in your job?

Apart from the usual set of mathematical skills ranging from probability theory and linear algebra to aspects of cryptography, the most valuable skill is the ability to think in a critical and dissecting way. Also, one mustn't be afraid to go in different directions and connect dots. In my particular case, I was lucky enough that I knew the foundations of quantum physics and the problems that cryptographers were facing and I was able to connect the two. So I would say it's important to have a good understanding of topics outside your narrow field of interest. Nature doesn't know that we divided all phenomena into physics, chemistry and biology, but we still put ourselves in those silos and don't communicate with each other.

What do you like best and least about your job?

Least is easy, all admin aspects of it. Best is meeting wonderful people. That means not only my senior colleagues – I was blessed with wonderful supervisors and mentors – but also the junior colleagues, students and postdocs that I work with. This job is a great excuse to meet interesting people.

What do you know today, that you wish you knew when you were starting out in your career?

That it's absolutely fine to follow your instincts and your interests without paying too much attention to practicalities. But of course that is a *post-factum* statement. Maybe you need to pay attention to certain practicalities to get to the comfortable position where you can make the statement I just expressed.

Nature doesn't know that we divided all phenomena into physics, chemistry and biology, but we still put ourselves in those silos and don't communicate with each other

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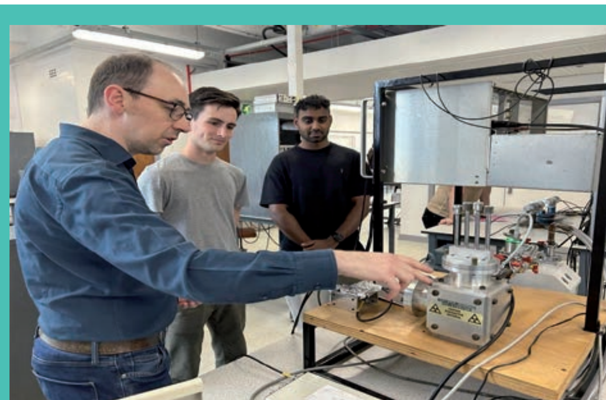

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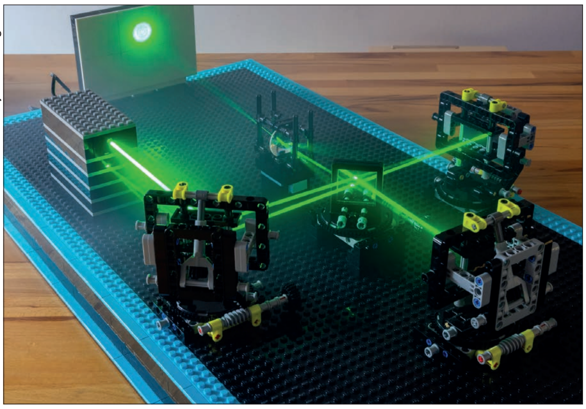
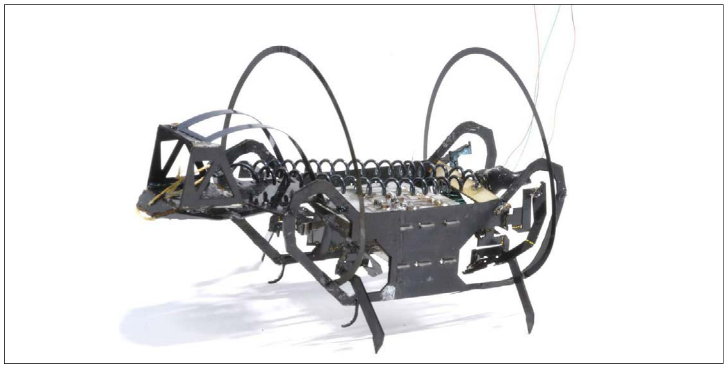
LEGO optics, Wild Card virus, leaping bots

Michael Banks picks his favourite stories and quotes from the weird and wonderful world of physics



University of Nottingham

Building blocks University of Nottingham researchers have developed a fully functional LEGO interferometer kit.



View this e-magazine online to watch a video of the jumping robot developed at Harvard inspired by bugs called globular springtails

We've already had a LEGO Large Hadron Collider, a LEGO quantum computer and even a LEGO Kibble balance. But now there's a LEGO interferometer to add to that list thanks to researchers from the University of Nottingham, UK. Working with LEGO student enthusiasts, they have developed a fully functional LEGO interferometer kit that consists of lasers, mirrors, beamsplitters and, of course, some LEGO bricks. The set, designed as a teaching aid for secondary-school pupils and older, is aimed at making quantum science more accessible and engaging as well as demonstrating the basic principles of interferometry such as interference patterns. A team at Cardiff University is now working on the design to develop resources that can be used to train science teachers with the hope that the sets will eventually be made available throughout the UK. If you want to see the LEGO interferometer in action for yourself, it is being showcased at the Cosmic Titans: Art, Science, and the Quantum Universe exhibition at Nottingham's Djanogly Art Gallery, which runs until 27 April.

Wild Card physics

The Wild Cards universe is a series of novels set largely during an alternate history of the US following the Second World War. The series follows events after an extraterrestrial virus, known as the Wild Card virus, has spread worldwide. It mutates human DNA causing profound changes in human physiology. The virus follows a fixed statistical distribution in that 90% of those infected die, 9% become physically mutated (referred to as "jokers") and 1% gain superhuman abilities (known as "aces"). Such capabilities include the ability to fly as well as being able to move between dimensions. Now, George R R Martin, the author who co-edits the Wild Cards series, has co-authored a paper examining the complex dynamics of the Wild Card virus together with Los Alamos National Laboratory theoretical physicist Ian Tregillis, who is also a science-fiction author (*Am. J. Phys.* **93** 127). The model takes into consideration the severity of the changes (for the 10% that don't instantly die) and the mix of joker/ace traits. The result is a dynamical system in which a carrier's state vector constantly evolves through the model space – until their "card" turns. At that point the state vector becomes fixed and its permanent location determines the fate of the carrier. "The fictional virus is really just an excuse to justify the world of Wild Cards, the characters who inhabit it, and the plot lines that spin out from their actions," says Tregillis.

This is history right here

Cosmologist **Emma Chapman** from the University of Nottingham outlines how physicists are campaigning to find a safer home for a blackboard that Einstein signed when visiting the university in 1930, and today sits in a staff room. (Source: *Times*)

It was a kind of holy relic

Historian **Stephen Snobelen** from the University of King's College in Halifax, Nova Scotia, commenting on Isaac Newton's beer mug going on public display at the Royal Society. It is thought that Newton gave the wooden flagon to his colleague John Wickins, whose family passed it down the generations. (Source: *Guardian*)

Jumping springtail robots

Globular springtails (*Dicyrtomina minuta*) are small bugs about 5 mm long that can be seen crawling through leaf litter and garden soil. While they do not have wings and cannot fly, they more than make up for it with their ability to hop relatively large heights and distances. This jumping feat is thanks to a tail-like appendage on their abdomen called a furcula, which is folded in beneath their body, held under tension. When released, it snaps against the ground in as little as 20 ms, flipping the springtail up to 6 cm into the air and 10 cm horizontally. Researchers at the Harvard John A Paulson School of Engineering and Applied Sciences have now created a robot that mimics this jumping ability (*Sci. Robot.* **10** eadp7854). The team found that the robot could jump 1.4 m horizontally, or 23 times its body length – the longest of any existing robot relative to body length. The work could help design robots that can traverse places that are hazardous to humans.

Michael Banks is news editor of *Physics World*

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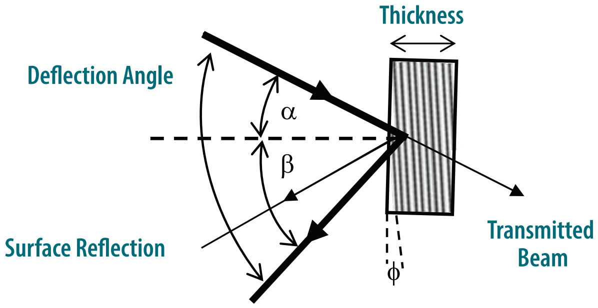

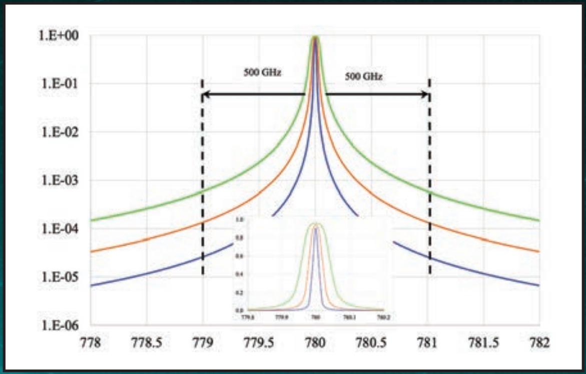

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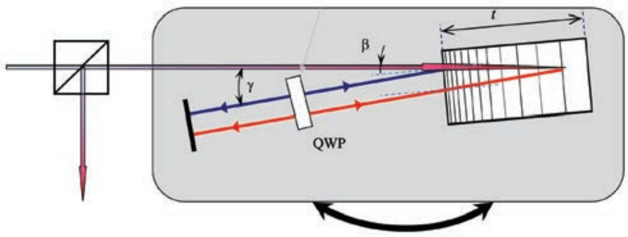
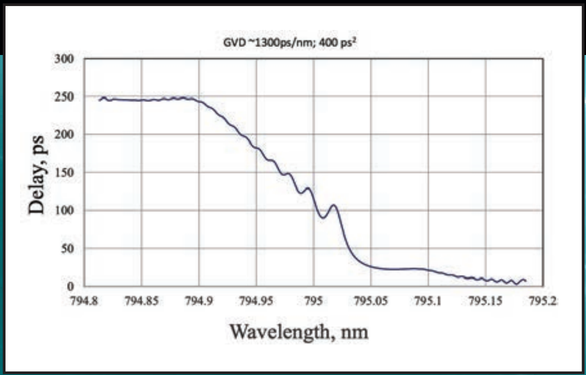


Schematic Diagram of CBG deployment for Qubit Filtering and Control

Group delay dispersion of Chirped Bragg grating (CBG)



PTR glass based highly dispersive CBGs enabled passively stable, efficient, method of fast amplitude modulation compatible for high power laser sources. *[H. Levine at al. "Dispersive optical systems for scalable Raman driving of hyperfine Qubits," Phys. Rev. A 105, 032618 (2022)]*

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