physicsworld

March 2025

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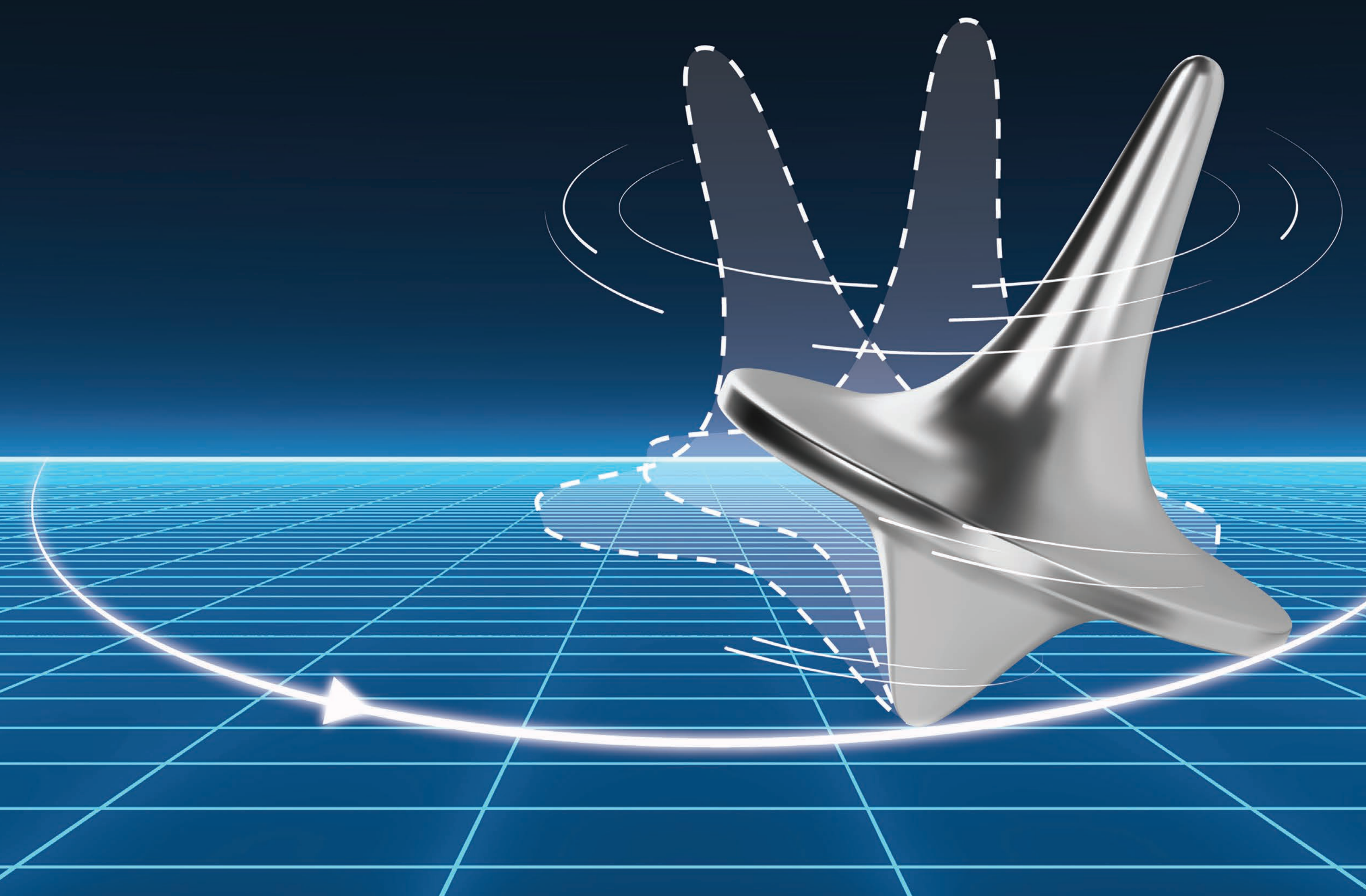
Career change How Michelle Lollie went from finance to quantum tech

Stuff of dreams The superconductor that could boost fusion reactors

Muon mystery

Will this particle's spin reveal new physics?



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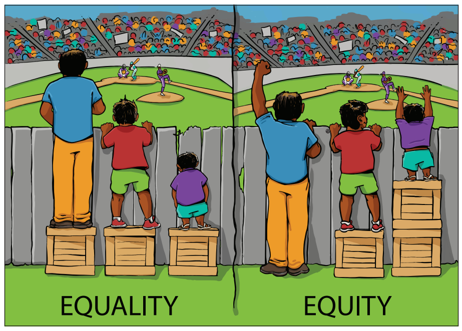

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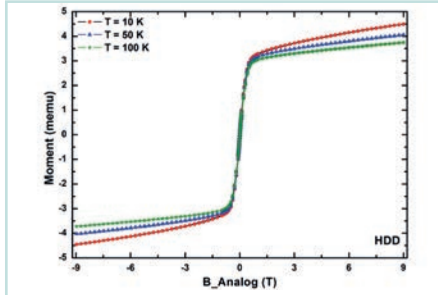

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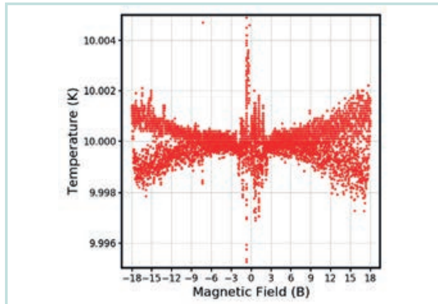

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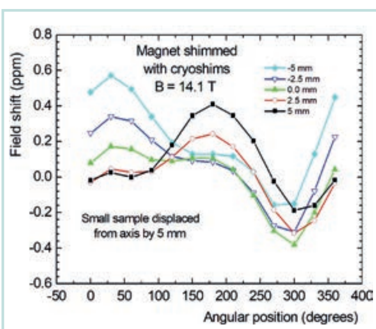
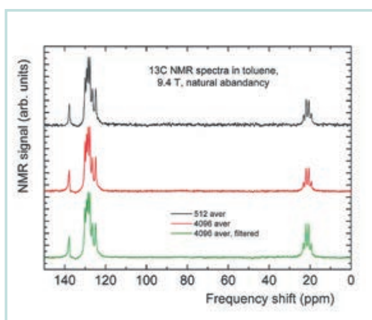


Magnetic Field Profile



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News & Analysis

Trump plunges US science into chaos

Donald Trump's second term as US president has begun with staff layoffs, slashed budgets, axed diversity programmes and cancelled conferences. **Peter Gwynne** examines the damage

Scientists across the US have been left reeling after a spate of executive orders from US President Donald Trump has led to research funding being slashed, staff being told to quit and key programmes being withdrawn. In response to the orders, government departments and external organizations have axed diversity, equity and inclusion (DEI) programmes, scrubbed mentions of climate change from websites, and paused research grants pending tests for compliance with the new administration's goals.

According to a report in *Politico*, the Trump administration has asked the National Science Foundation (NSF), which funds much US basic and applied research, to lay off between a quarter and a half of its staff in the next two months. Another report suggests there are plans to cut the agency's annual budget from roughly \$9bn to \$3bn. Meanwhile, former officials of the National Oceanic and Atmospheric Administration (NOAA) told CBS News that half its staff could be sacked and its budget slashed by 30%.

Even before they had learnt of plans to cut its staff and budget, officials at the NSF were starting to examine details of thousands of grants it had awarded for references to DEI, climate change and other topics that Trump does not like. The swiftness of the announcements has caused chaos, with recipients of grants suddenly finding themselves unable to access the NSF's award cash management service, which holds grantees' funds, including their salaries. In what is a highly fluid situation, there was some respite on 2 February when the NSF announced that access had been restored, with the system able to accept payment requests.

"Un-American" actions

Trump's anti-DEI orders have caused shockwaves throughout US science.

White House

Uncertain times Since taking up office on 20 January, US President Donald Trump has signed dozens of executive orders that have impacted science and scientists across the country.

According to *404 Media*, NASA staff were told on 22 January to "drop everything" to remove mentions of DEI, Indigenous people, environmental justice and women in leadership from public websites. Another victim has been NASA's Here to Observe programme, which links undergraduates from under-represented groups with scientists who oversee NASA's missions. *Science* reported that contracts for half the scientists involved in the programme had been cancelled by the end of January.

Anti-DEI initiatives have hit individual research labs too. *Physics World* understands that Fermilab – the US's premier particle-physics lab – suspended its DEI office and women in engineering group in January. The Fermilab LGBTQ+ group, called Spectrum, was ordered to cease all activities and its mailing list deleted, while the rainbow "Pride" flag was removed from the lab's iconic Wilson Hall.

Some US learned societies, despite being formally unaffiliated with the government, have also responded to pressure from the new administration. The American Geophysical Union (AGU) removed the word "diversity" from its diversity and inclusion page, although it backtracked after criticism of the move. Such a response – which some opponents denounce as going beyond what is legally required for fear of repercussions if no action is taken – has left it up to individual leaders to underline the importance of diversity in science.

Neal Lane, a former science adviser to President Bill Clinton, told *Physics World* that "dismantling all federal DEI programmes and related activities will damage the lives and careers of millions of American women and men, including scientists, engineers and technical workers – essentially everyone who contributes to advancing America's global leadership in science and technology".

Lane, who is now a science and technology policy fellow at Rice University in Texas, thinks that the new administration's anti-DEI actions "will weaken the US" and believes they should be considered "un-American". "The purpose of DEI policies, programmes and activities is to ensure all Americans have the opportunity to participate and the country is able to benefit from their participation," he says.

One senior physicist at a US university, who wishes to remain anonymous, told *Physics World* that those behind the executive orders are relying on institutions and individuals to "comply in advance" with what they perceive to be the spirit of the orders. "They are relying on people to ignore the fine print, which says that executive orders can't and don't overwrite existing law. But it is up to scientists to do the reading – and to follow our consciences. More than universities are on the line: the lives of our students and colleagues are on the line."

Another target of the Trump administration is the US Department of Education, which was set up in 1978 to oversee everything from pre-school to postgraduate education. It has already put dozens of its civil servants on leave, ostensibly because their work involves DEI issues. Meanwhile, the withholding of funds led to the cancellation of scientific meetings, mostly focusing on medicine and life sciences, that were due to be held in the US last month.

Colleges and universities in the US have also reacted to Trump's anti-DEI executive order. Academic divisions at Harvard University and the Massachusetts Institute of Technology, for example, have already indicated that they will no longer require applicants for jobs to show how they plan to advance the goals of DEI. Northeastern University in Boston removed the words "diversity" and "inclusion" from a section of its website. Not all academic organizations have fallen into line, however. Danielle Holly, president of the women-only Mount Holyoke College in South Hadley, Massachusetts, says it will forgo contracts with the federal government if they require abolishing DEI. "We obviously can't enter into contracts with people who don't allow DEI work," she told the *Boston Globe*. "So for us, that wouldn't be an option."

Climate concerns

For an administration that doubts the reality of climate change and opposes anti-pollution laws, the Environmental Protection Agency (EPA) is under fire too. Trump administration representatives were taking action even before the Senate approved Lee Zeldin, a former Republican Congressman from New York who has criticized much environmental legislation, as EPA administrator. They removed all outside advisers on the EPA's scientific advisory board and its clean air scientific advisory committee – purportedly to "depoliticize" the boards.

Once the Senate approved Zeldin on 29 January, the EPA sent an e-mail warning more than 1000 probationary employees who had spent less than a year at the agency that their roles could be "terminated" immediately. Then, according to the *New York Times*, the agency developed plans to demote longer-term employees who have overseen research, enforcement of anti-pollution laws, and clean-ups of hazardous waste. According to *Inside Climate News*, staff also found their individual pronouns scrubbed from their e-mails and websites without their permission – the result of an order to remove "gender ideology extremism".

Critics have also questioned the nomination of Neil Jacobs to lead the National Oceanic and Atmospheric Administration (NOAA). He was its acting head during Trump's first term in office, serving during the 2019 "Sharpiegate" affair when Trump used a Sharpie pen to alter a NOAA weather map to indicate that Hurricane Dorian would affect Alabama. While conceding Jacobs's experience and credentials, Rachel Cleetus of the Union of Concerned Scientists asserts that Jacobs is "unfit to lead" given that he "fail[ed] to uphold scientific integrity at the agency".

Quasi-official cost-slashing

Another concern for scientists is the quasi-official team led by "special government employee" and SpaceX founder Elon Musk. The administration has charged Musk and his so-called "department of government efficiency", or DOGE, to identify significant cuts to government spending. Though some of DOGE's activities have been blocked by US courts, agencies have nevertheless been left scrambling for ways to reduce day-to-day costs.

The National Institutes of Health (NIH), for example, has said it will significantly reduce its funding for "indirect" costs of research projects it supported – the overheads that, for example, cover the cost of maintaining laboratories, administering grants and paying staff salaries. Under the plans, indirect cost reimbursement for federally funded research would be capped at 15%, a drastic cut from its usual range.

NIH personnel have tried to put a positive gloss on its actions. "The United States should have the best medical research in the world," a statement from NIH declared. "It is accordingly vital to ensure that as many funds as possible go towards direct scientific research costs rather than administrative overhead."

They are relying on people to ignore the fine print, which says that executive orders can't and don't overwrite existing law. But it is up to scientists to do the reading – and to follow our consciences

Opponents of the Trump administration, however, are unconvinced. They argue that the measure will imperil critical clinical research because many academic recipients of NIH funds do not have the endowments to compensate for the losses. "Just because Elon Musk doesn't understand indirect costs doesn't mean Americans should have to pay the price with their lives," says US senator Patty Murray, a Democrat from Washington state.

Slashing universities' share of grants to below 15%, could, however, force institutions to make up the lost income by raising tuition fees, which could "go through the roof", according to the anonymous senior physicist contacted by *Physics World*. "Far from being a populist policy, these cuts to overheads are an attack on the subsidies that make university education possible for students from a range of socioeconomic backgrounds. The alternative is to essentially shut down the university research apparatus, which would in many ways be the death of American scientific leadership and innovation."

Musk and colleagues have also gained unprecedented access to government websites related to civil servants and the country's entire payments system. That access has drawn criticism, given that Musk is a recipient of significant government support through his SpaceX company. Some say that he could use the information for his own advantage.

"Musk has access to all the data on federal research grantees and contractors: social security numbers, tax returns, tax payments, tax rebates, grant disbursements and more," wrote physicist Michael Lubell from City College of New York. "Anyone who depends on the federal government and doesn't toe the line might become a target. This is right out of (Hungarian prime minister) Viktor Orbán's playbook."

As for the long-term impact of these changes, James Gates – a theoretical physicist at the University of Maryland and a past president of the US National Society of Black Physicists – is blunt. "My country is in for a 50-year period of a new dark ages," he told an audience at the Royal College of Art in London, UK, on 7 February.

Speaking at an event sponsored by the college's association for Black students – RCA BLK – and supported by the UK's organization for Black physicists, the Blackett Lab Family, he pointed out that the US has been through such periods before, citing the 1950s "Red Scare" and the period after 1876 when the federal government abandoned efforts to enforce the civil rights of Black Americans in southern states and elsewhere.

However, he is not entirely pessimistic. "Nothing is permanent in human behaviour. The question is the timescale," Gates said. "There will be another dawn, because that's part of the human spirit."

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

Publishing

Publish a top paper as a postdoc for career success

If you're a postdoc who wants to nail down that permanent faculty position, it's wise to publish a highly cited paper after your PhD. That's the conclusion of a study by an international team of researchers, which finds that publication rates and performance during the postdoc period is key to academic retention and early-career success. The analysis also reveals that more than four in 10 postdocs drop out of academia (*Proc. Natl Acad. Sci.* **122** e2402053122)

A postdoc is usually a temporary appointment that is seen as preparation for an academic career. Many researchers, however, end up doing several postdocs in a row as they hunt for a permanent job. "There are many more postdocs than there are faculty positions, so it is a kind of systemic bottleneck," says Petter Holme, a computer scientist at Aalto University in Finland, who led the study.

To eke out the effect of a postdoc, which has often been overlooked in studies of academic success, Holme and colleagues combined information of academics' career stages from LinkedIn with their publication history obtained from Microsoft Academic Graph. The resulting global dataset covered 45 572 careers spanning 25 years across all academic disciplines.

iStock

Publish or perish A study finds that publishing fewer papers as a postdoc makes you more likely to drop out of academia.

Overall, they found, 41% of postdocs left academia. But researchers who publish a highly cited paper as a postdoc are much more likely to pursue a faculty career – whether they published a highly cited paper during their PhD or not. Publication rate is also vital, with researchers who publish less as postdocs compared to their PhD days being more likely to drop out of academia. Conversely, as productivity increased, so did the likelihood of a postdoc gaining a faculty position.

Holme says the results suggest that a researcher only has a few years "to get on the positive feedback loop, where one success leads to another". A "moderate" change in research topic when moving from PhD to postdoc could improve future success, however. "It is a good thing to change your research focus, but not too much," explains Holme. This is because it widens perspective without having to learn a new topic from scratch.

Likewise, shifting perspective by moving abroad can also benefit postdocs. The analysis shows that a researcher moving abroad for a postdoc boosts their citations, but a move to a different institution in the same country has a negligible impact.

Michael Allen

Freedom in the Equation exhibition opens at Harvard Science Centre

A new exhibition dedicated to Ukrainian scientists has opened at Harvard Science Centre in Cambridge, Massachusetts, US. The exhibition – Freedom in the Equation – shares the stories of 10 scientists to highlight Ukraine's lost scientific potential due to Russia's aggression towards the country. Among them are Vasyl Kladko – a physicist who worked on semiconductor physics and was deputy director of the Institute of Semiconductor Physics in Kyiv. He was killed in 2022 at the age of 65 as he tried to help his family flee Russia's invasion. Also featured is the physicist Lev Shubnikov, who established a cryogenic lab at the Ukrainian Institute of Physics and Technology in Kharkiv (now the Kharkiv Institute of Physics and Technology) in the early 1930s. In 1937 Shubnikov was arrested during Stalin's regime and accused of espionage and was executed shortly after. The scientists were selected by Oleksii Boldyrev, a molecular biologist and founder of the online platform *myscience.ua*, together with Krystyna Semeryn, a literary scholar and publicist. The portraits were created by Niklas Elemehed, who is the official artist of the Nobel prize, with the text compiled by Olesia Pavlyshyn, editor-in-chief at the Ukrainian popular-science outlet *Kunsht*. The exhibition, which is part of the Science at Risk project, runs until 10 March.

Michael Banks

Science at Risk

Quantum year launches in style

The International Year of Quantum Science and Technology got under way at an event at UNESCO headquarters in Paris last month. **Matin Durrani** reports from Paris

INTERNATIONAL YEAR OF
Quantum Science
and Technology

More than 800 researchers, policy-makers and government officials from around the world gathered in Paris last month to attend the official launch of the International Year of Quantum Science and Technology (IYQ). Held at the headquarters of the United Nations Educational, Scientific and Cultural Organisation (UNESCO), the two-day event included contributions from four Nobel-prize-winning physicists – Alain Aspect, Serge Haroche, Anne l'Huillier and William Phillips.

Opening remarks came from Cephas Adjej Mensah, a research director in the Ghanaian government, which last year submitted the draft resolution to the United Nations for the IYQ. "Let us commit to making quantum science accessible to all," Mensah declared, reminding delegates that the IYQ is intended to be a global initiative, spreading the benefits of quantum equitably around the world. "We can unleash the power of quantum science and technology to make an equitable and prosperous future for all."

The keynote address was given by l'Huillier, a quantum physicist at Lund University in Sweden, who shared the 2023 Nobel Prize for Physics with Pierre Agostini and Ferenc Krausz for their work on attosecond pulses. "Quantum mechanics has been extremely successful," she said, explaining how it was invented 100 years ago by Werner Heisenberg on the island of Helgoland. "It has led to new science and new technology – and it's just the beginning."

Some of that promise was outlined by Phillips in his plenary lecture. The first quantum revolution led to lasers, semiconductors and transistors, he reminded participants, but said that the second quantum revolution promises more by exploiting effects such as quantum entanglement and superposition – even if its potential can be hard to grasp. "It's not that there's something deeply wrong with quantum mechanics – it's that there's something deeply wrong with our ability to understand it," Phillips explained.

It all starts here The International Year of Quantum Science and Technology kicked off at UNESCO headquarters in Paris on 4 February.

Matin Durrani

Listen to Matin Durrani describe the IYQ opening ceremony

AUDIO

The benefits of quantum technology to society were echoed by leading Chinese quantum physicist Jian-Wei Pan of the University of Science and Technology of China in Hefei. "The second quantum revolution will likely provide another human leap in human civilization," said Pan, who was not at the meeting, in a pre-recorded video statement. "Sustainable funding from government and private sector is essential. Intensive and proactive international co-operation and exchange will undoubtedly accelerate the benefit of quantum information to all of humanity."

Leaders of the burgeoning quantum tech sector were in Paris too. Addressing the challenges and opportunities of scaling quantum technologies to practical use was a panel made up of Quantinuum chief executive Rajeeb Hazra, QuEra president Takuya Kitawawa, IBM's quantum-algorithms vice president Katie Pizzoalato, ID Quantique boss Grégoire Ribordy and Microsoft technical fellow Krysta Svore. Also present was Alexander Ling from the National University of Singapore, co-founder of two hi-tech start-ups.

"We cannot imagine what weird and wonderful things quantum mechanics will lead to but you can sure it'll be marvellous," said Celia Merzbacher, executive director of the Quantum Economic Development Consortium (QED-C), who chaired the session. All panellists stressed the need for quantum scientists and engineers if the industry is to succeed. Hazra also underlined that new products based on "quantum 2.0" technology had to be developed with – and to serve the needs of – users if they are to turn a profit.

The ethical challenges of quantum advancements were also examined in a special panel, as was the need for responsible quantum innovation to avoid a "digital divide" where quantum technology benefits some parts of society but not others. "Quantum science should elevate human dignity and human potential," said Diederick Croese, a lawyer and director of the Centre for Quantum and Society at Quantum Delta NL in the Netherlands.

The cultural impact of quantum science and technology was not forgotten in Paris either. Delegates flocked to an art installation created by Berlin-based artist and game developer Robin Baumgarten. Dubbed *Quantum Jungle*, it attempts to "visualize quantum physics in a playful yet scientifically accurate manner" by using an array of lights controlled by flickable, bendy metal door stops. Baumgarten claims it is a "mathematically accurate model of a quantum object", with the brightness of each ring being proportional to the chance of an object being there.

Matin Durrani is editor-in-chief of *Physics World*

Say hi to Quinnie – the official mascot of IYQ 2025

Whether it's the Olympics or the FIFA World Cup, all big global events need a cheeky, fun mascot. So welcome to Quinnie – the official mascot for the International Year of Quantum Science and Technology (IYQ) 2025. Unveiled at the launch of the IYQ at the headquarters of UNESCO in Paris on 4 February, Quinnie has been drawn by Jorge Cham, the creator of the long-running cartoon strip *PHD Comics*.

Quinnie was developed for UNESCO in a collaboration between Cham and *Physics* magazine, which is published by the American Physical Society (APS) – one of the founding partners of IYQ. "Quinnie represents a young generation approaching quantum science with passion, ingenuity and energy," says *Physics* editor Matteo Rini. "We imagine her effortlessly surfing on quantum-mechanical wave functions and playfully engaging with the knottiest quantum ideas, from entanglement to duality." Quinnie is set to appear in a series of animated cartoons that the APS will release throughout the year.

Jorge Cham

Meet the mascot Quinnie was unveiled at UNESCO headquarters in Paris on 4 February.

Astronomy

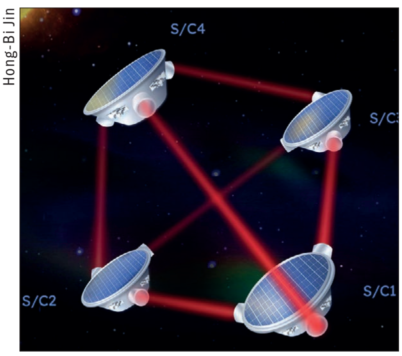
China researchers propose gravitational-wave observatory

Researchers in China have proposed a novel gravitational-wave observatory to search for cracks in Einstein's general theory of relativity. The Tetrahedron Constellation Gravitational Wave Observatory (TEGO) is designed to detect gravitational waves via four satellites that form a tetrahedral structure in space. If built, TEGO would offer significant advantages over designs consisting of a triangular configuration of three satellites.

Gravitational waves are distortions of space–time that occur when massive bodies, such as black holes, are accelerated. They were first detected in 2016 by researchers working on the Advanced Laser Interferometer Gravitational-wave Observatory (aLIGO) located in Hanford, Washington and Livingston, Louisiana. The current leading design for a space-based gravitational-wave detector is the Laser Interferometer Space Antenna (LISA). Led by the European Space Agency it is expected to launch in 2035 and cost about €1.5bn. LISA comprises three identical satellites in an equilateral triangle in space, with each side of the triangle being 2.5 million kilometres.

While ground-based instruments detect gravitational waves with a frequency from a few hertz to a kilohertz, a space-based mission could pick up gravitational waves with frequencies of 10^{-4}–10^{-1} Hz.

Hong-Bi Jin



Four's company An artist's impression of the Tetrahedron Constellation Gravitational Wave Observatory.

China has two proposals for a space-based gravitational-wave mission. Dubbed TAIJI and TianQin, they would be launched in the 2030s and, like LISA, consists of three spacecraft in a triangular formation each separated by 2.5 million km.

According to Hong-Bo Jin from the National Astronomical Observatories, Chinese Academy of Sciences, in Beijing, one disadvantage of a triangular array is that when the direction of gravitational-wave propagation is parallel to the plane of the triangle, it is more difficult to detect the source of the gravitational wave. A tetrahedral configuration could get around this problem, while Jin says that an additional benefit is the extra combinations of optical paths possible with six arms. This means it could be sensitive to six polarization modes of gravitational waves. Einstein's general theory of relativity predicts that gravitational waves have only two tensor polarization modes, so any detection of so-called vector or scalar polarization modes could signal new physics.

Yet such a design will come with costs. Given that the equipment for TEGO, including the telescopes and optical benches, is twice that of a triangular configuration, estimates for a tetrahedral set-up could also be double. While TEGO has a separate technical route than TAIJI, Jin says it can "refer" to some of its mature technologies. Given that many technologies still need to be demonstrated and developed, however, TEGO has no specific timeline for launch.

Italian gravitational-wave physicist Stefano Vitale, a former principal investigator of the LISA Pathfinder mission, told *Physics World* that "polyhedric" configurations of gravitational-wave detectors are "not new" and are much more difficult to implement than LISA. He adds that even aligning a three-satellite configuration such as LISA is "extremely challenging" and is something the aerospace community has never tried before. "TEGO opens a completely new chapter [and] cannot be considered as incremental relative to LISA," adds Vitale.

Michael Banks

Fusion

EAST smashes fusion record

A fusion tokamak in China has broken its previous fusion record of maintaining a steady-state plasma. Scientists working on the Experimental Advanced Superconducting Tokamak (EAST) announced in late January that they have produced a steady-state high-confinement plasma for 1066 seconds, breaking EAST's previous 2023 record of 403 seconds.

EAST is an experimental superconducting tokamak fusion device located in Hefei, China. Operated by the Institute of Plasma Physics (ASIPP) at the Hefei Institute of Physical Science, it began operations in 2006. It is the first tokamak to contain a deuterium plasma using superconducting niobium-titanium toroidal and poloidal magnets.

EAST has recently undergone several upgrades, notably with new plasma diagnostic tools and a doubling in the power of the plasma heating system. EAST is also acting as a testbed for the ITER experimental fusion reactor that is currently being built in Cadarache, France.

The EAST tokamak is able to maintain a plasma in the so-called "H-mode". This is the high-confinement regime that modern tokamaks, including ITER, employ. It occurs when the plasma undergoes intense heating by a neutral beam and results in a sudden improvement of plasma confinement by a factor of two.

In 2017 scientists at EAST broke the 100 seconds barrier for a steady-state H-mode plasma and then in 2023 achieved 403 seconds, a world record at the time. EAST officials say they have now almost tripled that time, delivering H-mode operation for 1066 seconds.

ASIPP director Song Yuntao notes that the new record is "monumental" and represents a "critical step" toward realizing a functional fusion reactor. "A fusion device must achieve stable operation at high efficiency for thousands of seconds to enable the self-sustaining circulation of plasma," he says, "which is essential for the continuous power generation of future fusion plants."

Michael Banks

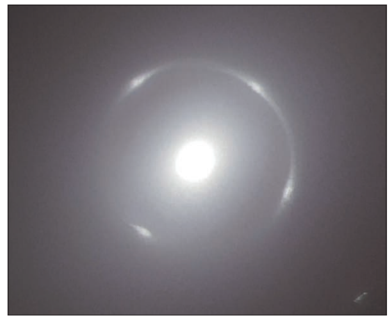
Space

Euclid mission spots Einstein ring

The European Space Agency (ESA) has released a spectacular image of an Einstein ring – a circle of light formed around a galaxy by gravitational lensing. Taken by the €1.4bn Euclid mission, the ring is a result of the gravitational effects of a galaxy located around 590 million light-years from Earth.

Euclid was launched in July 2023 and is currently located at Lagrange Point 2 – a gravitational balance point some 1.5 million kilometres beyond the Earth's orbit around the Sun. Euclid has a 1.2 m-diameter telescope, a camera and a spectrometer that it uses to plot a 3D map of the distribution of more than two billion galaxies. The images it takes are about four times as sharp as current ground-based telescopes.

Einstein's general theory of relativity predicts that light will bend around objects in space, so that they focus the light like a giant lens. This gravitational lensing effect is bigger for more massive objects and means we can sometimes see the light from distant galaxies that would otherwise be hidden. If the alignment is just right, the light from the distant source galaxy bends to form a spectacular ring around the foreground object. In this case, the mass of galaxy NGC 6505 is bending and magnifying the light from a more distant galaxy, which is about 4.42 billion light-years away, into a ring.



Spectacular circle The ring is due to the gravitational effects of a galaxy located around 590 million light-years from Earth.

Euclid's first science results were released in May 2024, following its first shots of the cosmos in November 2023. Hints of the ring were first spotted in September 2023 when Euclid was being tested. Studying such rings can also shed light on dark energy and dark matter.

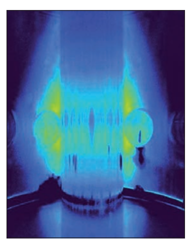
Michael Banks

Fusion

SMART spherical tokamak reaches first plasma

A novel fusion device based at the University of Seville in Spain has achieved its first plasma. The SMall Aspect Ratio Tokamak (SMART) is a spherical tokamak that can operate with a "negative triangularity" – the first such device to do so. Work performed on the machine could be useful when designing compact spherical tokamak power plants.

SMART has been constructed by the university's Plasma Science and Fusion Technology Laboratory. With a vessel dimension of 1.6 × 1.6 m, SMART has a 30 cm diameter solenoid wrapped around 12 toroidal field coils while eight poloidal field coils are used to shape the plasma. Triangularity refers to the shape of the plasma relative to the tokamak. The cross section of the plasma in a tokamak is typically shaped like a "D". When the straight part of the D faces the centre of the tokamak, it is said to have positive triangularity. When the curved part of the plasma faces the centre, however, the plasma has negative triangularity.



Hot stuff The first plasma at the SMall Aspect Ratio Tokamak at the University of Seville.

It is thought that negative triangularity configurations are better at suppressing plasma instabilities that expel particles and energy from the plasma, helping to prevent damage to the tokamak wall. Last year, researchers at the university began to prepare the tokamak's inner walls for a high-pressure plasma by heating argon gas with microwaves. When those tests were successful, engineers then worked toward producing the first plasma. "This is an important achievement as we are now entering the operational phase," notes SMART principal investigator Manuel García Muñoz.

Michael Banks

Research updates

New quantum particles proposed

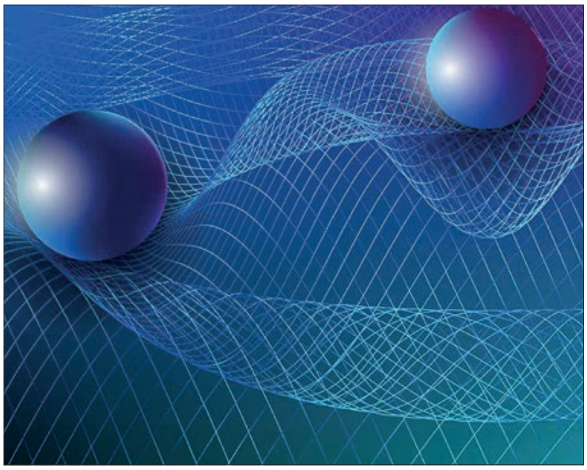
So-called "paraparticles" would be fundamentally different from bosons and fermions and could be created using ultracold atoms, as **Andrey Feldman** explains

Two theoretical physicists have identified a new class of quasiparticle called the "paraparticle". Their calculations suggest that paraparticles exhibit quantum properties that are fundamentally different from those of familiar bosons and fermions such as photons and electrons, respectively (*Nature* **637** 314).

In quantum mechanics, the behaviour of particles and quasiparticles – particle-like collective excitation of a system – is probabilistic in nature and is described by mathematical entities known as wavefunctions. These govern the likelihood of finding a particle in a particular state as defined by properties like position, velocity and spin. The exchange statistics of a specific type of particle dictates how its wavefunction behaves when two identical particles swap places.

For bosons such as photons, the wavefunction remains unchanged when particles are exchanged. Many bosons can therefore occupy the same quantum state, enabling phenomena like lasers and superfluidity. In contrast, when fermions such as electrons are exchanged, the sign of the wavefunction flips from positive to negative or vice versa – preventing fermions from occupying the same quantum state. This underpins the Pauli exclusion principle and results in the electronic structure of atoms and the nature of the periodic table.

Until now, physicists believed that these two types of particle statistics – bosonic and fermionic – were the only possibilities in 3D space. This is the result of fundamental principles like locality, which states that events occurring at one point in space cannot instantaneously influence events at a distant location. Yet work by Kaden Hazzard at Rice University in the US and his former graduate student Zhiyuan Wang, now at the Max Planck Institute of Quantum Optics in Germany, overturns the notion that 3D systems are limited to bosons and fermions. They have shown that new types of particle statistics, called parastatistics, can exist without violating locality. "Our main finding is that it is possible for particles to have exchange statistics different from those of fermions or bosons, while still satisfying the important physical principles of locality and causality," Hazzard explains.


Shutterstock/Evgenia-Fux

Seeing is believing Zhiyuan Wang and Kaden Hazzard believe that so-called "paraparticles" could be spotted in trapped ultracold atoms.

Hidden properties

The key insight in their theory lies in the concept of hidden internal characteristics. Beyond familiar properties like position and spin, paraparticles require additional internal parameters that enable more complex wavefunction behaviour. This hidden information allows paraparticles to exhibit exchange statistics that go beyond the binary distinction of bosons and fermions. Paraparticles exhibit phenomena that resemble – but are distinct from – fermionic and bosonic behaviours. For example, while fermions cannot occupy the same quantum state, up to two paraparticles could be allowed to coexist in the same point in space. This behaviour strikes a balance between the exclusivity of fermions and the clustering tendency of bosons.

While no elementary particles are known to exhibit paraparticle behaviour, the researchers believe that paraparticles might manifest as quasiparticles in engineered quantum systems or certain materials. A familiar example is the hole created in a semiconductor when a valence-band electron is excited to the conduction band. The vacancy (or hole) left in the valence band behaves as a positively-charged particle that can travel through the semiconductor lattice.

Experimental systems of ultracold atoms created by collaborators of the duo could be another place to look for the exotic particles. "We are working to see if we can detect paraparticles there," says Wang. In ultracold atom experiments, lasers and magnetic fields are used to trap and manipulate atoms at temperatures near absolute zero. Under these conditions, atoms can mimic the behaviour of more exotic particles. The team hopes that similar set-ups could be used to observe paraparticle-like behaviour in higher-dimensional systems, such as 3D space. However, further theoretical advances are needed before such experiments can be designed.

The discovery of paraparticles could have far-reaching implications for physics and technology. Fermionic and bosonic statistics have already shaped our understanding of phenomena ranging from the stability of neutron stars to the behaviour of superconductors. Paraparticles could similarly unlock new insights into the quantum world. "Fermionic statistics underlie why some systems are metals and others are insulators, as well as the structure of the periodic table," Hazzard explains. "Bose-Einstein condensation [of bosons] is responsible for phenomena such as superfluidity. We can expect a similar variety of phenomena from paraparticles, and it will be exciting to see what these are."

Researchers believe that paraparticles might manifest as quasiparticles in engineered quantum systems or certain materials

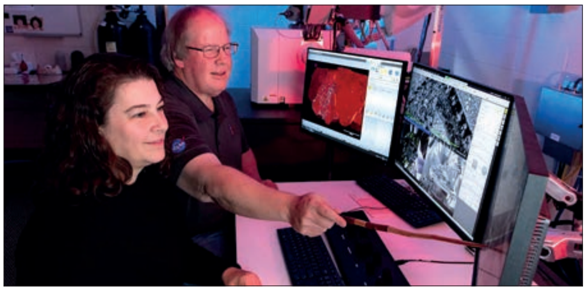
Space

Building blocks of life seen in samples from the asteroid Bennu

A sample of asteroid dirt brought back to Earth by NASA's OSIRIS-REx mission contains amino acids, the nucleobases of RNA and DNA as well as brines that could have facilitated the formation of organic molecules. The finding bolsters the hypothesis that asteroids like Bennu could have delivered the raw ingredients to Earth prior to the emergence of life (*Nature* **637** 1072 and *Nat. Astron.* doi:10.1038/s41550-024-02472-9).

Bennu is 565 m across at its widest point and was once part of a much larger parent body, possibly 100 km in diameter, that was smashed apart in a collision in the Asteroid Belt between 730 million and 1.55 billion years ago. In 2023 OSIRIS-REx collected about 120 g of material from Bennu, which was returned to Earth in 2023. Researchers have now analysed these samples and identified a diverse range of salt minerals, including sodium-bearing phosphates and carbonates that formed brines when liquid water on Bennu's parent body either evaporated or froze.

The liquid water would have been present on Bennu's parent during the dawn of the Solar System, in the first few million years after the planets began to form. Heat generated by the radioactive decay of aluminium-26 would have kept pockets of water liquid deep inside Bennu's parent body. The brines that this liquid water bequeathed would have played a role in kickstarting organic chemistry.


James Di Loreto, Smithsonian

Stuff of life Tim McCoy (right), curator of meteorites at the Smithsonian's National Museum of Natural History, and research geologist Cari Corrigan and colleagues have discovered that Bennu contains a diverse range of salt minerals.

Tim McCoy of the Smithsonian's National Museum of Natural History says that brines produce the minerals that serve as templates for organic molecules. "As an example, brines precipitate phosphates that can serve as a template on which sugars needed for life are formed," he says. The phosphate is like a pegboard with holes, and atoms can use those spaces to arrange themselves into sugar molecules. The organic molecules that have formed on the minerals are then released back into the brine, where they can combine with other organic molecules to form more complex compounds.

A separate study led by Dan Glavin and Jason Dworkin of NASA's Goddard Space Flight Center, focused on the detection of 14 of the 20 amino acids used by life to build proteins, deepening the mystery of why life only uses "left-handed" amino acids. Lacking rotational symmetry, amino acids can randomly be either left- or right-handed, a property known as chirality. But all life on Earth uses left-handed amino acids and one hypothesis was that due to some quirk, amino acids that formed in space and were brought to Earth in impacts had a bias for being left-handed. This possibility now looks unlikely after Glavin and Dworkin's team discovered that the amino acids in the Bennu sample are a mix of left- and right-handed. "For now, why life turned left on Earth remains a mystery," says Glavin.

Keith Cooper

Particle physics

Antimatter partner of hyperhelium-4 is spotted at CERN

Researchers in the ALICE collaboration at CERN have found the first evidence for antihyperhelium-4 – an antimatter hypernucleus that is a heavier version of antihelium-4. The antihyperhelium-4 was created by smashing lead nuclei together at CERN's Large Hadron Collider (LHC) (arXiv: 2410.17769, submitted to *Physical Review Letters*).

Hypernuclei are rare, short-lived atomic nuclei made up of protons, neutrons, and at least one hyperon, which is any baryon containing one or more strange quarks, but no charm, bottom, or top quarks. Hypernuclei and their antimatter counterparts can be formed within a quark–gluon plasma (QGP), which is created when heavy ions such as lead collide at high energies. A QGP is an extreme state of matter that also existed in the first millionth of a second following the Big Bang.


CERN/ J Ditzel with AI-assistance

Smashing result Antihyperhelium-4 – a bound state of two antiprotons, an antineutron and an antilambda – has been created in lead–lead collisions at CERN.

Just a few hundred picoseconds after being formed in collisions, antihypernuclei will decay via the weak force – creating two or more distinctive decay products that can be detected. The first antihypernucleus to be observed was a form of antihyperhydrogen called antihypertriton, which contains an antiproton, an antineutron and an antilambda hyperon. It was discovered in 2010 by the STAR Collaboration, who smashed together gold nuclei at Brookhaven National Laboratory's Relativistic Heavy Ion Collider. Then in 2024, the STAR Collaboration reported the first observations of the decay products of antihyperhydrogen-4, which contains one more antineutron than antihypertriton.

Now, ALICE physicists have analysed data taken at the LHC in 2018 – where lead ions were collided at 5 TeV. They identified the same signature of antihyperhydrogen-4 detected by the STAR Collaboration but also found evidence for antihyperhelium-4. It contains two antiprotons, an antineutron and an antilambda baryon (containing three antiquarks – up, down and strange). It decays almost instantly into an antihelium-3 nucleus, an antiproton, and a charged pion, which is a meson comprising a quark–antiquark pair.

While the observation has a statistical significance of 3.5σ – below the 5σ level that is generally accepted as a discovery – it is in line with the Standard Model of particle physics. The detection therefore helps constrain theories beyond the Standard Model that try to explain why the universe contains much more matter than antimatter.

Sam Jarman

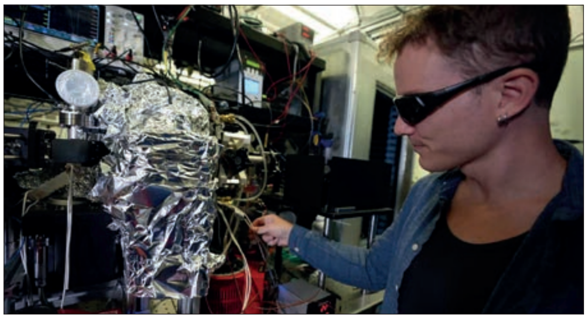
Measurement and instrumentation

Thermometer uses Rydberg atoms to make measurements

A new way to measure the temperatures of objects by studying the effect of their black-body radiation on Rydberg atoms has been demonstrated by researchers at the US National Institute of Standards and Technology (NIST). The system, which provides a direct, calibration-free measure of temperature has a systematic temperature uncertainty of around 1 part in 2000 (*Phys. Rev. Research* 7 L012020).

The black-body temperature of an object is defined by the spectrum of the photons it emits. In the laboratory and in everyday life, however, temperature is usually measured by comparison to a reference. This latest work offers a more direct way of determining temperature and involves measuring the black-body radiation emitted by an object directly, using atoms as a reference standard. Such a sensor does not need calibration because quantum mechanics dictates that every atom of the same type is identical.

Rydberg atoms have electrons promoted to highly excited states – making the atoms much larger, less tightly bound and more sensitive to external perturbations. Central to the new apparatus is a magneto-optical trap inside a vacuum chamber containing a pure rubidium vapour. Every 300 ms, the researchers load a new packet of rubidium atoms into the trap, cool them to around 1 mK and excite them from the 5S energy level to the 32S Rydberg state using lasers.



R Jacobson/NIST

Feeling the heat By monitoring how giant Rydberg atoms interact with heat in their environment, Noah Schlossberger and colleagues have measured temperature with remarkable accuracy.

They then allow them to absorb black-body radiation from the surroundings for around 100 μs, causing some of the 32S atoms to change state. Finally, they apply a strong, ramped electric field, ionizing the atoms. "The higher energy states get ripped off easier than the lower energy states, so the electrons that were in each state arrive at the detector at a different time. That's how we get this readout that tells us the population in each of the states," explains NIST's Noah Schlossberger. The researchers used this ratio to infer the spectrum of the black-body radiation absorbed by the atoms and, therefore, the temperature of the black body itself.

The researchers calculated the fractional systematic uncertainty of their measurement as 0.006, which corresponds to around 2 K at room temperature. Schlossberger concedes that this sounds relatively unimpressive compared to many commercial thermometers, but he notes that their thermometer measures absolute temperature, not relative temperature. One application of their system, the researchers say, could lie in optical clocks, where frequency shifts due to thermal background noise are a key source of uncertainty.

Tim Wogan

Environment

Filter inspired by deep-sea sponge cleans up oil spills

Researchers from Harbin Institute of Technology in China have developed a new approach to oil clean-up that takes inspiration from the deep-sea glass sponge *E. aspergillum*. By mimicking the skeletal architecture and filter feeding patterns of the sponge, they have created a filter that can clean up oil spills under turbulent flow (*Nat. Commun.* **16** 209).

Oil spills can pollute large volumes of surrounding water – thousands of times greater than the spill itself – causing long-term economic, environmental, social and ecological damage. Effective methods for *in situ* capture of spilled oil are essential to minimize such disasters. Yet many oil spill clean-up technologies exhibit poor hydrodynamic stability under complex flow conditions, which leads to poor oil-capture efficiency.

To address this, the researchers turned to *E. aspergillum*. The sponge lives at depths of up to 1000 m in the Pacific Ocean and has an excellent ability to filter feed with a high effectiveness, selectivity and robustness. What's more, the food particles it ingests share similarities with oil droplets. "The *E. aspergillum* has a multilayered skeleton–flagellum architecture, which creates 3D streamlines with frequent collision, deflection, convergence and separation," notes lead author Shijie You. "This can dissipate macro-scale turbulent flows into small-scale swirling flow patterns called low-speed vortical flows within the body cavity, which reduces hydrodynamic load and enhances interfacial mass transfer."

For the sponges, this allows them to maintain a high mechanical stability while absorbing nutrients from the water. The same principles can be applied to synthetic materials for cleaning up oil spills. The researchers designed a vortex-anchored filter (VAF) – a synthetic form of the sponge's architecture – that according to You "is capable of transferring kinematic energy from an external water flow into multiple small-scale low-speed vortical flows within the body cavity to enhance hydrodynamic stability and oil capture efficiency".

NOAA Okeanos Explorer Program, Gulf of Mexico 2012 Expedition

Going with the flow Researchers from Harbin Institute of Technology have designed a vortex-anchored filter based on the structure of a deep-sea glass sponge known as Venus' flower basket.

The tubular outer skeleton of the VAF comprises a helical ridge and chequerboard lattice. It is this skeleton that creates a slow vortex field inside the cavity and enables mass transfer of oil during the filtering process. Once the oil has been forced into the filter, the internal area – composed of flagellum-shaped adsorbent materials – provides a large interfacial area for oil adsorption. When put into practice, the VAF was able to capture more than 97% of floating, underwater and emulsified oils, even under strong turbulent flows.

Liam Critchley

Optics

Flexible tactile sensor reads braille in real time

Researchers in China have created a tactile braille recognition system that can accurately read braille in real time. The team says that the sensor can advance intelligent braille recognition with further potential in smart medical care and intelligent robotics (*Optics Express* **33** 2512).

Learning to read braille can be challenging, which has prompted researchers to create automated braille recognition technologies. They often involve imaging the dots and using algorithms to extract the required information. This visual method, however, struggles with the small size of braille characters and can be hampered by differing light levels. As for tactile sensors, they are not sensitive enough, with small pressure variations leading to incorrect readings.

At the core of the latest braille sensor is an optical fibre ring resonator (FRR) – a resonant cavity made from a loop of fibre containing circulating laser light. Zhuo Wang from Beijing Normal University and colleagues embedded an optical fibre in a flexible polymer and connected it into the FRR ring. Three small polymer protrusions on top of the sensor act as probes to transfer the applied pressure to the optical fibre. Spaced 2.5 mm apart to align with the dot spacing, each protrusion responds to the pressure from one of the three braille dots (or absence of a dot) in a vertical column.

Zhuo Wang, Beijing Normal University in China

Reading record The tactile braille sensor could enable the creation of smart readers that convert braille to speech or text.

As the sensor is scanned over the braille surface, the pressure exerted by the raised dots slightly changes the length and refractive index of the fibre, causing tiny shifts in the frequency of the light travelling through the FRR. The device employs a technique called Pound-Drever-Hall demodulation to "lock" onto these shifts, amplify them and convert them into readable data.

The eight possible configurations of three dots generate eight distinct pressure signals, with each braille character defined by two pressure outputs (one per column). Each protrusion has a slightly different hardness level, enabling the sensor to differentiate pressures from each dot. Rather than measuring each dot individually, the sensor reads the overall pressure signal and instantly determines the combination of dots and the character they correspond to.

To assess its ability to read braille dots, the team used the sensor to read eight different arrangements of three dots. Using a multilayer perceptron (MLP) neural network, the system effectively distinguished the eight different tactile pressures with a classification accuracy of 98.57%. Next, the researchers trained a long short-term memory (LSTM) neural network to classify signals generated by five English words and used the MLP-LSTM model to read short sentences, either sliding the sensor manually or scanning it electronically to maintain a consistent contact force. In both cases, the sensor accurately recognized the phrases.

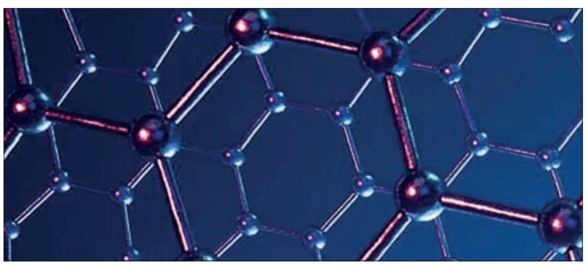
Tami Freeman

Condensed-matter physics

Anomalous Hall crystal is made from twisted graphene

An international team of physicists has identified an anomalous Hall crystal, where the quantum Hall effect emerges from an in-built electronic structure rather than an applied magnetic field. Led by Josh Folk at the University of British Columbia, the group observed the effect in a stack of bilayer and trilayer graphene that is twisted at a specific angle (*Nature* 637 1084).

In a classical electrical conductor, the Hall voltage and its associated resistance appear perpendicular both to the direction of an applied electrical current and an applied magnetic field. A similar effect is also seen in 2D electron systems that have been cooled to ultra-low temperatures. But in this case, the Hall resistance becomes quantized in discrete steps. This quantum Hall effect can emerge in electronic crystals, known as Wigner crystals. These are arrays of electrons that are held in place by their mutual repulsion. Some researchers wondered if a similar effect occurs in topological electronic crystals (TECs), but without an applied magnetic field. This is called the "quantum anomalous Hall effect".



Shutterstock/Rost9

Anomalous effect A topological electronic crystal has been observed in a multilayer twisted graphene system.

Folk and colleagues investigated two or more flakes of graphene that are stacked on top of each other and twisted relative to each other at different angles. In most cases, the twisted structures had moiré patterns that were very disordered. Moiré patterns occur when two lattices are overlaid and rotated relative to each other. Yet out of tens of thousands of permutations of twisted graphene stacks, one structure appeared to be different and according to Folk had "exceptionally low levels of disorder".

As they studied this highly ordered structure, the team found that its moiré pattern helped to modulate the system's electronic properties, allowing a TEC to emerge. "We observed the first clear example of a TEC in a device made up of bilayer graphene stacked atop trilayer graphene with a small, 1.5° twist," Folk explains. "The underlying topology of the electronic system, combined with strong electron–electron interactions, provide the essential ingredients for the crystal formation." Folk adds that further work could show that the TEC hosts new kinds of particles.

Sam Jarman

CAEN Electronic Instrumentation

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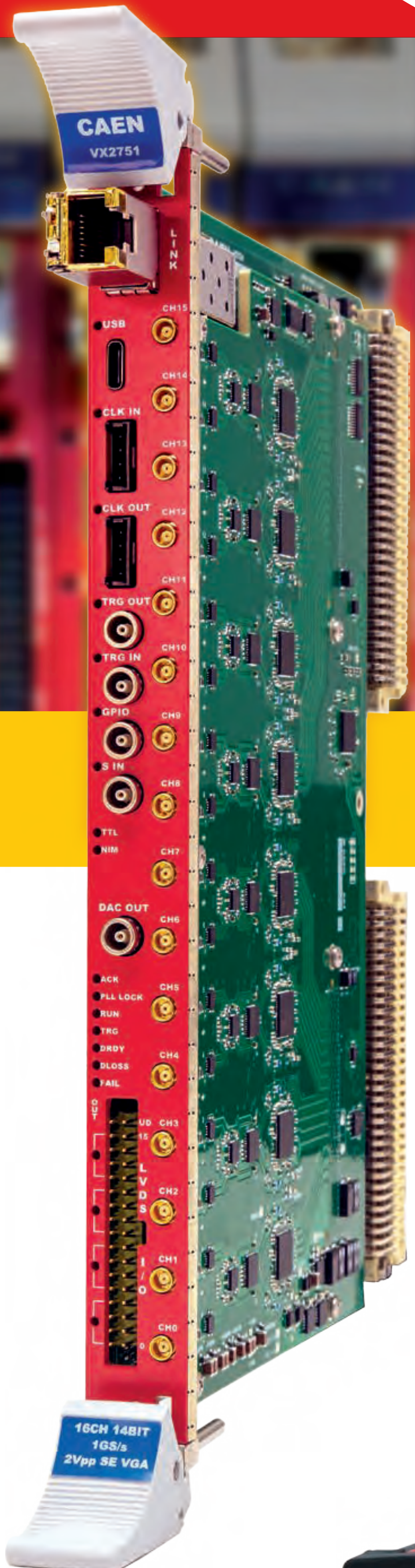

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Times of turmoil

US science faces unprecedented difficulties with Trump re-elected as US president

As physicists, we like to think that physics and politics are – indeed, ought to be – unconnected. And a lot of the time, that's true. Certainly, the value of the magnetic moment of the muon (see pp30–34) or the behaviour of superconductors in a fusion reactor (see pp40–44) have nothing do with where anyone sits on the political spectrum. It's subjects like climate change, evolution and medical research that tend to get caught in the political firing line.

United States government work

But scientists of all disciplines in the US are now feeling the impact of politics at first hand (pp3–4). The new administration of Donald Trump has ordered the National Institutes of Health to slash the "indirect" costs of its research projects, threatening medical science and putting the universities that support it at risk. The National Science Foundation, which funds much of US physics, is under fire too, with staff sacked and grant funding paused.

Trump has also signed a flurry of executive orders that, among other things, ban federal government initiatives to boost diversity, equity and inclusion (DEI) and instruct government departments to "combat illegal private-sector DEI preferences, mandates, policies, programs and activities". Some organizations are already abandoning such efforts for fear of these future repercussions.

What's troubling for physics is that attacks on diversity initiatives fall most heavily on people from under-represented groups, who are more likely to quit physics or not go into it in the first place. That's bad news for our subject as a whole because we know that a diverse community brings in smart ideas, new approaches and clever thinking (see pp37–39).

The speed of changes in the US is bewildering too. Yes, the proportion from federal grants for indirect costs might be too high, but making dramatic changes at short notice, with no consultation is bizarre. There's also a danger that universities will try to recoup lost money by raising tuition fees, which will hit poorer students the hardest.

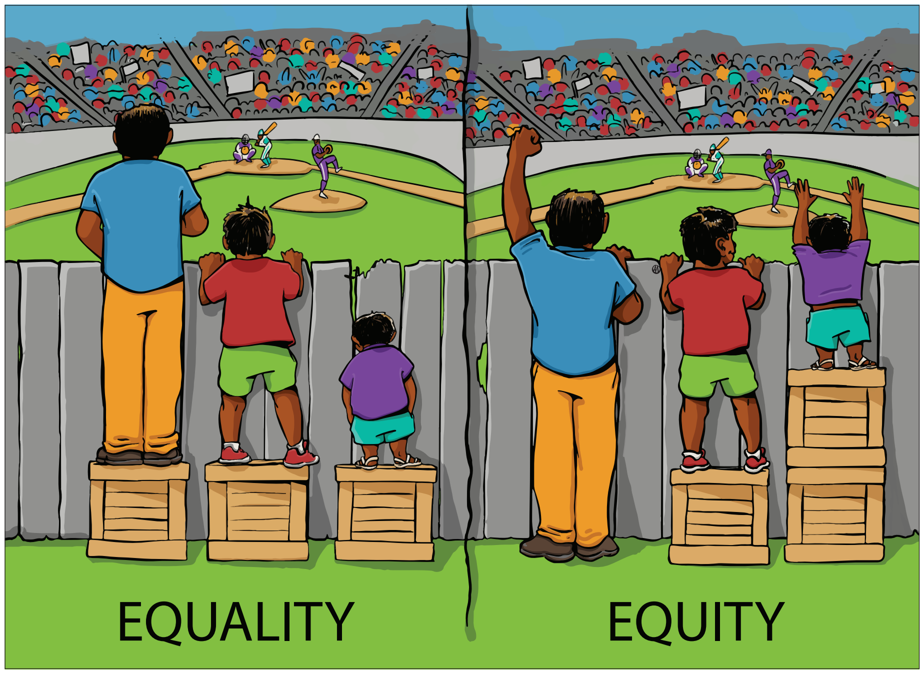
US science has long been a beacon of excellence. But many scientists are fearful of speaking out, scared that they or their institutions will pay a price for any opposition. So far, it's been left to senior leaders such as James Gates – a theoretical physicist at the University of Maryland – to warn of the dangers in store. "My country," he said last month, "is in for a 50-year period of a new dark ages."

I sincerely hope he's wrong.

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

From equality to equity

Nicola Wilkin and **Chris Millward** consider how to think about equity in the "hyper-meritocratic" world of physics



Interaction Institute for Social Change/Artist: Angus Maguire

Equal footing Physicists must examine their culture, support under-represented and marginalized voices and tackle unacceptable behaviour to ensure greater inclusivity.

If you have worked in a university, research institute or business during the past two decades you will be familiar with the term equality, diversity and inclusion (EDI). There is likely to be an EDI strategy that includes measures and targets to nurture a workforce that looks more like the wider population and a culture in which everyone can thrive. You may find a reasoned business case for EDI, which extends beyond the organization's legal obligations, to reflect and understand the people that you work with.

Look more closely and it is possible that the "E" in EDI is not actually equality, but rather equity. Equity is increasingly being used as a more active commitment, not least by the Institute of Physics, which publishes *Physics World*. How, though, is equity different to equality? What is causing this change of language and will it make any difference in practice?

These questions have become more pressing as discussions around equality and equity have become entwined in the culture wars. This is a particularly live issue in the US as Donald Trump's second term as US president has begun to withdraw funding from EDI activities. But it has also influenced science policy in the UK.

The distinction between equality and equity is often illustrated by a cartoon published in 2016 by the UK artist Angus Maguire (above). It shows a fence and people of variable height gaining an equal view of a baseball match thanks to different numbers of crates that they stand on. This has itself, however, resulted in arguments about other factors such as the conditions necessary to watch the game in the stadium, or indeed even join in. That requires consideration about how the teams and the stadium could adapt to the needs of all potential participants, but also how these changes might affect the experience of others involved.

In terms of education, the Organization for Economic Co-operation and Development (OECD) states that equity "does not mean that all students obtain equal education outcomes, but rather that differences in students' outcomes are unrelated to their background or to economic and social circumstances over which the students have no control". This is an admirable goal, but there are questions about how to achieve it.

In OECD member countries, freedom of choice and competition yield social inequalities that flow through to education and careers. This means that governments are continually balancing the benefits of inspiring and rewarding individuals alongside concerns about group injustice.

In 2024 we hosted a multidisciplinary workshop about equity in science, and especially physics. Held at the University of Birmingham, it brought together physicists at different career stages with social scientists and people who had worked on science and education in government, charities and learned societies. At the event, social scientists told us that equality is commonly conceived as a basic right to be treated equally and not discriminated against, regardless of personal characteristics. This right provides a platform for "equality of opportunity" whereby barriers are removed so talent and effort can be rewarded.

In the UK, the promotion of equality of opportunity is enshrined within the country's Equality Act 2010 and underpins current EDI work in physics. This includes measures to promote physics to young people in deprived areas, and to women and ethnic minorities, as well as mentoring and additional academic and financial support through all stages of education and careers. It extends to re-shaping the content and promotion of physics courses in universities so they are more appealing and responsive to a wider constituency. In many organizations, there is also training for managers to combat discrimination and bias, whether conscious or not.

Actions like these have helped to improve participation and progression across physics education and careers, but there is still significant under-representation and marginalization due to gender, ethnicity and social background. This is not unusual in open and competitive societies where the effects of promoting equal opportunities are often outweighed by the resources and connections of people with characteristics that are highly represented. Talent and effort are crucial in "high-performance" sectors such as academia and industry, but they are not the only factors influencing success.

Physicists at the meeting told us that they are motivated by intellectual curiosity, fascination with the natural world and love for their subject. Yet there is also, in physics, a culture of "genius" and competition, in which confidence is crucial. Facilities and working conditions, which often involve short-term contracts and international mobility, are difficult to balance alongside other life commitments. Although inequalities and exclusions are recognized, they are often ascribed to broader social factors or the inherent requirements of research. As a result, physicists tend not to accept responsibility for inequities within the discipline.

Many physicists want merit to be a reflection of talent and effort. But we identified that physics has a culture of "hyper-meritocracy" where being correct counts more than respecting others. Across the community, some believe in positive action beyond the removal of discrimination, but others can be actively hostile to any measure associated with EDI. This is a challenging environment for any young researcher and we heard distressing stories of isolation from women and colleagues who had hidden disabilities or those who were the first in their family to go to university.

The experience, positive or not, when joining a research group as a postgraduate or postdoctoral researcher is often linked with the personality of leaders. Peer groups and networks have helped many physicists through this period of their career, but it is also where the culture in a research group or department can drive some to the margins and ultimately out of the profession. In environments like this, equal opportunities have proved insufficient to advance diversity, let alone inclusion.

Culture change

Organizations that have replaced equality with equity want to signal a commitment not just to equal treatment, but also more equitable outcomes. However, those who have worked in government told us that some people become disengaged, thinking such efforts can only be achieved by reducing standards and threatening cultures they value. Given that physics needs technical proficiency and associated resources and infrastructure, it is not a discipline where equity can mean an equal distribution of positions and resources.

Physics can, though, counter the influence of wider inequalities by helping colleagues who are under-represented to gain the attributes, experiences and connections that are needed to compete successfully for doctoral studentships, research contracts and academic positions. It can also face up to its cultural problems, so colleagues who are minoritized feel less marginalized and they are ultimately recognized for their efforts and contributions.

This will require physicists giving more prominence to marginalized voices as well as critically and honestly examining their culture and tackling unacceptable behaviour. We believe we can achieve this by collaborating with our social science colleagues. That includes gathering and interpreting qualitative data, so there is shared understanding of problems, as well as designing strategies with people who are most affected, so that everyone has a stake in success.

If this happens, we can look forward to a physics community that genuinely practices equity, rather than espousing equality of opportunity.

● This article was based on conference contributions from Saher Ahmed, Clara Barker, Fern Elsdon-Baker, Diane Grayson, Pauline Leonard, Kimberley Scott, David Sweeney and Marika Taylor.


Nicola Wilkin is a professor of physics and academic director of digital education and equity at the University of Birmingham, UK, and **Chris Millward** is professor of practice in education policy, also at Birmingham

Critical Point Rebellious thoughts

Freeman Dyson once saw scientists as rebels, fighting other academics who don't respect them. Robert P Crease says that scientists now have far more fearsome opponents

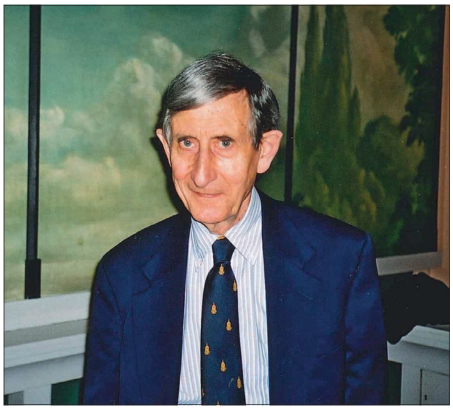
Three decades ago – in May 1995 – the British-born mathematical physicist Freeman Dyson published an article in the *New York Review of Books*. Entitled "The scientist as rebel", it described how all scientists have one thing in common. No matter what their background or era, they are rebelling against the restrictions imposed by the culture in which they live.

"For the great Arab mathematician and astronomer Omar Khayyam, science was a rebellion against the intellectual constraints of Islam," Dyson wrote. Leading Indian physicists in the 20th century, he added, were rebelling against their British colonial rulers and the "fatalistic ethic of Hinduism". Even Dyson traced his interest in science as an act of rebellion against the drudgery of compulsory Latin and football at school.

"Science is an alliance of free spirits in all cultures rebelling against the local tyranny that each culture imposes," he wrote. Through those acts of rebellion, scientists expose "oppressive and misguided conceptions of the world". The discovery of evolution and of DNA changed our sense of what it means to be human, he said, while black holes and Gödel's theorem gave us new views of the universe and the nature of mathematics.

But Dyson feared that this view of science was being occluded. Writing in the 1990s, which was a time of furious academic debate about the "social construction of science", he feared that science's liberating role was becoming hidden by a cabal of sociologists and philosophers who viewed scientists as like any other humans, governed by social, psychological and political motives. Dyson didn't disagree with that view, but underlined that nature is the ultimate arbiter of what's important.

One wonders what Dyson, who died in 2020, would make of current events were he alive today. It's no longer just a small band of academics disputing science. Its opponents also include powerful and highly placed politicians, who are tarring scientists and scientific findings for lacking objectivity and being politically motivated. Science, they say, is politics by other means. They then use that charge to justify ignoring or openly rejecting scientific findings when creating regulations and making decisions.



Free spirit What would the ever-rebellious Freeman Dyson have made of today's opponents of science?

Thousands of researchers, for instance, contribute to efforts by the United Nations Intergovernmental Panel on Climate Change (IPCC) to measure the impact and consequences of the rising amounts of carbon dioxide in the atmosphere. Yet US President Donald Trump –speaking after Hurricane Helene left a trail of destruction across the south-east US last year – called climate change "one of the great scams". Meanwhile, US chief justice John Roberts once rejected using mathematics to quantify the partisan effects of gerrymandering, calling it "sociological gobbledygook".

These attitudes are not only anti-science but also undermine democracy by sidelining experts and dissenting voices, curtailing real debate, scapegoating and harming citizens. A worrying precedent for how things may play out in the Trump administration occurred in 2012 when North Carolina's legislators passed House Bill 819. By prohibiting the use of models of sea-level rise to protect people living near the coast from flooding, the bill damaged the ability of state officials to protect its coastline, resources and citizens. It also prevented other officials from fulfilling their duty to advise and protect people against threats to life and property.

In the current superheated US political climate, many scientific findings are charged with being agenda-driven rather than the outcomes of checked and peer-reviewed investigations. In the first Trump administration, bills were introduced in the US Congress to stop politicians from using science produced by the Department of Energy in policies to avoid admitting the reality of climate change.

We can expect more anti-scientific efforts, if the first Trump administration is anything to go by. Dyson's rebel alliance, it seems, now faces not just posturing academics but a Galactic Empire.

The critical point

In his 1995 essay, Dyson described how scientists can be liberators by abstaining from political activity rather than militantly engaging in it. But how might he have seen them meeting this moment? Dyson would surely not see them turning away from their work to become politicians themselves. After all, it's abstaining from politics that empowers scientists to be "in rebellion against the restrictions" in the first place. But Dyson would also see them as aware that science is not the driving force in creating policies; political implementation of scientific findings ultimately depends on politicians appreciating the authority and independence of these findings.

One of Trump's most audacious "Presidential Actions", made in the first week of his presidency, was to define sex. The action makes a female "a person belonging, at conception, to the sex that produces the large reproductive cell" and a male "a person belonging, at conception, to the sex that produces the small reproductive cell". Trump ordered the government to use this "fundamental and incontrovertible reality" in all regulations.

An editorial in *Nature* (**563** 5) said that this "has no basis in science", while cynics, citing certain biological interpretations that all human zygotes and embryos are initially effectively female, gleefully insisted that the order makes all of us female, including the new US president. For me and other Americans, Trump's action restructures the world as it has been since *Genesis*.

Still, I imagine that Dyson would still see his rebels as hopeful, knowing that politicians don't have the last word on what they are doing. For, while politicians can create legislation, they cannot legislate creation.

Sometimes rebels have to be stoic.

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 Who are you at work?

It's often assumed that people will start their career as artisans before becoming architects and then artists. **Honor Powrie** believes, however, that all three roles are vital for any organization to succeed

Shutterstock/is1003

Take your pick Most people in work situations naturally adopt one of three different personas: artisan, architect and artist.

We tend to define ourselves by the subjects we studied, and I am no different. I originally did physics before going on to complete a PhD in aeronautical engineering, which has led to a lifelong career in aerospace.

However, it took me quite a few years before I realized that there is more than one route to an enjoyable and successful career. I used to think that a career began at the "coal face" – doing things you were trained for or had a specialist knowledge of – before managing projects then products or people as you progressed to loftier heights.

At some point, I began to realize that while companies often adopt this linear approach to career paths, not everyone is comfortable with it. In fact, I now think that many of us naturally fall into one of three fundamental roles: artisan, architect or artist. So which are you?

Artisans are people who focus on creating functional, practical and often decorative items using hands-on methods or skills. Their work emphasizes craftmanship, attention to detail and the quality of the finished product. For scientists and engineers, artisans are highly skilled people who apply their technical knowledge and know-how. Let's be honest: they are the ones who get the "real work" done. From programmers to machinists and assemblers, these are the people who create detailed designs and make or maintain a high-quality product.

Architects, on the other hand, combine vision with technical knowledge to create functional and effective solutions. Their work involves designing, planning and overseeing. They have a broader view of what's happening and may be responsible for delivering projects. They need to ensure tasks are appropriately prioritized and keep things on track and within budget.

Architects also help with guiding on best practice and resolving or unblocking issues. They are the people responsible for ensuring that the end result meets the needs of users and, where applicable, comply with regulations. Typically, this role involves running a project or team – think principal investigator, project manager, software architect or systems engineer.

Predominantly artisans are practical, architects are tactical and artists are strategic but there is an overlap between these qualities

As for artists, they are the people who have a big picture view of the world – they will not have eyes for the finer details. They are less constrained by a framework and are comfortable working with minimal formal guidance and definition. They have a vision of what will be needed for the future – whether that's new products and strategic goals or future skills and technology requirements.

Artists set the targets for how an organization, department or business needs to grow and they define strategies for how a business will develop its competitive edge. Artists are often leaders and chiefs.

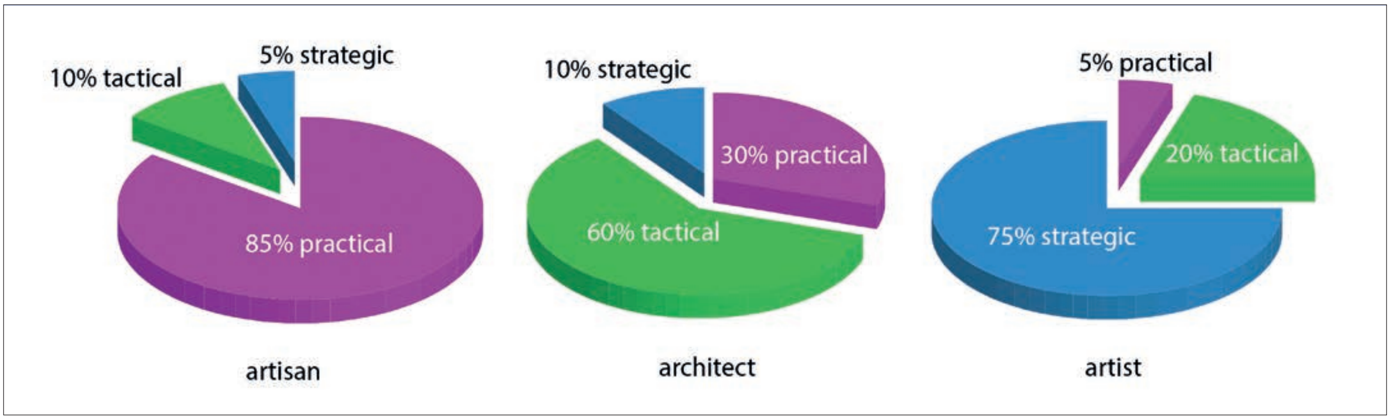
Typical behaviour

To see how these personas work in practice, imagine working for a power utility provider. If there's a power outage, the artisans will be the people who get the power back on by locating and fixing damaged power lines, repairing substations and so on. They are practical people who know how to make things work.

The architect will be organizing the repair teams, working out who goes to which location, and what to prioritize, ensuring that customers are kept happy and senior leaders are kept informed of progress. The artist, meanwhile, will be thinking about the future. How, for example, can utilities protect themselves better from storm damage and what new technologies or designs can be introduced to make the supply more resilient and minimize disruption?

Predominantly artisans are practical, architects are tactical and artists are strategic but there is an overlap between these qualities. Artisans, architects and artists differ in their goals and methods, but the boundaries between them are blurred. Based on my gut experience as a physicist in industry, I'd say the breakdown between different skills is roughly as shown in the figure over the page.

Now this breakdown is not hard and fast. To succeed in your career, you need to be creative, inventive and skilful – whatever your role. While working with your colleagues, you need to engage in common processes such as adhering to relevant standards, regulations and quality requirements to deliver quality solutions and products. But thinking of ourselves as artisans,



Varying values Artisans, architects and artists are practical, tactical and strategic in different proportions. The numbers shown here are based on the author's gut feeling after working in industry for more than 30 years.

architects or artists may explain why each of us is suited to a certain role.

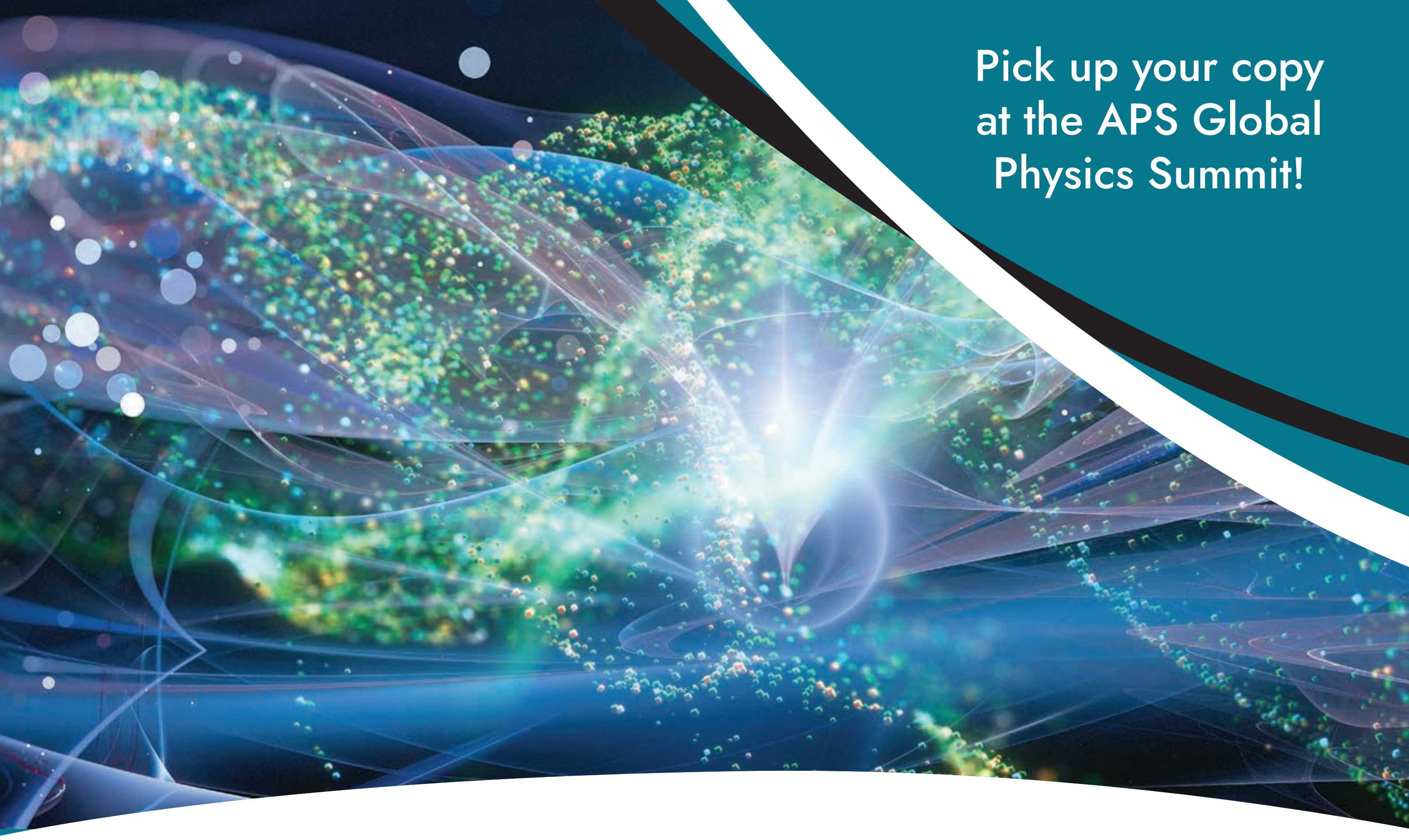
Know your strengths

Even though we all have something of the other personas in us, what's important is to know what your own core strength is. I used to believe that the only route for a successful career was to work through each of these personas by starting out as artisan, turning into an architect, and then ultimately becoming an artist. And to be fair, this is how many career paths are structured, which his why we're often encouraged to think this way.

However, I have worked with people who liked "hands on" work so much, that didn't want to move to a different role, even though it meant turning down a significant promotion. I also know others who have indeed moved between different personas, only to discover the new type of work did not suit them.

Trouble is, although it's usually possible to retrace steps, it's not always straightforward to do so. Quite why that should be the case is not entirely clear. It's certainly not because people are unwilling to accept a pay cut, but more because changing tack is seen as a retrograde step for both employees and their employers.

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



Feedback

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

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

Being wise about AI

In response to Clare Malone's feature article "Trust me? I'm an AI!" about the impact of artificial intelligence (AI) on science communication (December 2024 pp31–34).

Malone's article was informative and balanced, both extolling the virtues of AI and advocating caution. However, my apprehension goes much deeper and I am increasingly concerned at the speed at which AI is spreading. To my mind there is a direct parallel with the development of nuclear energy, when those fertile minds working on the Manhattan Project were horrified when they witnessed the first detonation of a nuclear bomb. Many of those sincere, dedicated folk were later devastated when they saw the results of their work in Japan, after control had been passed to politicians and the military.

As well as being concerned about the inherent deficiencies in AI itself, I worry about the sinister possibility of much darker places to which it may lead us in the hands of unscrupulous users. Stories are already emerging of trails of misery and devastation being left in its wake. Although AI could be a fantastic tool for the world, it could also do great harm.

Control of AI may already have passed into the hands of a few greedy, control-obsessed, faceless individuals, working from the shadows and having their wishes implemented by other greedy, ambitious disciples, operating openly and who are easily recognized, even trusted. There are even signs we may be moving towards a mandatory, cashless, fully digital world, with everyone's full data held in a central storage facility. The Doomsday Clock is already at 90 seconds to midnight – but how much closer would it get if AI also influenced its setting?

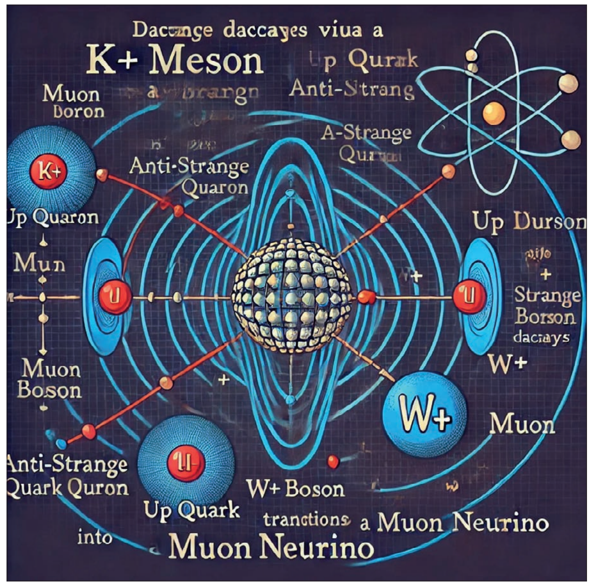
Peter Wright
London, UK

As a fourth-year undergraduate master's student, I have used ChatGPT (and other forms of AI) during the course of my degree and it's been cool to see things develop so much even during that time. I've found ChatGPT to be excellent at explaining topics; in fact, the more specific you are in your questions, the better it is. Even on the free version, it can take a PDF of a problem sheet or lecture notes as input, which is handy.

For me, where ChatGPT most often fails is in calculating the steps of a problem. It can show and explain exactly what must be done, but then – say – neglects a minus sign. Frustratingly, even when explaining the problem and having it "acknowledge" its mistake, it will continue to make the same error. Hardly surprising, of course, since ChatGPT obviously does not "know" any physics, but just predicts what may come next in an explanation.

In Malone's article, I particularly enjoyed the weird, anatomically incorrect picture of a rat created by an AI image generator, which appeared in a journal paper that was subsequently retracted. So I tried making my own AI image using the prompt "Can you draw me a Feynman diagram for a K+ meson decaying to muon and neutrino". Thinking this would be a fairly straightforward task for ChatGPT and that I'd save myself some time, the results left a lot to be desired (see image above).

Josh Saunders
University of Bristol, UK



Generated by ChatGPT

From 1996 to 2016, I wrote press releases about events organized by the London and South-East Branch of the Institute of Physics. When I started, it was still common to send items by snail mail, but as e-mail took over, I found it harder to get newspaper editors to take an interest in my work. I put this down to the fact that it costs almost nothing to send an e-mail, which led to a large increase in material being sent to newspapers.

Advances in technology, in other words, made science communication harder – not easier – and the danger is that AI will do so too by producing a similar explosion of material. What's more, I fear that AI, through machine learning, will work out what is newsworthy and twist things to make them so – just as human reporters do, only worse.

Alex McDowell
South Ruislip, UK

Cloudy thinking

In response to the feature article "Cloudy with a chance of warming" by Michael Allen, which examined how clouds affect the Earth's climate (January pp35–40).

Allen covered many impacts of clouds, but did not say anything about the contribution of aircraft to stratospheric cloud formation. We know, however, that certain altitudes and atmospheric conditions are predisposed to generate "contrails" brought on by energy input or pollution from aviation. Aircraft aerofoils all displace air downwards, generating a powerful trailing vortex. Sometimes the drop in air pressure in these vortices starts the formation of contrails, which spread out to cause still-larger cloud formations in the stratosphere.

What's more, today's turbofans, which emit carbon dioxide and aerosols associated with combustion as well as water vapour, contribute to the seeding of these high-level clouds. Although most aircraft in 20 years' time are likely to use hydrogen-powered fuel cells driving electric propulsion fans – and will therefore create less of today's type of pollution – they will still cause a massive increase in the daily injection of water vapour into the stratosphere.

Researchers have tried to mitigate the generation of contrails by making flight path changes. Flight planning can enable pilots to climb quickly through or avoid contrail sensitive zones to minimize stratospheric cloud formation. Sadly, this cloud generation can never be avoided completely, so our skies will still be crisscrossed with contrails far into the

future unless we make it mandatory that all intercontinental transport operate within earth low orbits.
John Budden
Bridport, UK

Bird brained in Helgoland

In response to Robert P Crease's feature about the upcoming meeting on Helgoland celebrating the centenary of quantum mechanics, pioneered on the island by Werner Heisenberg in 1925 (January pp24–29).

I spent a week on Helgoland in 1999 as a delegate at an international conference marking the centenary of bird ringing, which is my long-term hobby. According to my friend Franz Bairlein, who recently retired as director of the Institute of Avian Research in Wilhelmshaven, which manages bird observation and ringing activities on Helgoland, there is now a commemorative plaque on the island to Heisenberg (see photo, right).

Located on the top of the south side of the island, it was placed there in June 2000 by the Max Planck Institute for Physics, the Werner Heisenberg Institute and the German Physical Society to mark the 75th anniversary of Heisenberg's work. I do hope participants at the meeting this year are photographed next to it.
David Norman
Runcorn, UK

A photo in Crease's feature showed Werner Heisenberg and Erwin Schrödinger at the Nobel-prize ceremony in Stockholm in 1933. Standing between them was not King Gustav V, as stated in the caption, but in fact his eldest son – Crown Prince Gustav Adolf, later King Gustav VI Adolf.
Jonas Persson
Norwegian University of Science and Technology, Trondheim, Norway

Carbon conundrum

In response to a news story about the UK's £22bn carbon capture and storage plans (December 2024 pp10–11).

The article states that "globally there are around 45 commercial facilities that capture about 50 million tonnes of carbon annually, roughly 0.14% of emissions". But unless storage (which implies human

supervision) can be turned into disposal (with no supervision) – and/or we create a circular use for the captured carbon dioxide such as synthetic fuels – I fear our efforts will be futile.
Gareth Neighbour
Brackley, UK

Chadwick was right

In response to the feature "Proving Chadwick wrong" by Rosie de Laune and colleagues from the ISIS Muon and Neutron Source, which marked 40 years of neutron scattering at the lab (December 2024 pp26–30).

According to the article, Chadwick supposedly said: "I am afraid neutrons will not be of any use to anyone." However, it is hard to believe that Chadwick would have been so dismissive of a particle he had been chasing for so many years. The actual quote – that the discovery of the neutron "to humanity in general…would make no difference" – was most likely a journalistic invention. It appears in an article headlined "A new ray; Dr Chadwick's search for neutrons" in *The Times* of 29 February 1932.

Chadwick's opinion of the neutron's worth was probably that recorded by his friend, the distinguished science correspondent of the *Manchester Guardian*, J G Crowther. Having been invited by Chadwick to hear him announce the neutron's discovery, Crowther reported in that paper on 27 February 1932 that practical applications of the neutron "would doubtless be discovered before long".

If Chadwick were wrong about anything, it was in his belief, shared by Ernest Rutherford at the time, that the neutron is a composite of proton and electron. He saw the neutron as "the first step in the evolution of matter, the first step in building up the common materials of everyday life out of the primeval electrons and protons".
Frank Close
Author of *Destroyer of Worlds: the Deep History of the Nuclear Age*

Einstein's chalk

In response to Matin Durrani's review of *Einstein in Oxford* by Andrew Robinson (December 2024 p46).

Durrani mentions "the famous blackboard – saved for posterity – on which [Albert Einstein] had written while giving a public lecture" at the University of Oxford in the early 1930s. It might be inferred that this blackboard is unique, but there is also one at the University of Nottingham, which I saw on display there during a visit some 70 years ago. I recently phoned the university and was assured that the board is still there, in the physics department, and in fine condition. The date of Einstein's Nottingham visit is given as 6 June 1930.

One wonders how many other such boards there might be slumbering quietly in the archives of our older universities. But there is more to the Nottingham story: I was told that at the end of Einstein's lecture, an enterprising member of the audience took the piece of chalk Einstein had been using into his own safe keeping. He subsequently broke the chalk stick into two pieces, one of which still resides in the physics department at Nottingham. Where the other might be, who knows?
Peter Stanley
Wilmslow, UK

More praise for NPL

In response to the plea by Andrew Wallard (December 2024 p25) that more recognition be given to the National Physical Laboratory (NPL) for its work in the early days of computer science.

I believe an enormous amount of good work, across many different fields, was carried out at NPL after the Second World War. The work was extensively exploited, even if much of it went unrecognized in the wider world.

In 1958 I started working in NPL's mathematics division, writing computer programs in binary machine code for its new Automatic Computing Engine (ACE), which supported work at the NPL for about a decade. Binary machine code was laborious and assembly code versions for it soon appeared. I shared an office with Clifford Nott who, under Mike Woodger, wrote a compiler to run programs on ACE written in ALGOL 58. It was a stack of “Hollerith” punched cards roughly 6 cm thick.

While construction of the ACE was being finalized, NPL’s local area network (LAN) was also being fleshed out by Donald Davies, Derek Barber and Roger Scantelbury. Davies had been part of the eclectic mix of mathematicians and engineers, who in 1947 had been given the task of realizing Alan Turing’s design for a stored-program computer. They decided that a pilot version of his computer was the first priority, demonstrating it to the press in 1950. Turing worked at NPL for about a year.

As Wallard mentions, NPL also pioneered LAN packet switching – at about the same time that Paul Baran in the US independently developed packet switching for a wide-area network, which led to ARPANet and ultimately the Internet. Other NPL research involved stability in numerical algorithms under James Wilkinson and in pattern recognition, with John Parks using ACE and DEUCE (a commercial version of the pilot ACE) developing a character set that is still seen on UK bank cheques.

Michael Bacon
Watford, UK

Don’t follow fashion

In response to a news article about a study showing that scientific knowledge is growing only linearly despite an exponential increase in publications (November 2024 p13).

Your article, which suggests a slowdown in science, is a salutary reminder of the importance of physics to come up with solutions for many of the huge challenges facing the world, especially when it comes to energy and the environment. But could that slowdown also be dampening our ability to solving problems in other parts of society too?

Remarkably, the science-fiction writer James Blish anticipated this situation in his 1957 book *They Shall Have Stars*. His solution was for us to sift through ideas from able people who had been marginalized by the mainstream. The mathematical physicist Freeman Dyson said something similar in his

Dyson pointed to the dangers of too many students tackling problems deemed “fashionable” by those who fund science

1981 Princeton University lecture “Unfashionable pursuits”.

Dyson pointed to the dangers of too many students tackling problems deemed “fashionable” by those who fund science – because that’s where the grant funding lies. Making room for a minority to tackle other supposedly non-mainstream areas was vital too, he insisted. “We ought,” he said, “to seek out and encourage the rare individualists who do not fit into the prevailing pattern.” It’s a message we should do well to heed.

Howie Firth
Elgin, UK

The muon mystery deepens

In 2021 the Muon g-2 Experiment at Fermilab found a significant discrepancy between the theoretical prediction and the experimental measurement of the anomalous magnetic moment of the muon, indicating the existence of new physics. More recently, however, an alternative prediction has found the Fermilab result to be consistent with the Standard Model. **Alex Keshavarzi** investigates which side will come out on top

Alex Keshavarzi is a Royal Society university research fellow at the University of Manchester, UK. He works on both the Muon g-2 Experiment at Fermilab and the Muon g-2 Theory Initiative

A tense particle-physics showdown will reach new heights in 2025. Over the past 25 years researchers have seen a persistent and growing discrepancy between the theoretical predictions and experimental measurements of an inherent property of the muon – its anomalous magnetic moment. Known as the "muon g-2", this property serves as a robust test of our understanding of particle physics.

Theoretical predictions of the muon g-2 are based on the Standard Model of particle physics (SM). This is our current best theory of fundamental forces and particles, but it does not agree with everything observed in the universe. While the tensions between g-2 theory and experiment have challenged the foundations of particle physics and potentially offer a tantalizing glimpse of new physics beyond the SM, it turns out that there is more than one way to make SM predictions.

In recent years, a new SM prediction of the muon g-2 has emerged that questions whether the discrepancy exists at all, suggesting that there is no new physics in the muon g-2. For the particle-physics community, the stakes are higher than ever.

Rising to the occasion?

To understand how this discrepancy in the value of the muon g-2 arises, imagine you're baking some cupcakes. A well-known and trusted recipe tells you that by accurately weighing the ingredients using your kitchen scales you will make enough batter to give you 10 identical cupcakes of a given size. However, to your surprise, after portioning out the batter, you end up with 11 cakes of the expected size instead of 10.

What has happened? Maybe your scales are imprecise. You check and find that you're confident that your measurements are accurate to 1%. This means each of your 10 cupcakes could be 1% larger than they should be, or you could have enough leftover mixture to make 1/10th of an extra cupcake, but there's no way you should have a whole extra cupcake.

You repeat the process several times, always with the same outcome. The recipe clearly states that you should have batter for 10 cupcakes, but you always end up with 11. Not only do you now have a worrying number of cupcakes to eat but, thanks to all your repeated experiments, you're more confident that you are following all the steps and measurements accurately. You start to wonder whether something is missing from the recipe itself.

Before you jump to conclusions, it's worth checking that there isn't something systematically wrong with your scales. You ask several friends to follow the same recipe using their own scales. Amazingly, when each friend follows the recipe, they all end up with 11 cupcakes. You are more sure than ever that the cupcake recipe isn't quite right.

You're really excited now, as you have corroborating evidence that something is amiss. This is unprecedented, as the recipe is considered sacrosanct. Cupcakes have never been made differently and if this recipe is incomplete there could be other, larger implications. What if all cake recipes are incomplete? These claims are causing a stir, and people are starting to take notice.

Then, a new friend comes along and explains that they checked the recipe by simulating baking the cupcakes using a computer. This approach doesn't need physical scales, but it uses the same recipe. To your shock, the simulation produces 11 cupcakes of the expected size, with a precision as good as when you baked them for real.

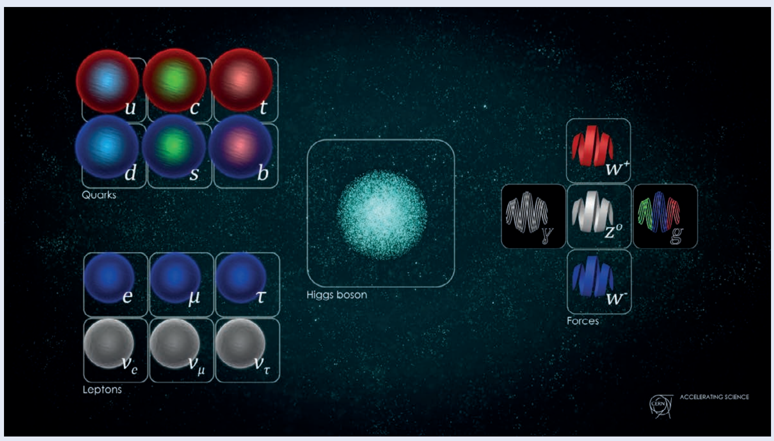
There is no explaining this. You were certain that the recipe was missing something crucial, but now a computer simulation is telling you that the recipe has always predicted 11 cupcakes.

Of course, one extra cupcake isn't going to change the world. But what if instead of cake, the recipe was particle physics' best and most-tested theory of everything, and the ingredients were the known particles and forces? And what if the number of cupcakes was a measurable outcome of those particles interacting, one hurtling towards a pivotal bake-off between theory and experiment?

What is the muon g-2?

Muons are an elementary particle in the SM that have a half-integer spin, and are similar to electrons, but are some 207 times heavier. Muons interact directly with other SM particles via electromagnetism (photons) and the weak force (W and Z bosons, and the Higgs particle). All quarks and leptons – such as electrons and muons – have a magnetic moment due to their intrinsic angular

"Virtual" particles



CERN

The Standard Model of particle physics (SM) describes the basic building blocks – the particles and forces – of our universe. It includes the elementary particles – quarks and leptons – that make up all known matter as well as the force-carrying particles, or bosons, that influence the quarks and leptons. The SM also explains three of the four fundamental forces that govern the universe –electromagnetism, the strong force and the weak force. Gravity, however, is not adequately explained within the model.

"Virtual" particles arise from the universe's underlying, non-zero background energy, known as the vacuum energy. Heisenberg's uncertainty principle states that it is impossible to simultaneously measure both the position and momentum of a particle. A non-zero energy always exists for "something" to arise from "nothing" if the "something" returns to "nothing" in a very short interval – before it can be observed. Therefore, at every point in space and time, virtual particles are rapidly created and annihilated.

The "g-factor" in muon g-2 represents the total value of the magnetic moment of the muon, including all corrections from the vacuum. If there were no virtual interactions, the muon's g-factor would be exactly $g = 2$. The first confirmation of $g > 2$ came in 1948 when Julian Schwinger calculated the simplest contribution from a virtual photon interacting with an electron (*Phys. Rev.* **73** 416). His famous result explained a measurement from the same year that found the electron's g-factor to be slightly larger than 2 (*Phys. Rev.* **74** 250). This confirmed the existence of virtual particles and paved the way for the invention of relativistic quantum field theories like the SM.

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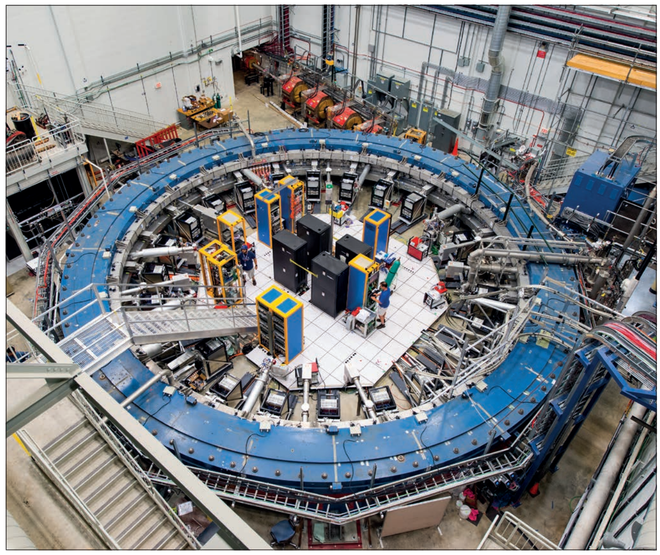
The Great Muon g-2 bake-off Like a trusted cake recipe, the Standard Model has been incredibly successful at predicting the behaviour of fundamental particles and forces. However, there are instances where the Standard Model breaks down, and scientists are hunting for new physics that will explain this.



Reidar Hahn/Fermilab, US Department of Energy

Magnetic muons The Muon g-2 experiment at the Fermi National Accelerator Laboratory.

momentum or "spin". Quantum theory dictates that the magnetic moment is related to the spin by a quantity known as the "g-factor". Initially, this value was predicted to be at $g = 2$ for both the electron and the muon.

However, these calculations did not take into account the effects of "radiative corrections" – the continuous emission and re-absorption of short-lived "virtual particles" (see box on p31) by the electron or muon – which increases g by about 0.1%. This seemingly minute difference is referred to as "anomalous g-factor", $a_\mu = (g-2)/2$. As well as the electromagnetic and weak interactions, the muon's magnetic moment also receives contributions from the strong force, even though the muon does not itself participate in strong interactions. The strong contributions arise through the muon's interaction with the photon, which in turn interacts with quarks. The quarks then themselves interact via the strong-force mediator, the gluon.

This effect, and any discrepancies, are of particular interest to physicists because the g-factor acts as a probe of the existence of other particles – both known particles such as electrons and photons, and other, as yet undiscovered, particles that are not part of the SM.

The muon, the (lighter) electron and the (heavier) tau lepton all have an anomalous magnetic moment. However, because the muon is heavier than the electron, the impact of heavy new particles on the muon g-2 is amplified. While tau leptons are even heavier than muons, tau leptons are extremely short-lived (muons have a lifetime of 2.2 μs, while the lifetime of tau leptons is 0.29 ns), making measurements impracticable with current technologies. Neither too light nor too heavy, the muon is the perfect tool to search for new physics.

New physics beyond the Standard Model (commonly known as BSM physics) is sorely needed because, despite its many successes, the SM does not provide the answers to all that we observe in the universe, such as the existence of dark matter. "We know there is something beyond the predictions of the Standard Model, we just don't know where," says Patrick Koppenburg, a physicist at the Dutch National Institute for Subatomic Physics (Nikhef) in the Netherlands, who works on the LHCb Experiment at CERN and on future collider experiments. "This new physics will provide new particles that we haven't observed yet. The LHC collider experiments are actively searching for such particles but haven't found anything to date."

New physics beyond the Standard Model is sorely needed because, despite its many successes, the Standard Model does not provide the answers to all that we observe in the universe, such as the existence of dark matter

Testing the Standard Model: experiment vs theory

In 2021 the Muon g-2 experiment at Fermilab in the US captured the world's attention with the release of its first result (*Phys. Rev. Lett.* **126** 141801). It had directly measured the muon g-2 to an unprecedented precision of 460 parts per billion (ppb). While the LHC experiments attempt to produce and detect BSM particles directly, the Muon g-2 experiment takes a different, complementary approach – it compares precision measurements of particles with SM predictions to expose discrepancies that could be due to new physics. In the Muon g-2 experiment, muons travel round and round a circular ring, confined by a strong magnetic field. In this field, the muons precess like spinning tops (see image on p30). The frequency of this precession is the anomalous magnetic moment and it can be extracted by detecting where and when the muons decay.

Having led the experiment as manager and run coordinator, Muon g-2 is an awe-inspiring feature of science and engineering, involving more than 200 scientists from 35 institutions in seven countries. I have been involved in both the operation of the experiment and the analysis of results. "A lot of my favourite memories from g-2 are 'firsts'," says Saskia Charity, a researcher at the University of Liverpool in the UK and a principal analyser of the Muon g-2 experiment's results. "The first time we powered the magnet; the first time we stored muons and saw particles in the detectors; and the first time we released a result in 2021."

The Muon g-2 result turned heads because the measured value was significantly higher than the best SM prediction (at that time) of the muon g-2 (*Phys. Rep.* **887** 1). This SM prediction was the culmination of years of collaborative work by the Muon g-2 Theory Initiative, an international consortium of roughly 200 theoretical physicists (myself among them). In 2020 the collaboration published one community-approved number for the muon g-2. This value had a precision comparable to the Fermilab experiment – resulting in a deviation between the two that has a chance of 1 in 40 000 of being a statistical fluke – making the discrepancy all the more intriguing.

While much of the SM prediction, including contributions from virtual photons and leptons, can be calculated from first principles alone, the strong force contributions involving quarks and gluons are more difficult. However, there is a mathematical link between the strong force contributions to muon g-2 and the probability of experimentally producing hadrons (composite particles made of quarks) from electron–positron annihilation. These so-called "hadronic processes" are something we can observe with existing particle colliders; much like weighing cupcake ingredients, these measurements determine how much each hadronic process contributes to the SM correction to the muon g-2. This is the approach used to calculate the 2020 result, producing what is called a "data-driven" prediction.

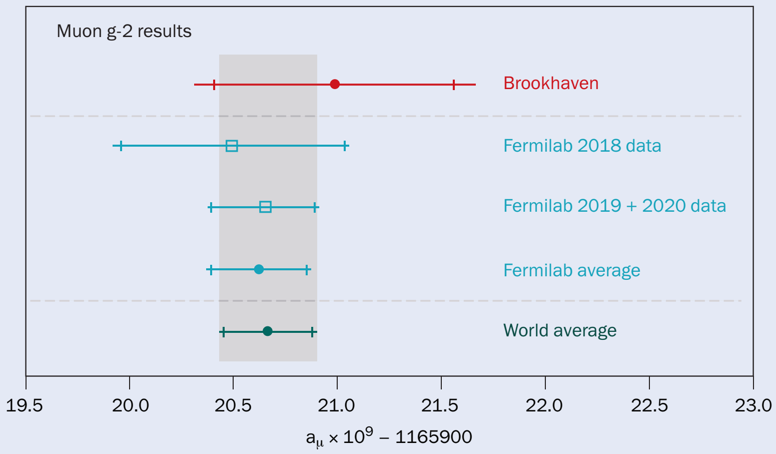
Measurements were performed at many experiments, including the BaBar Experiment at the Stanford Linear Accelerator Center (SLAC) in the US, the BESIII Experiment at the Beijing Electron–Positron Collider II in China, the KLOE Experiment at DAFNE Collider in Italy, and the SND and CMD-2 experiments at the VEPP-2000 electron–positron collider in Russia. These different experiments measured a complete catalogue of hadronic processes in different ways over several decades. Myself and other members of the Muon g-2 Theory Initiative combined these findings to produce the data-driven SM prediction of the muon g-2. There was (and still is) strong, corroborating evidence that this SM prediction is reliable.

This discrepancy strongly indicates, to a very high level of confidence, the existence of new physics. It seemed more likely than ever that BSM physics had finally been detected in a laboratory..

That was until the release of the first SM prediction of the muon g-2 using an alternative method called lattice QCD (*Nature* **593** 51). Like the data-driven prediction, lattice QCD is a way to tackle the tricky hadronic contributions, but it doesn't use experimental results as a basis for the calculation. Instead, it treats the universe as a finite box containing a grid of points (a lattice) that represent points in space and time. Virtual quarks and gluons are simulated inside this box, and the results are extrapolated to a universe of infinite size and continuous space and time. This method requires a huge amount of computer power to arrive at an accurate, physical result but it is a powerful tool that directly simulates the strong-force contributions to the muon g-2.

The researchers who published this new result are also part of the Muon g-2 Theory Initiative. Several other groups within the consortium have since published QCD calculations, producing values for g-2 that are in good agreement with each other and the experiment at Fermilab. "Striking agreement, to better than 1%, is seen between results from multiple groups," says Christine Davis of the University of Glasgow in the UK, a member

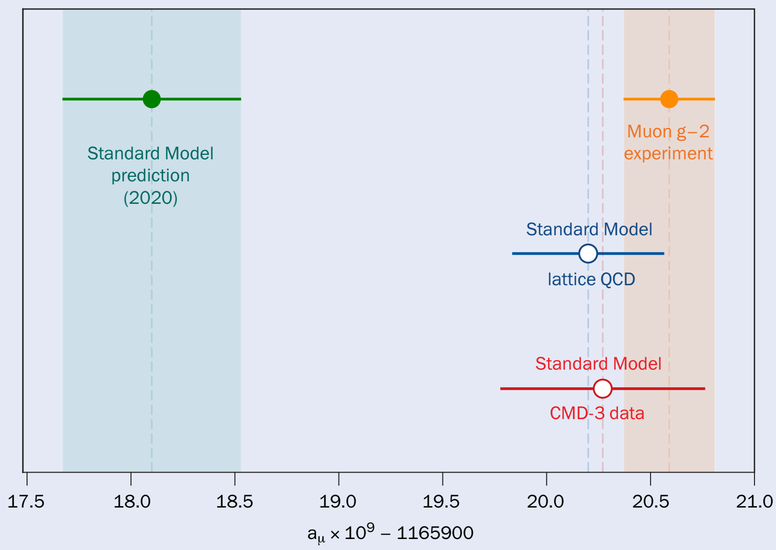
1 Eyes on the prize



Muon g-2 collaboration/IOP Publishing

Over the last two decades, direct experimental measurements of the muon g-2 have become much more precise. The predecessor to the Fermilab experiment was based at Brookhaven National Laboratory in the US, and when that experiment ended, the magnetic ring in which the muons are confined was transported to its current home at Fermilab.

2 Which Standard Model?



Alex Keshavarzi/IOP Publishing

Summary of the four values of the anomalous magnetic moment of the muon a_μ that have been obtained from different experiments and models. The 2020 and CMD-3 predictions were both obtained using a data-driven approach. The lattice QCD value is a theoretical prediction and the Muon g-2 experiment value was measured at Fermilab in the US. The positions of the points with respect to the y axis have been chosen for clarity only.

KEK-IPNS

International consensus
The Muon g-2 Theory Initiative pictured at their seventh annual plenary workshop at the KEK Laboratory, Japan in September 2024.

of the High-precision lattice QCD (HPQCD) collaboration within the Muon g-2 Theory Initiative. "A range of methods have been developed to improve control of uncertainties meaning further, more complete, lattice QCD calculations are now appearing. The aim is for several results with 0.5% uncertainty in the near future."

If these lattice QCD predictions are the true SM value, there is no muon g-2 discrepancy between experiment and theory. However, this would conflict with the decades of experimental measurements of hadronic processes that were used to produce the data-driven SM prediction.

To make the situation even more confusing, a new experimental measurement of the muon g-2's dominant hadronic process was released in 2023 by the CMD-3 experiment (*Phys. Rev. D* **109** 112002). This result is significantly larger than all the other, older measurements of the same process, including its own predecessor experiment, CMD-2 (*Phys. Lett. B* **648** 28). With this new value, the data-driven SM prediction of $a_\mu = (g-2)/2$ is in agreement with the Muon g-2 experiment and lattice QCD. Over the last few years, the CMD-3 measurements (and all older measurements) have been scrutinized in great detail, but the source of the difference between the measurements remains unknown.

Since then, the Muon g-2 experiment at Fermilab has confirmed and improved on that first result to a precision of 200 ppb (*Phys. Rev. Lett.* **131** 161802). "Our second result based on the data from 2019 and 2020 has been the first step in increasing the precision of the magnetic anomaly measurement," says Peter Winter of Argonne National Laboratory in the US and co-spokesperson for the Muon g-2 experiment.

The new result is in full agreement with the SM predictions from lattice QCD and the data-driven prediction based on CMD-3's measurement. However, with the increased precision, it now disagrees with the 2020 SM prediction by even more than in 2021.

The community therefore faces a conundrum. The muon g-2 either exhibits a much-needed discovery of BSM physics or a remarkable, multi-method confirmation of the Standard Model.

On your marks, get set, bake!

In 2025 the Muon g-2 experiment at Fermilab will release its final result. "It will be exciting to see our final result for g-2 in 2025 that will lead to the ultimate precision of 140 parts-per-billion," says Winter. "This measurement of g-2 will be a benchmark result for years to come for any extension to the Standard Model of particle physics." Assuming this agrees with the previous results, it will further widen the discrepancy with the 2020 data-driven SM prediction.

For the lattice QCD SM prediction, the many groups calculating the muon's anomalous magnetic moment have since corroborated and improved the precision of the first lattice QCD result. Their next task is to combine the results from the various lattice QCD predictions to arrive at one SM prediction from lattice QCD. While this is not a trivial task, the agreement between the groups means a single lattice QCD result with improved precision is likely within the next year, increasing the tension with the 2020 data-driven SM prediction.

New, robust experimental measurements of the muon g-2's dominant hadronic processes are also expected over the next couple of years. The previous experiments will update their measurements with more precise results and a newcomer measurement is expected from the Belle-II experiment in Japan. It is hoped that they will confirm either the catalogue of older hadronic measurements or the newer CMD-3 result. Should they confirm the older data, the potential for new physics in the muon g-2 lives on, but the discrepancy with the lattice QCD predictions will still need to be investigated. If the CMD-3 measurement is confirmed, it is likely the older data will be superseded, and the muon g-2 will have once again confirmed the Standard Model as the best and most resilient description of the fundamental nature of our universe.

The task before the Muon g-2 Theory Initiative is to solve these dilemmas and update the 2020 data-driven SM prediction. Two new publications are planned. The first will be released in 2025 (to coincide with the new experimental result from Fermilab). This will describe the current status and ongoing body of work, but a full, updated SM prediction will have to wait for the second paper, likely to be published several years later.

It's going to be an exciting few years. Being part of both the experiment and the theory means I have been privileged to see the process from both sides. For the SM prediction, much work is still to be done but science with this much at stake cannot be rushed and it will be fascinating work. I'm looking forward to the journey just as much as the outcome. ■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From banking to quantum optics: a unique journey

INTERNATIONAL YEAR OF Quantum Science and Technology

Michelle Lollie transitioned from a career in finance to developing quantum optical systems in industry. She talks to Tushna Commissariat about the American Physical Society (APS) Bridge Program; as well as her unique journey, including the challenges and triumphs of navigating the field as a Black woman

Michelle Lollie is an advanced laser scientist at Quantinuum, supporting the design, development and construction of complex optical systems that will serve as the foundations of world-class quantum computers. Lollie also participates in various diversity, equity, inclusion and accessibility initiatives, advocating for those who are marginalized in STEM fields, particularly in physics. Outside of wrangling photons, you can often find her at home practicing the violin.

Michelle Lollie

Quantum attraction Michelle Lollie.

Your initial bachelor's degree was in finance, and you went on to work in the field through your 20s before pivoting to physics – what made you take the leap to make this change, and what inspired you to pick physics for your second bachelor's degree?

I had dreams of working in finance since high school – indeed, at the time I was on my way to being the most dedicated, most fashionable, and most successful investment banker on Wall Street. I would like to think that, in some other quantum universe, there's still a Michelle Lollie – investment banker extraordinaire.

So my interest in physics wasn't sparked until much later in life, when I was 28 years old – I was no longer excited by a career in finance, and was looking for a professional pivot. I came across a groundbreaking theory paper about the quantum teleportation of states. I honestly thought that it referred to "Beam me up, Scotty" from *Star Trek*, and I was amazed.

But all jokes aside, quantum physics holds many a mystery that we're still exploring. As a field, it's quite new – there are approximately 100 years of dedicated quantum study and discovery, compared to millennia of classical physics. Perusing the paper and understanding about 2% of it, I just decided that this is what I would study. I wanted to learn about this "entanglement" business – a key concept of quantum physics. The rest is history.

Can you tell me a bit about your PhD pathway? You were a part of the APS Bridge Program at Indiana University – how did the programme help you?

After deciding to pursue a physics degree, I had to pick an academic institution to get said degree. What was news to me was that, for second baccalaureate degrees, funding at a public university was hard to come by. I was looking for universities with a strong optics programme, having decided that quantum optics was for me.

I learned about the Rose-Hulman Institute of Technology, in Terre Haute, Indiana by searching for optical engineering programmes. What I didn't know was that, in terms of producing top engineers, you'd be hard pressed to find a finer institution. The same can be said for their pure science disciplines, although those disciplines aren't usually ranked. I reached out to inquire about enrolment, was invited to visit and fell in love with the campus. I was funded and my physics journey began.

Prior to graduation, I was struggling with most of my grad-school applications being denied. I wasn't the most solid student at Rose (it's a rigorous place), but I wasn't a poorly performing student, either. Enter the APS Bridge Program, which focuses on students who, for whatever reason, were having challenges applying to grad school. The programme funded two years of education, wherein the student could have more exposure to coursework (which was just what I needed) or have more opportunity for research, after which they could achieve a master's degree and continue to a PhD.

I was accepted at a bridge programme site at Indiana University Bloomington. The additional two years allowed for a repeat of key undergraduate courses in the first year, with the second year filled with grad courses. I continued on and obtained my master's degree. I decided to leave IU to collaborate with a professor at Louisiana State University (LSU) who I had always wanted to work with and had done prior research with. So I transferred to LSU and obtained

Samuel Cooper/@photoscoops

Beyond beamlines Alongside her days spent in the lab, Michelle Lollie is a keen violinist.

my PhD, focusing on high-dimensional orbital angular momentum states of light for fibre-based quantum cryptography and communication protocols. Without the Bridge Program, it's likely that you might not be reading this article.

You then went on to Louisiana State University where, in 2022, you were the first African American woman to complete a PhD in physics – what was that like?

It's funny, but at the time, no-one was really talking about this. I think, for the individual who has to face various challenges due to race, sexual orientation and preference, gender, immigration status and the like, you just try to take your classes and do your research. But, just by your existence and certain aspects that may come along with that, you are often faced with a decision to advocate for yourself in a space that historically was not curated with you or your value in mind.

So while no-one was going up and down the halls saying "Hey, look at us, we have five Black students in our department!", most departments would bend over backwards for those diversity numbers. Note that five Black students in a department of well over 100 is nothing to write home about. It should be an order of magnitude higher, with 20–30 Black students at least. This is the sad state of affairs across physics and other sciences: people get excited about one Black student and think that they're doing something great. But, once I brought this fact to the attention of those in the front office and my adviser, a bit of talk started. Consequently, and fortuitously, the president of the university happened to visit our lab the fall before my graduation. Someone at that event noticed me, a Black woman in the physics department, and reached out to have me participate in several high-profile opportunities within the LSU community. This sparked more interest in my identity as a Black woman in the field; and it turned out that I was the first Black woman who would be getting a PhD from the department, in 2022. I am happy to report that three more Black women have earned degrees (one master's in medical physics, and two PhDs in physics) since then.

My family and I were featured on LSU socials for the historic milestone, especially thanks to Mimi LaValle, who is the media relations guru for the LSU Physics and Astronomy department. They even shared my grandmother's experience as a Black woman growing up in the US during the 1930s, and the juxtaposition of her opportunities versus mine were highlighted. It was a great moment and I'm glad that LSU not only acknowledged this story, but they emphasized and amplified it. I will always be grateful that I was able to hand my doctoral degree to my grandmother at graduation. She passed away in August 2024, but was always proud of my achievements. I was just as proud of her, for her determination to survive. Different times indeed.

What are some barriers and challenges you have faced through your education and career, if any?

The barriers have mostly been structural, embedded within the culture and fabric of physics. But this has made my dedication to be successful in the field a more unique and customized experience that only those who can relate to my identity will understand. There is a concerted effort to say that science doesn't see colour, gender, etc., and so these societal aspects shouldn't affect change within the field. I'd argue that human beings do science, so it is a decidedly "social" science, which is impacted significantly by culture – past and present. In fact, if we had more actual social scientists doing research on effecting change in the field for us physical scientists, the negative aspects of working in the field – as told by those who have lived experience – would be mitigated and true scientific broadening could be achieved.

What were the pitfalls, or stresses, of following this career random walk?

Other than the internal work of recognizing that, on a daily basis, I have to make space for myself in a field that's not used to me, there hasn't been anything of the sort. I have definitely had to advocate for myself and my presence within the field. But I love what I do and that I get to explore the mysteries of quantum physics. So, I'm not going anywhere anytime soon. The more space that I create, others can come in and feel just fine.

I want things to be as comfortable as possible for future generations of Black scientists. I am a Black woman, so I will always advocate for Black people within the space. This is unique to the history of the African Diaspora. I often advocate for those with cross-marginalized identities not within my culture, but no-one else has as much incentive to root for Black people but Black people. I urge everyone to do the same in highlighting those in their respective cultures and identities. If not you, then who?

What were the next steps for you after your PhD – how did you decide between staying in academia or pursuing a role in industry?

I always knew I was going to industry. I was actually surprised to learn that many physics graduates plan to go into academia. I started interviewing shortly before graduation, I knew what companies I had on my radar. I applied to them, received several offers, and decided on Quantinuum.

You are now an advanced laser scientist with Quantinuum – what does that involve, and what's a "day in the life" like for you now?

Nowadays, I can be found either doing CAD models of beamlines, or in the lab building said beamlines. This involves a lot of lasers, alignment, testing and validation. It's so cool to see an optical system that you've designed come to life on an optical table. Its even more satisfying when it is integrated within a full ion-trap system, and it works. I love practical work in the lab – when I have been designing a system for too long, I often say "Okay, I've been in front

I have definitely had to advocate for myself and my presence within the field

of this screen long enough. Time to go get the goggles and get the hands dirty."

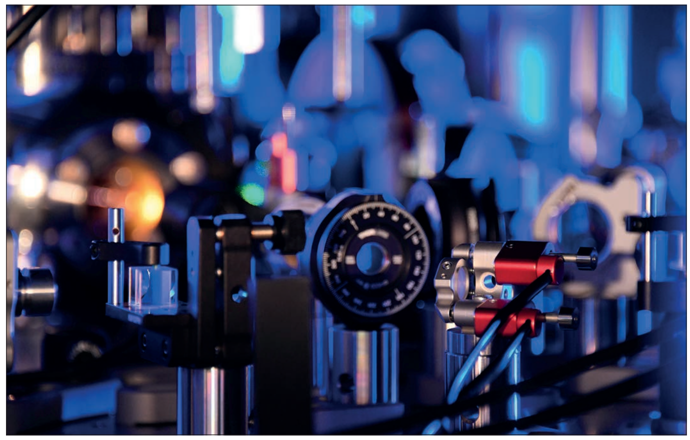
What do you know today, that you wish you knew when you were starting your career?

Had I known what I would have had to go through, I might not have ever done it. So, the ignorance of my path was actually a plus. I had no idea what this road entailed so, although the journey was a course in who-is-Michelle-going-to-be-101, I would wish for the "ignorance is bliss" state – on any new endeavour, even now. It's in the unknowing that we learn who we are.

What's your advice for today's students hoping to pursue a career in the quantum sector?

I always highlight what I've learned from Garfield Warren, a physics professor at Indiana University, and one of my mentors. He always emphasized learning skills beyond science that you'll need to be successful. Those who work in physics often lack direct communication skills, and there can be a lot of miscommunication. Be direct and succinct, and leave no room for speculation about what you are saying. This skill is key.

Also, learn the specific tools of your trade. If you're in optics, for example, learn the ins and outs of how lasers work. If you have opportunities to build laser set-ups, do so. Learn what the knobs do. Determine what it takes for you to be confident that the read-out data is what you want. You should understand each and every component that relates to work that you are doing. Learn all that you can for each project that you work on. Employers know that they will need to train you on company-specific tasks, but technical acumen is assumed to a point. Whatever the skills are for your area, the more that you understand the minutiae, the better.



Quantinuum

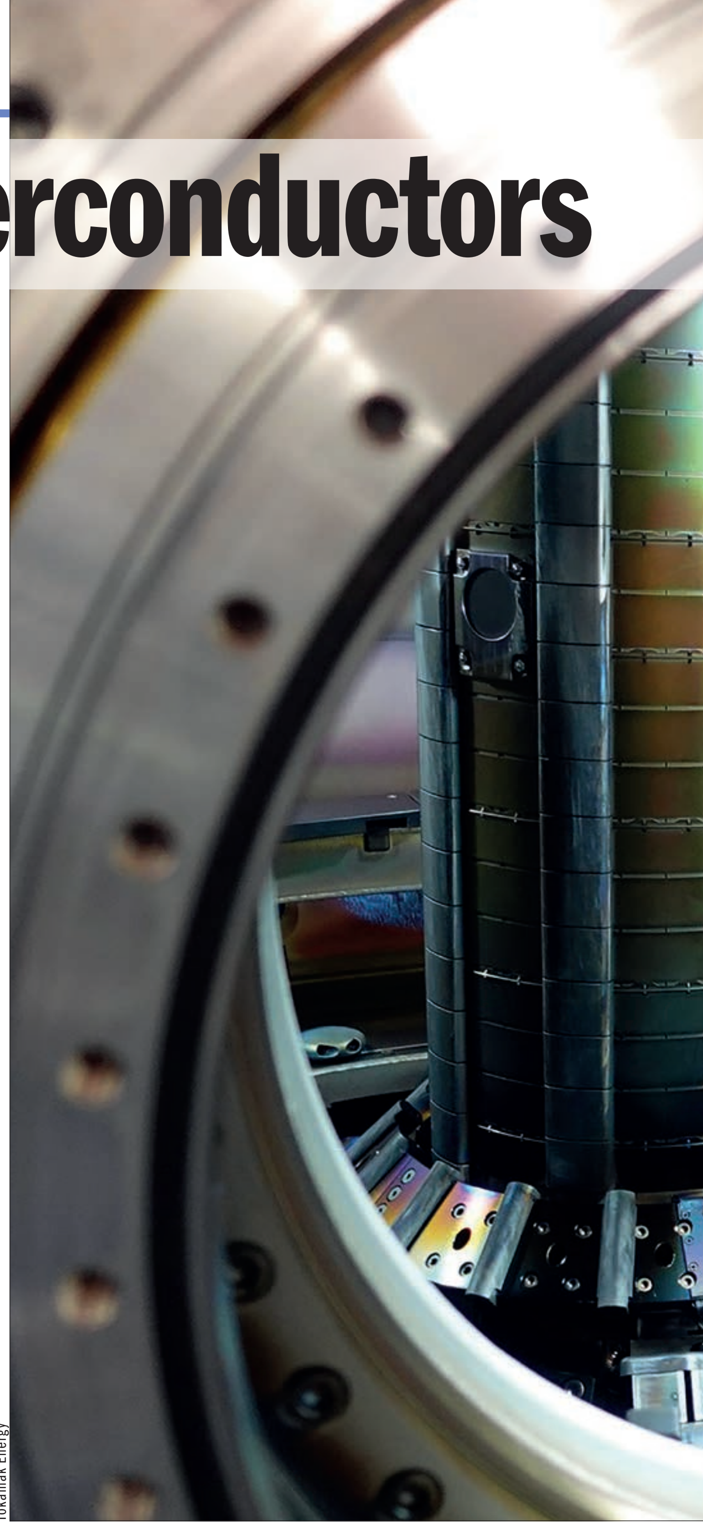
Tools of the trade At Quantinuum, Michelle Lollie works on the lasers and optics of quantum computers.

● First published in *APS Careers 2025*

Tushna Commissariat is the features editor of *Physics World*

Fusion puts superconductors to the test

Superconducting magnets inside a fusion reactor will experience conditions that aren't seen anywhere on Earth. Materials scientists **Susie Speller** and **Chris Grovenor** are trying to predict how long these components can last in this extreme environment



Tokamak Energy

Susie Speller and **Chris Grovenor** are professors of materials science at the University of Oxford in the UK

Fusion – the process that powers the Sun – offers a tantalizing opportunity to generate almost unlimited amounts of clean energy. In the Sun's core, matter is more than 10 times denser than lead and temperatures reach 15 million K. In these conditions, ionized isotopes of hydrogen (deuterium and tritium) can overcome their electrostatic repulsion, fusing into helium nuclei and ejecting high-energy neutrons. The products of this reaction are slightly lighter than the two reacting nuclei, and the excess mass is converted to lots of energy.

The Sun's core is kept hot and dense by the enormous gravitational force exerted by its huge mass. To achieve nuclear fusion on Earth, different tactics are needed. Instead of gravity, the most common approach uses strong superconducting magnets operating at ultracold temperatures to confine the intensely hot hydrogen plasma.

The engineering and materials challenges of creating what is essentially a "Sun in a freezer", and harnessing its power to make electricity, are formidable. This is partly because, over time, high-energy neutrons from the fusion reaction will damage the surrounding materials. Superconductors are incredibly sensitive to this kind of damage, so substantial shielding is needed to maximize the lifetime of the reactor.

The traditional roadmap towards fusion power, led by large international projects, has set its sights on bigger and bigger reactors, at greater and greater expense. However these are moving at a snail's pace, with the first power to the grid not anticipated until the 2060s, leading to the common perception that "fusion power is 30 years away, and always will be."

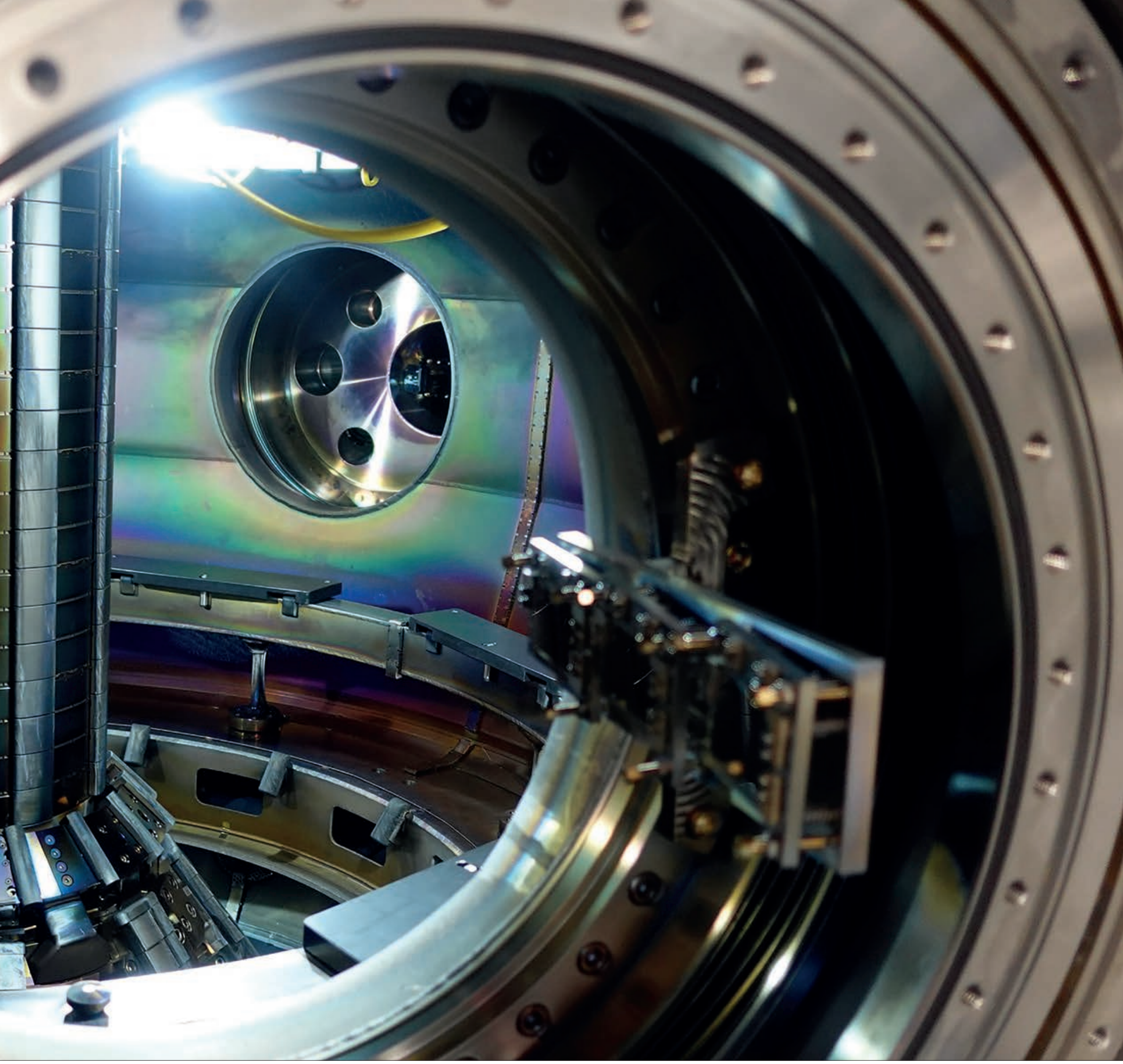
There is therefore considerable interest in alternative concepts for smaller, simpler reactors to speed up the fusion timeline. Such novel reactors will need a different toolkit of superconductors. Promising materials exist, but because fusion can still only be sustained in brief bursts, we have no way to directly test how these compounds will degrade over decades of use.

> The engineering and materials challenges of creating what is essentially a "Sun in a freezer" are formidable

Is smaller better?

A leading concept for a nuclear fusion reactor is a machine called a tokamak, in which the plasma is confined to a doughnut-shaped region. In a tokamak, D-shaped electromagnets are arranged in a ring around a central column, producing a circulating (toroidal) magnetic field. This exerts a force (the Lorentz force) on the positively charged hydrogen nuclei, making them trace helical paths that follow the field lines and keeping them away from the walls of the vessel.

In 2010, construction began in France on ITER, a tokamak that is designed to demonstrate the viability



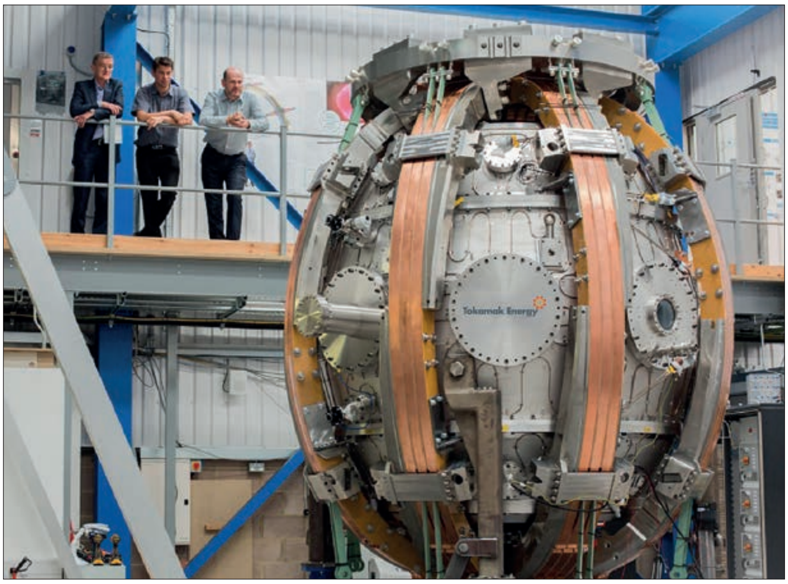
of nuclear fusion for energy generation. The aim is to produce burning plasma, where more than half of the energy heating the plasma comes from fusion in the plasma itself, and to generate, for short pulses, a tenfold return on the power input.

But despite being proposed 40 years ago, ITER's projected first operation was recently pushed back by another 10 years to 2034. The project's budget has also been revised multiple times and it is currently expected to cost tens of billions of euros. One reason ITER is such an ambitious and costly project is its sheer size. ITER's plasma radius of 6.2 m is twice that of the JT-60SA in Japan, the world's current largest tokamak. The power generated by a tokamak roughly scales with the radius of the doughnut cubed which means that doubling the radius should yield an eight-fold increase in power.

However, instead of chasing larger and larger tokamaks, some organizations are going in the opposite direction. Private companies like Tokamak Energy in the UK and Commonwealth Fusion Systems in the US are developing compact tokamaks that, they hope, could bring fusion power to the grid in the 2030s. Their approach is to ramp up the magnetic field rather than the size of the tokamak. The fusion power of a tokamak has a stronger dependence on the magnetic field than the radius, scaling with the fourth power.

The drawback of smaller tokamaks is that the materials will sustain more damage from neutrons during operation. Of all the materials in the tokamak, the superconducting magnets are the most sensitive to this. If the reactor is made more compact, they are also closer to the plasma and there will be less space for shielding. So if

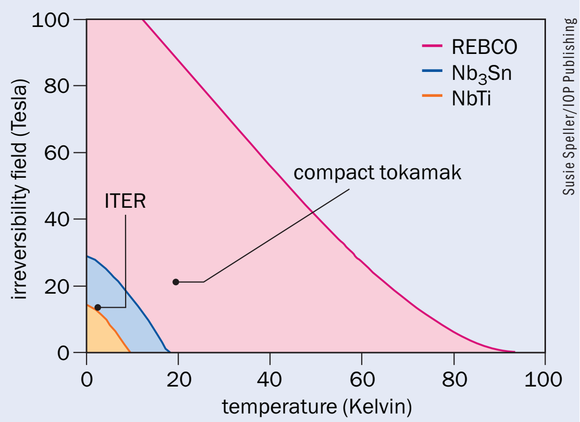
Inside view
Private companies like Tokamak Energy in the UK are developing compact tokamaks that, they hope, could bring fusion power to the grid in the 2030s.



Tokamak Energy

Small but mighty Tokamak Energy's ST40 compact tokamak uses copper electromagnets, which would be unsuitable for long-term operation due to overheating. REBCO compounds, which are high-temperature superconductors that can generate very high magnetic fields, are an attractive alternative.

1 Superconductors



Susie Speller/IOP Publishing

Operation window for Nb-Ti, Nb_3Sn and REBCO superconductors.

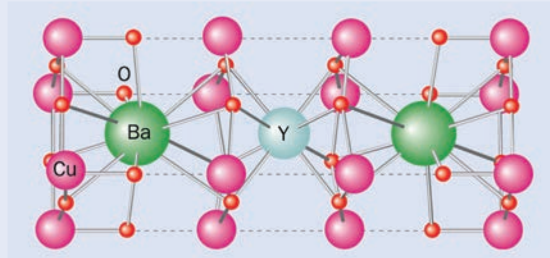
Superconductors are materials that have zero electrical resistance when they are cooled below a certain critical temperature (Tc). Superconducting wires can therefore carry electricity much more efficiently than conventional resistive metals like copper.

What's more, a superconducting wire can carry a much higher current than a copper wire of the same diameter because it has zero resistance and so no heat is generated. In contrast, as you pass ever more current through a copper wire, it heats up and its resistance rises even further, until eventually it melts.

Without this resistive heating, a superconducting wire can carry a much higher current than a copper wire of the same diameter. This increased current density (current per unit cross-sectional area) enables high-field superconducting magnets to be more compact than resistive ones.

However, there is an upper limit to the strength of the magnetic field that a superconductor can usefully tolerate without losing the ability to carry lossless current. This is known as the "irreversibility field", and for a given superconductor its value decreases as temperature is increased, as shown above.

2 REBCO crystal



Wikimedia Commons/IOP Publishing

The unit cell of a REBCO high-temperature superconductor. Here the pink atoms are copper and the red atoms are oxygen, the barium atoms are in green and the rare-earth element here is yttrium in blue.

compact tokamaks are to succeed commercially, we need to choose superconducting materials that will be functional even after many years of irradiation.

High-performance fusion materials

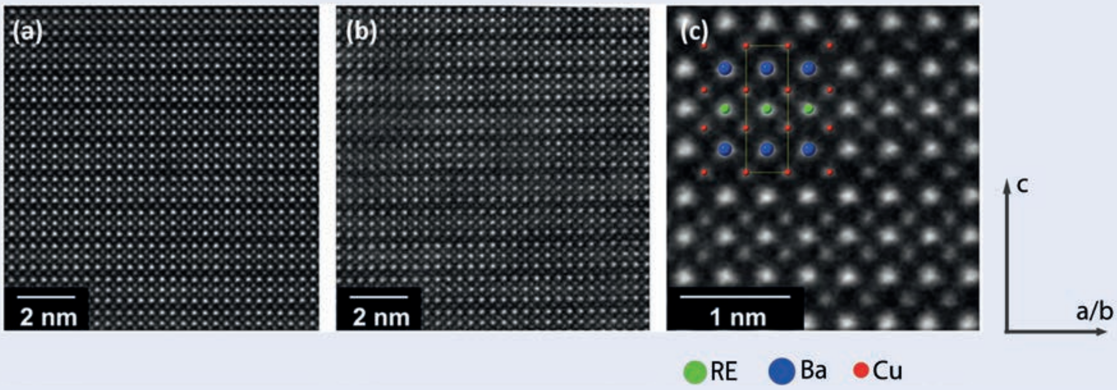
Superconductors are a class of materials that, when cooled below a characteristic temperature, conduct with no resistance (see box 1 "Superconductors"). Magnets made from superconducting wires can carry high currents without overheating, making them ideal for generating the very high fields required for fusion. Superconductivity is highly sensitive to the arrangement of the atoms; whilst some amorphous superconductors exist, most superconducting compounds only conduct high currents in a specific crystalline state. A few defects will always arise, and can sometimes even improve the material's performance. But introducing significant disorder to a crystalline superconductor will eventually destroy its ability to superconduct.

The most common material for superconducting magnets is a niobium-titanium (Nb-Ti) alloy, which is used in MRI machines in hospitals and CERN's Large Hadron Collider. A Nb-Ti superconducting magnet is relatively cheap and easy to manufacture, but – like all superconducting materials – it has an upper limit to the magnetic field in which it can superconduct, known as the irreversibility field. This value in Nb-Ti is too low for this material to be used for the high-field magnets in ITER. The ITER tokamak will instead use a niobium-tin (Nb_3Sn) superconductor, which has a higher irreversibility field than Nb-Ti, even though it is much more expensive and challenging to work with.

Needing stronger magnetic fields, compact tokamaks require a superconducting material with an even higher irreversibility field. Over the last decade, another class of superconducting materials called "REBCO" have been proposed as an alternative. Short for rare earth barium copper oxide, these are a family of superconductors with the chemical formula $REBa_2Cu_3O_7$, where RE is a rare-earth element such as yttrium, gadolinium or europium, (see box 2 "REBCO crystal").

REBCO compounds are high-temperature superconductors, which are defined as having transition temperatures above 77 K, meaning they can be cooled with liquid nitrogen rather than the more expensive liquid helium. REBCO compounds also have a much higher irreversibility field than niobium-tin, and so can sustain the high fields necessary for a small fusion reactor.

3 Spot the difference



Transmission electron microscopy images of REBCO before (a) and after (b) helium ion irradiation. The image on the right (c) shows only the positions of the copper, barium and rare-earth atoms – the oxygen atoms in the crystal lattice cannot be imaged using this technique. After ion irradiation, REBCO materials exhibit a lower superconducting transition temperature. However, the above images show no corresponding defects in the lattice, indicating that defects caused by oxygen atoms being knocked out of place are responsible for this effect.

R.J. Nicholls, S. Diaz-Moreno, W. Iliffe *et al.* *Communications Materials* **3** 52

REBCO wires: Bendy but brittle

REBCO materials have attractive superconducting properties, but it is not easy to manufacture them into flexible wires for electromagnets. REBCO is a brittle ceramic so can't be made into wires in the same way as ductile materials like copper or Nb-Ti, where the material is drawn through progressively smaller holes.

Instead, REBCO tapes are manufactured by coating metallic ribbons with a series of very thin ceramic layers, one of which is the superconducting REBCO compound. Ideally, the REBCO would be a single crystal, but in practice, it will be comprised of many small grains. The metal gives mechanical stability and flexibility whilst the underlying ceramic "buffer" layers protect the REBCO from chemical reactions with the metal and act as a template for aligning the REBCO grains. This is important because the boundaries between individual grains reduce the maximum current the wire can carry.

Another potential problem is that these compounds are chemically sensitive and are "poisoned" by nearly all the impurities that may be introduced during manufacture. These impurities can produce insulating compounds that block supercurrent flow or degrade the performance of the REBCO compound itself.

Despite these challenges, and thanks to impressive materials engineering from several companies and institutions worldwide, REBCO is now made in kilometre-long, flexible tapes capable of carrying thousands of amps of current. In 2024, more than 10 000 km of this material was manufactured for the burgeoning fusion industry. This is impressive given that only 1000 km was made in 2020. However, a single compact tokamak will require up to 20 000 km of this REBCO-coated conductor for the magnet systems, and because the superconductor is so expensive to manufacture it is estimated that this would account for a considerable fraction of the total cost of a power plant.

Pushing superconductors to the limit

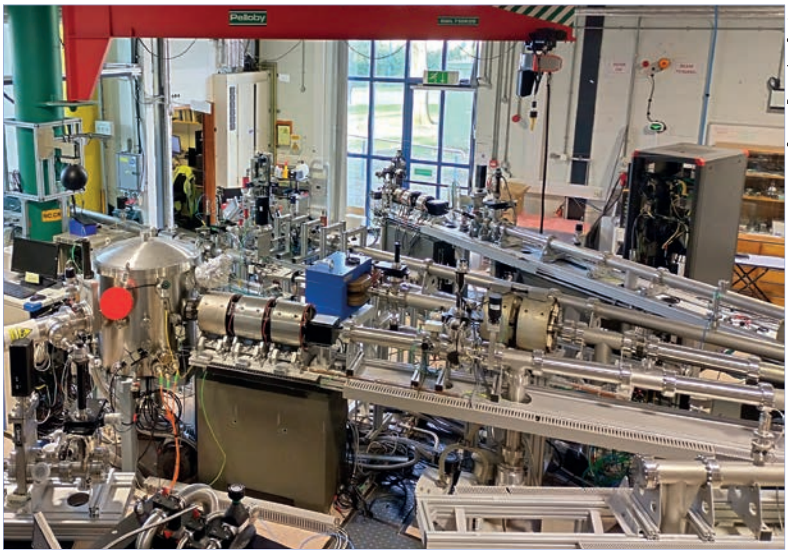
Another problem with REBCO materials is that the temperature below which they superconduct falls steeply once they've been irradiated with neutrons. Their lifetime in service will depend on the reactor design and amount of shielding, but research from the Vienna University of Technology in 2018 suggested that REBCO materials can withstand about a thousand times less damage than structural materials like steel before they start to lose performance (*Supercond. Sci. Technol.* **31** 044006).

Even if we could get a sample of REBCO inside a working tokamak, the maximum runtime of current machines is measured in minutes

These experiments are currently being used by the designers of small fusion machines to assess how much shielding will be required, but they don't tell the whole story. The 2018 study used neutrons from a fission reactor, which have a different spectrum of energies compared to fusion neutrons. They also did not reproduce the environment inside a compact tokamak, where the superconducting tapes will be at cryogenic temperatures, carrying high currents and under considerable strain from Lorentz forces generated in the magnets.

Even if we could get a sample of REBCO inside a working tokamak, the maximum runtime of current machines is measured in minutes, meaning we cannot do enough damage to test how susceptible the superconductor will be in a real fusion environment. The current record for tokamak power is 69 megajoules, achieved in a 5-second burst at the Joint European Torus (JET) tokamak in the UK.

Given the difficulty of using neutrons from fusion reactors, our team is looking for answers using ions instead. Ion irradiation is much more readily available, quicker to perform, and doesn't make the samples radioactive. It is also possible to access a wide range of energies and ion species to tune the damage mechanisms in the material.



Surrey Beam Ion Centre

The Surrey Ion Beam Centre allows users to carry out a wide variety of research using ion implantation, ion irradiation and ion beam analysis.

The trouble is that because ions are charged they won't interact with materials in exactly the same way as neutrons, so it is not clear if these particles cause the same kinds of damage or by the same mechanisms.

To find out, we first tried to directly image the crystalline structure of REBCO after both neutron and ion irradiation using transmission electron microscopy (TEM). When we compared the samples, we saw small amorphous regions in the neutron-irradiated REBCO where the crystal structure was destroyed (*J. Microsc.* **286** 3), which are not observed after light ion irradiation (see box 3 "Spot the difference" on p43).

We believe these regions to be collision cascades generated initially by a single violent neutron impact that knocks an atom out of its place in the lattice with enough energy that the atom ricochets through the material, knocking other atoms from their positions. However, these amorphous regions are small, and superconducting currents should be able to pass around them, so it was likely that another effect was reducing the superconducting transition temperature.

Searching for clues

The TEM images didn't show any other defects, so on our hunt to understand the effect of neutron irradiation, we instead thought about what we couldn't see in the images. The TEM technique we used cannot resolve the oxygen atoms in REBCO because they are too light to scatter the electrons by large angles. Oxygen is also the most mobile atom in a REBCO material, which led us to think that oxygen point defects – single oxygen atoms that have been moved out of place and which are distributed randomly throughout the material – might be responsible for the drop in transition temperature.

In REBCO, the oxygen atoms are all bonded to copper, so the bonding environment of the copper atoms can be used to identify oxygen defects. To test this theory we switched from electrons to photons, using a technique called X-ray absorption spectroscopy. Here the sample is illuminated with X-rays that preferentially excite the copper atoms; the precise energies where absorption is highest indicate specific bonding arrangements, and therefore point to specific defects. We have started to identify the defects that are likely to be present in the irradiated samples, finding spectral changes that are consistent with oxygen atoms moving into unoccupied sites (*Communications Materials* **3** 52).

We see very similar changes to the spectra when we irradiate with helium ions and neutrons, suggesting that similar defects are created in both cases (*Supercond. Sci. Technol.* **36** 10LT01). This work has increased our confidence that light ions are a good proxy for neutron damage in REBCO superconductors, and that this damage is due to changes in the oxygen lattice.

Another advantage of ion irradiation is that, compared to neutrons, it is easier to access experimentally relevant cryogenic temperatures. Our experiments are performed at the Surrey Ion Beam Centre, where a cryocooler can be attached to the end of the ion accelerator, enabling us to recreate some of the conditions inside a fusion reactor.

We have shown that when REBCO is irradiated at cryogenic temperatures and then allowed to warm to room temperature, it recovers some of its superconducting properties (*Supercond. Sci. Technol.* **34** 09LT01). We attribute this to annealing, where rearrangements of atoms occur in a material warmed below its melting point, smoothing out defects in the crystal lattice. We have shown that further recovery of a perfect superconducting lattice can be induced using careful heat treatments to avoid loss of oxygen from the samples (*MRS Bulletin* **48** 710).

Lots more experiments are required to fully understand the effect of irradiation temperature on the degradation of REBCO. Our results indicate that room temperature and cryogenic irradiation with helium ions lead to a similar rate of degradation, but similar work by a group at the Massachusetts Institute of Technology (MIT) in the US using proton irradiation has found that the superconductor degrades more rapidly at cryogenic temperatures (*Rev. Sci. Instrum.* **95** 063907). The effect of other critical parameters like magnetic field and strain also still needs to be explored.

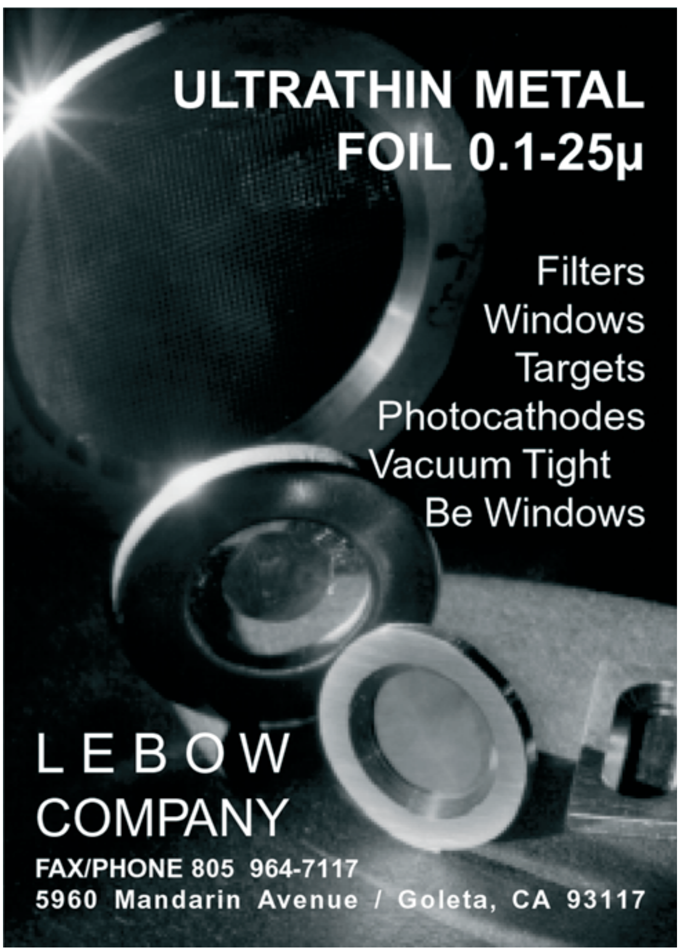
Towards net zero

The remarkable properties of REBCO high-temperature superconductors present new opportunities for designing fusion reactors that are substantially smaller (and cheaper) than traditional tokamaks, and which private companies ambitiously promise will enable the delivery of power to the grid on vastly accelerated timescales. REBCO tape can already be manufactured commercially with the required performance but more research is needed to understand the effects of neutron damage that the magnets will be subjected to so they will achieve the desired service lifetimes.

Scale-up of REBCO tape production opens up extensive new applications, such as lossless transmission cables, wind turbine generators and magnet-based energy storage devices

Scale-up of REBCO tape production is already happening at pace, and it is expected that this will drive down the cost of manufacture. This would open up extensive new applications, not only in fusion but also in power applications such as lossless transmission cables, for which the historically high costs of the superconducting material have proved prohibitive. Superconductors are also being introduced into wind turbine generators, and magnet-based energy storage devices.

This symbiotic relationship between fusion and superconductor research could lead not only to the realization of clean fusion energy but also many other superconducting technologies that will contribute to the achievement of net zero. ■



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Reviews

Reaching for the stars

Andrew Glester reviews the film *Spacewoman* directed by Hannah Berryman

NASA

On a mission
Eileen Collins in the pilot's station of the NASA Space Shuttle *Discovery* in 1995. Collins's first space flight, this mission carried out a rendezvous with the Russian Mir Space Station.

Spacewoman
Dir. Hannah Berryman
A Haviland Digital Film in association with Tigerlily Productions

"What makes a good astronaut?" asks director Hannah Berryman in the opening scene of *Spacewoman*. It's a question few can answer better than Eileen Collins. As the first woman to pilot and command a NASA Space Shuttle, her career was marked by historic milestones, extraordinary challenges and personal sacrifices. Collins looks down the lens of the camera and, as she pauses for thought, we cut to footage of her being suited up in astronaut gear for the third time. "I would say…a person who is not prone to panicking."

In *Spacewoman*, Berryman crafts a thoughtful, emotionally resonant documentary that traces Collins's life from a determined young girl in Elmira, New York, to a spaceflight pioneer.

The film's strength lies in its compelling balance of personal narrative and technical achievement. Through intimate interviews with Collins, her family and former colleagues, alongside a wealth of archival footage, *Spacewoman* paints a vivid portrait of a woman whose journey was anything but straightforward. From growing up in a working-class family affected by her parents' divorce and Hurricane Agnes's destruction, to excelling in the male-dominated world of aviation and space exploration, Collins's resilience shines through.

Berryman wisely centres the film on the four key missions that defined Collins's time at NASA. While this approach necessitates a brisk overview of her early military career, it allows for an in-depth exploration of the stakes, risks and triumphs of spaceflight. Collins's pioneering 1995 mission, STS-63, saw her pilot the Space Shuttle *Discovery* in the first rendezvous with the Russian space station Mir, a mission fraught with political and technical challenges. The archival footage from this and subsequent missions provides gripping, edge-of-your-seat moments that demonstrate both the precision and unpredictability of space travel.

Perhaps *Spacewoman*'s most affecting thread is its examination of how Collins's career intersected with her family life. Her daughter, Bridget, born shortly after her first mission, offers a poignant perspective on growing up with a mother whose job carried life-threatening risks. In one of the film's most emotionally charged scenes, Collins recounts explaining the *Challenger* disaster to a young Bridget. Despite her mother's assurances that NASA had learned from the tragedy, the subsequent *Columbia* disaster two weeks later underscores the constant shadow of danger inherent in space exploration.

These deeply personal reflections elevate *Spacewoman* beyond a straightforward biographical documentary. Collins's son Luke, though younger and less directly affected by his mother's missions, also shares touching memories, offering a fuller picture of a family shaped by space exploration's highs and lows. Berryman's thoughtful editing intertwines these recollections with historic footage, making the stakes feel immediate and profoundly human.

The film's tension peaks during Collins's final mission, STS-114, the first "return to flight" after Columbia. As the mission teeters on the brink of disaster due to familiar technical issues, Berryman builds a heart-pounding narrative, even for viewers unfamiliar with the complexities of spaceflight. Without getting bogged down in technical jargon, she captures the intense pressure of a mission fraught with tension – for those on Earth, at least.

Berryman's previous films include *Miss World 1970: Beauty Queens and Bedlam* and *Banned, the Mary Whitehouse Story*. In a recent episode of the *Physics World Stories* podcast, she told me that she was inspired to make the film after reading Collins's autobiography *Through the Glass Ceiling to the Stars*. "It was so personal," she said, "it took me into space and I thought maybe we could do that with the viewer." Collins herself joined us for that podcast episode and I found her to be that same calm, centred, thoughtful person we see in the film and who NASA clearly very carefully chose to command such an important mission.

AUDIO

Listen to Hannah Berryman and Eileen Collins in conversation with Andrew Glester

Spacewoman isn't just about near-misses and peril. It also celebrates moments of wonder: Collins describing her first sunrise from space or recalling the chocolate shuttles she brought as gifts for the Mir cosmonauts. These light-hearted anecdotes reveal her deep appreciation for the unique experience of being an astronaut. On the podcast, I asked Collins what one lesson she would bring from space to life on Earth. After her customary moment's pause for thought, she replied "Reading books about science fiction is very important." She was a fan of science fiction in her younger years , which enabled her to dream of the future that she realized at NASA and in space. But, she told me, these days she also reads about real science of the future (she was deep into a book on artificial intelligence when we spoke) and history too. Looking back at Collins's history in space certainly holds lessons for us all.

Berryman's directorial focus ultimately circles back to a profound question: how much risk is acceptable in the pursuit of human progress? *Spacewoman* suggests that those committed to something greater than themselves are willing to risk everything. Collins's career embodies this ethos, defined by an unshakeable resolve, even in the face of overwhelming odds.

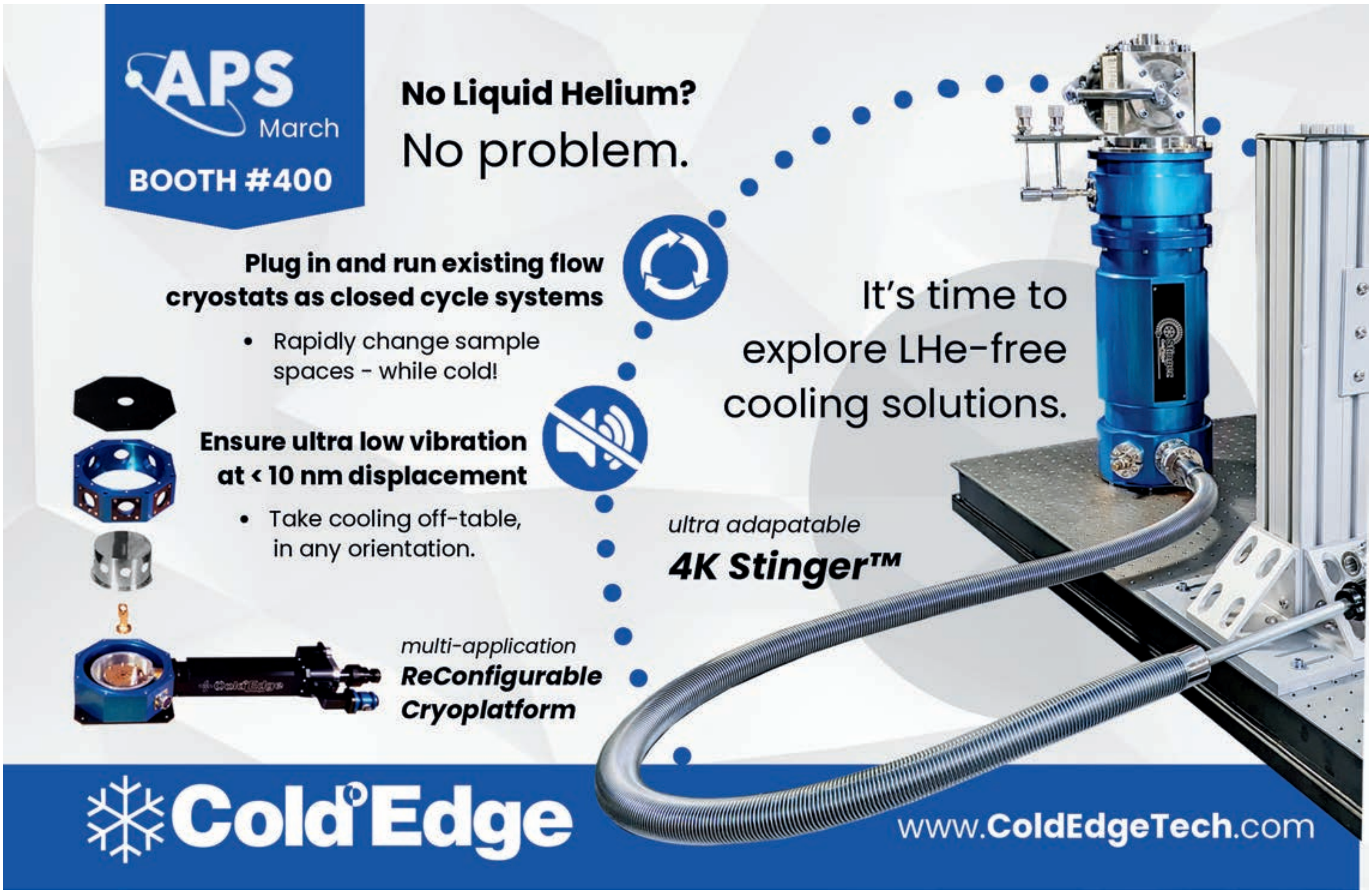
In the film's closing moments, we see Collins speaking to a wide-eyed girl at a book signing. The voiceover from interviews talks of the women slated to be instrumental in humanity's return to the Moon and future missions to Mars. If there's one thing I would change about the film, it's that the final word is given to someone other than Collins. The message is a fitting summation of her life and legacy, but I would like to have seen it delivered with her understated confidence of someone who has lived it. It's a quibble though in a compelling film that I would recommend to anyone with an interest in space travel or the human experience here on Earth.

When someone as accomplished as Collins says that you need to work hard and practise, practise, practise it has a gravitas few others can muster. After all, she spent 10 years practising to fly the Space Shuttle – and got to do it for real twice. We see Collins speak directly to the wide-eyed girl in a flight suit as she signs her book and, as she does so, you can feel the words really hit home precisely because of who says them: "Reach for the stars. Don't give up. Keep trying because you can do it."

Spacewoman is more than a tribute to a trailblazer; it's a testament to human perseverance, curiosity and courage. In Collins's story, Berryman finds a gripping, deeply personal narrative that will resonate with audiences across the planet.

● *Spacewoman* premiered at DOC NYC in November 2024 and is scheduled for theatrical release in 2025

Andrew Glester is a producer and presenter of the *Physics World Stories* podcast. He is also a senior lecturer teaching filmmaking, podcasting, radio and science communication at UWE Bristol, UK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No problem.
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Ensure ultra low vibration at < 10 nm displacement
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Careers

Gaining a quantum advantage in the workplace

Sarah Sheldon, an engineering physicist from IBM, talks to Joe McEntee about the company's efforts to open up the next frontier in quantum computing – and why the emerging quantum technology industry is brimming with opportunity for ambitious scientists and engineers

Connie Zhou for IBM

Life lessons Sarah Sheldon (right) enjoys the interdisciplinary nature of quantum technology, which allows her to be "constantly learning something new" from her IBM co-workers.

IBM is on a mission to transform quantum computers from applied research endeavour to mainstream commercial opportunity. It wants to go beyond initial demonstrations of "quantum utility", where these devices outperform classical computers only in a few niche applications, and reach the new frontier of "quantum advantage". That'll be where quantum computers routinely deliver significant, practical benefits beyond approximate classical computing methods, calculating solutions that are cheaper, faster and more accurate.

Unlike classical computers, which rely on the binary bits that can be either 0 or 1, quantum computers exploit quantum binary bits (qubits), but as a superposition of 0 and 1 states. This superposition, coupled with quantum entanglement (a correlation of two qubits), enables quantum computers to perform some types of calculation significantly faster than classical machines, such as problems in quantum chemistry and molecular reaction kinetics.

In the vanguard of IBM's quantum R&D effort is Sarah Sheldon, a principal research scientist and senior manager of quantum theory and capabilities at the IBM Thomas J Watson Research Center in Yorktown Heights, New York. After a double-major undergraduate degree in physics and nuclear science and engineering at Massachusetts Institute of Technology (MIT), Sheldon received her PhD from MIT in 2013 – though she did much of her graduate research in nuclear science and engineering as a visiting scholar at the Institute for Quantum Computing (IQC) at the University of Waterloo, Canada.

At IQC, Sheldon was part of a group studying quantum control techniques, manipulating the spin states of nuclei in nuclear-magnetic-resonance (NMR) experiments. "Although we were using different systems to today's leading quantum platforms, we were applying a lot of the same kinds of control techniques now widely deployed across the quantum tech sector," Sheldon explains.

"Upon completion of my PhD, I opted instinctively for a move into industry, seeking to apply all that learning in quantum physics into immediate and practical engineering contributions," she says. "IBM, as one of only a few industry players back then with an experimental group in quantum computing, was the logical next step."

Physics insights, engineering solutions

Sheldon currently heads a cross-disciplinary team of scientists and engineers developing techniques for handling noise and optimizing performance in novel experimental demonstrations of quantum computers. It's ambitious work that ties together diverse lines of enquiry spanning everything from quantum theory and algorithm development to error mitigation, error correction and techniques for characterizing quantum devices.

"From algorithms to applications," says Sheldon, "we're investigating what can we do with quantum computers: how to extract the optimum performance from current machines online today as well as from future generations of quantum computers – say, five or 10 years down the line."

A core priority for Sheldon and colleagues is how to manage the environmental noise that plagues current quantum computing systems. Qubits are all too easily disturbed, for example, by their interactions with environmental fluctuations in temperature, electric and magnetic fields, vibrations, stray radiation and even interference between neighbouring qubits.

The ideal solution – a strategy called error correction – involves storing the same information across multiple qubits, such that errors are detected and corrected when one or more of the qubits are impacted by noise. But the problem with these so-called "fault-tolerant" quantum computers is they need millions of qubits, which is impossible to implement in today's small-scale quantum architectures. (For context, IBM's latest Quantum Development Roadmap outlines a practical path to error-corrected quantum computers by 2029.)

"Ultimately," Sheldon notes, "we're working towards large-scale error-corrected systems, though for now we're exploiting near-term techniques like error mitigation and other ways of managing noise in these systems." In practical terms, this means implementing quantum architectures without increasing the number of qubits – essentially, integrating them with classical computers to reduce noise through increasing samples on the quantum computer combined with classical processing.


Connie Zhou for IBM

Computing reimagined Quantum scientists and engineers at the IBM Thomas J Watson Research Center are working to deliver IBM's Quantum Development Roadmap and a practical path to error-corrected quantum computers by 2029.

Strength in diversity

For Sheldon, one big selling point of the quantum tech industry is the opportunity to collaborate with people from a wide range of disciplines. "My team covers a broad-scope R&D canvas," she says. There are mathematicians and computer scientists, for example, working on complexity theory and novel algorithm development; physicists specializing in quantum simulation and incorporating error suppression techniques; as well as quantum chemists working on simulations of molecular systems.

"Quantum is so interdisciplinary – you are constantly learning something new from your co-workers," she adds. "I started out specializing in quantum control techniques, before moving onto experimental demonstrations of larger multiqubit systems while working ever more closely with theorists."

External research collaborations are also mandatory for Sheldon and her colleagues. Front-and-centre is the IBM Quantum Network, which provides engagement opportunities with more than 250 organizations across the "quantum ecosystem". These range from top-tier labs – such as CERN, the University of Tokyo and the UK's National Quantum Computing Centre – to quantum technology start-ups like Q-CTRL and Algorithmiq. It also encompasses established industry players aiming to be early-adopting end-users of quantum technologies (among them Bosch, Boeing and HSBC).

"There's a lot of innovation happening across the quantum community," says Sheldon, "so external partnerships are incredibly important for IBM's quantum R&D programme. While we have a deep and diverse skill set in-house, we can't be the domain experts across every potential use-case for quantum computing."

Opportunity knocks

Notwithstanding the pace of innovation, there are troubling clouds on the horizon. In particular, there is a shortage of skilled workers in the quantum workforce, with established technology companies and start-ups alike desperate to attract more physical scientists and engineers. The task is to fill not only specialist roles – be it error-correction scientists or quantum-algorithm developers – but more general positions such as test and measurement engineers, data scientists, cryogenic technicians and circuit designers.

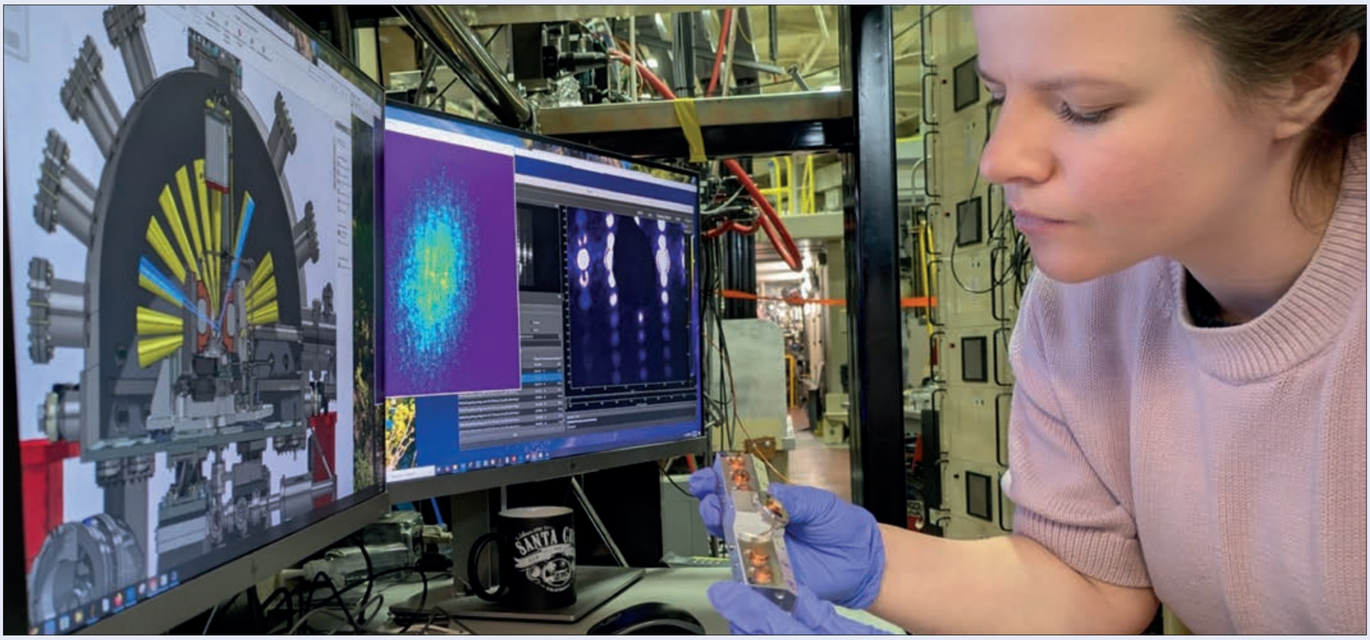
Yet Sheldon remains upbeat about addressing the skills gap. "There are just so many opportunities in the quantum sector," she notes. "The field has changed beyond all recognition since I finished my PhD." Perhaps the biggest shift has been the dramatic growth of industry engagement and, with it, all sorts of attractive career pathways for graduate scientists and engineers. Those range from firms developing quantum software or hardware to the end-users of quantum technologies in sectors such as pharmaceuticals, finance or healthcare.

"As for the scientific community," argues Sheldon, "we're also seeing the outline take shape for a new class of quantum computational scientist. Make no mistake, students able to integrate quantum computing capabilities into their research projects will be at the leading edge of their fields in the coming decades."

Ultimately, Sheldon concludes, early-career scientists shouldn't necessarily over-think things regarding that near-term professional pathway. "Keep it simple and work with people you like on projects that are going to interest you – whether quantum or otherwise."

Joe McEntee is a consultant editor based in South Gloucestershire, UK

Ask me anything: Sophie Morley



Sophie Morley, who has a PhD in physics from the University of Leeds in the UK, is a staff scientist at the Advanced Light Source (ALS) synchrotron facility – part of Lawrence Berkeley National Laboratory in California – where she helps visiting researchers to probe the fundamental properties of quantum materials.

The outreach activity is exciting and challenging in equal measure – whether that's initiating dialogue with quantum experts at scientific conferences or making first contact using Teams or Zoom

What skills do you use every day in your job?

I am one of two co-chairs, along with my colleague Hendrik Ohldag, of the Quantum Materials Research and Discovery Thrust Area at ALS. Among other things, our remit is to advise ALS management on long-term strategy regarding quantum science, We launch and manage beamline development projects to enhance the quantum research capability at ALS and, more broadly, establish collaborations with quantum scientists and engineers in academia and industry.

In terms of specifics, the thrust area addresses problems of condensed-matter physics related to spin and quantum properties – for example, in atomically engineered multilayers, 2D materials and topological insulators with unusual electronic structures. As a beamline scientist, active listening is the key to establishing productive research collaborations with our scientific end-users – helping them to figure out the core questions they're seeking to answer and, by extension, the appropriate experimental techniques to generate the data they need.

The task, always, is to translate external users' scientific goals into practical experiments that will run reliably on the ALS beamlines. High-level organizational skills, persistence and exhaustive preparation go a long way: it takes a lot of planning and dialogue to ensure scientific users get high-quality experimental results.

What do you like best and least about your job?

A core part of my remit is to foster the collective conversation between ALS staff scientists and the quantum community, demystifying synchrotron science and the capabilities of the ALS with prospective end-users. The outreach activity is exciting and challenging in equal measure – whether that's initiating dialogue with quantum experts at scientific conferences or making first contact using Teams or Zoom.

Internally, we also track the latest advances in fundamental quantum science and applied R&D. In-house colloquia are mandatory, with guest speakers from the quantum community engaging directly with ALS staff teams to figure out how our portfolio of synchrotron-based techniques – whether spectroscopy, scattering or imaging – can be put to work by users from research or industry. This learning and development programme, in turn, underpins continuous improvement of the beamline support services we offer to all our quantum end-users.

As for downsides: it's never ideal when a piece of instrumentation suddenly "breaks" on a Friday afternoon. This sort of troubleshooting is probably the part of the job I like least, though it doesn't happen often and, in any case, is a hit I'm happy to take given the flexibility inherent to my role.

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

It's still early days, but I guess the biggest lesson so far is to trust in my own specialist domain knowledge and expertise when it comes to engaging with the diverse research community working on quantum materials. My know-how in photon science – from coherent X-ray scattering and X-ray detector technology to *in situ* magnetic- and electric-field studies and automated measurement protocols – enables visiting researchers to get the most out of their beamtime at ALS.

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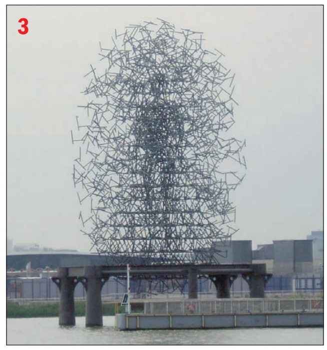
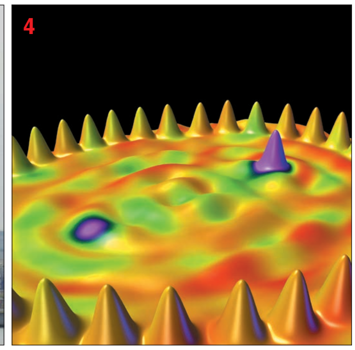
Quantum year quiz

INTERNATIONAL YEAR OF
Quantum Science
and Technology

Quantum physics can be baffling but see how much you know in this quiz devised by **Matin Durrani** to mark the International Year of Quantum Science and Technology (IYQ)

Jorge Cham; IOP Publishing





Andy Roberts IBM Research/Science Photo Library

1 Can you name the mascot for IYQ 2025?

2 In quantum cryptography, who eavesdrops on Alice and Bob?

3 Which artist made the *Quantum Cloud* sculpture in London?

4 IBM used which kind of atoms to create its *Quantum Mirage* image?

5 When Werner Heisenberg developed quantum mechanics on Helgoland in June 1925, he had travelled to the island to seek respite from what?
A His allergies
B His creditors
C His funders
D His lovers

6 According to the *State of Quantum 2024* report, how many countries around the world had government initiatives in quantum technology at the time of writing?
A 6
B 17
C 24
D 33

7 The E91 quantum cryptography protocol was invented in 1991. What does the E stand for?
A Edison
B Ehrenfest
C Einstein
D Ekert

8 British multinational consumer-goods firm Reckitt sells a "Quantum" version of which of its household products?
A Air Wick freshener
B Finish dishwasher tablets
C Harpic toilet cleaner
D Vanish stain remover

9 John Bell's famous theorem of 1964 provides a mathematical framework for understanding what quantum paradox?
A Einstein–Podolsky–Rosen
B Quantum indefinite causal order
C Schrödinger's cat
D Wigner's friend

10 Which celebrated writer popularized the notion of Schrödinger's cat in the mid-1970s?
A Douglas Adams
B Margaret Atwood
C Arthur C Clarke
D Ursula K le Guin

11 Which of these companies is not a real quantum company?
A Qblox
B Qruise
C Qrypt
D Qtips

12 Which celebrity was spotted in the audience at a meeting about quantum computers and music in London in December 2022?
A Peter Andre
B Peter Capaldi
C Peter Gabriel
D Peter Schmeichel

13 What of the following birds has not yet been chosen by IBM as the name for different versions of its quantum hardware?
A Condor
B Eagle
C Flamingo
D Peregrine

14 When quantum theorist Erwin Schrödinger fled Nazi-controlled Vienna in 1938, where did he hide his Nobel-prize medal?
A In a filing cabinet
B Under a pot plant
C Behind a sofa
D In a desk drawer

15 What destroyed the Helgoland guest house where Heisenberg stayed in 1925 while developing quantum mechanics?
A A bomb
B A gas leak
C A rat infestation
D A storm

● This quiz is for fun and there are no prizes. Answers will be revealed on the *Physics World* website in April.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