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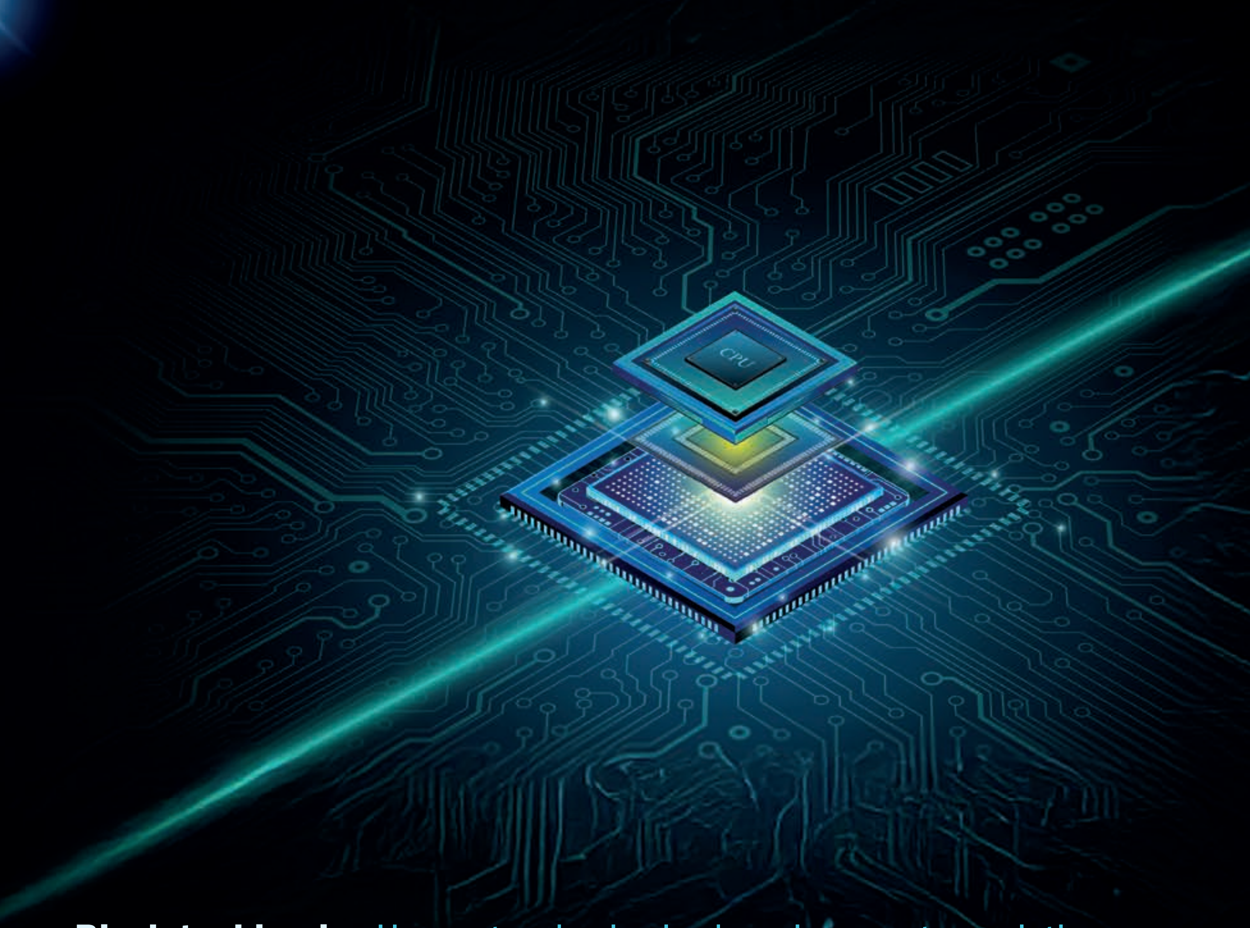
December 2025

Quantum computers: where next?

Error corrections, algorithms and applications



Big data, big wins How astrophysics is changing sports analytics

Curious thinker Thaisa Storchi Bergmann on her career in astronomy

Festive reviews From female quantum pioneers to the birth of the Web

physicsworld
Volume 38 No 12

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AUDIO *Physics World* editors discuss their highlights of the December issue

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Wrapping up IYQ

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physicsworld.com/p/magazine/archive/physics-world-quantum-briefing-part-2-2025

News & Analysis

NASA centre hit by major downsizing

The US space agency's Goddard Space Flight Center has already seen a third of its buildings shut over the past few months, as **Peter Gwynne** reports

NASA's Goddard Space Flight Center (GSFC) looks set to lose a big proportion of its budget as a two-decade reorganization plan for the centre is being accelerated. The move, which is set to be complete by March, has left the Goddard campus with empty buildings and disillusioned employees. Some staff even fear that the actions during the 43-day US government shutdown, which ended on 12 November, could see the end of much of the centre's activities.

Based in Greenbelt, Maryland, the GSFC has almost 10 000 scientists and engineers, about 7000 of whom are directly employed by NASA contractors. Responsible for many of NASA's most important uncrewed missions, telescopes and probes, the centre is currently working on the Nancy Grace Roman Space Telescope, which is scheduled to launch in 2027, as well as the Dragonfly mission that is due to head for Saturn's largest moon Titan in 2028.

The ability to meet those schedules has now been put in doubt by the Trump administration's proposed budget for financial year 2026, which started in September. It calls for NASA to receive almost $19bn – far less than the $25bn it has received for the past two years. If passed, Goddard would lose more than 42% of its staff. Congress, which votes on the final budget, is not planning to cut NASA so deeply as it prepares its 2026 budget proposal. But on 24 September, Goddard managers began what they told employees was "a series of moves…that will reduce our footprint into fewer buildings". The shift is intended to "bring down overall operating costs while maintaining the critical facilities we need for our core capabilities of the future".

While this is part of a 20-year "master plan" for the GSFC that NASA's leadership approved in 2019, the management's memo stated that "all planned moves will take place over the next several months and be completed by March 2026". A report in September by Democratic members of the Senate Committee on Commerce, Science, and Transportation, which is responsible for NASA, asserts that the cuts are "in clear violation of the [US] constitution [without] regard for the impacts on NASA's science missions and workforce".

Under threat
With NASA's budget potentially dropping from $25bn to $19bn, its Goddard Space Flight Center has closed a third of its buildings since September.

On 3 November the Goddard Engineers, Scientists and Technicians Association, a union representing NASA workers, reported that the GSFC had already closed over a third of its buildings, including some 100 labs. This had been done, it says, "with extreme haste and with no transparent strategy or benefit to NASA or the nation". The union adds that the "closures are being justified as cost-saving but no details are being provided and any short-term savings are unlikely to offset a full account of moving costs and the reduced ability to complete NASA missions".

> The closures are being justified as cost-saving but no details are being provided

Accounting for the damage

Zoe Lofgren, the lead Democrat on the House of Representatives Science Committee, has demanded of Sean Duffy, NASA's acting administrator, that the agency "must now halt" any laboratory, facility and building closure and relocation activities at Goddard. In a letter to Duffy dated 10 November, she also calls for the "relocation, disposal, excessing or repurposing of any specialized equipment or mission-related activities, hardware and systems" to also end immediately.

As *Physics World* went to press, Lofgren demanded that NASA complete a "full accounting of the damage inflicted on Goddard thus far". Owing to the government shutdown, no GSFC or NASA official responded to *Physics World*'s requests for comment.

Meanwhile, the Trump administration has renominated billionaire entrepreneur Jared Isaacman as NASA's administrator. Trump had originally nominated Isaacman, who had flown on a private SpaceX mission and carried out a spacewalk, on the recommendation of SpaceX founder Elon Musk. But the administration withdrew the nomination in May following concerns among some Republicans that Isaacman had funded the Democrat party.

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

Education

Lower exam stakes could cut the gender grade gap

Female university students do much better in introductory physics exams if they have the option of retaking the tests. That's according to a new analysis of almost two decades of US exam results for more than 26 000 students. The study's authors say it shows that female students benefit from lower-stakes assessments and that the persistent "gender grade gap" in physics exam results does not reflect a gender difference in physics knowledge or ability (*Phys. Rev. Phys. Educ. Res.* **21** 020134).

The study has been carried out by David Webb from the University of California, Davis, and Cassandra Paul from San Jose State University. It builds on previous work they did in 2023, which showed that the gender gap disappears in introductory physics classes that offer the chance for all students to retake the exams. That study did not, however, explore why the offer of a retake has such an impact.

In the new work, the duo analysed exam results from 1997 to 2015 for a series of introductory physics classes at a public university in the US. The dataset included 26 783 students, mostly in biosciences, of whom about 60% were female. Some of the classes let students retake exams while others did not, thereby letting the researchers explore why retakes close the gender gap. When Webb and Paul examined the data for classes that offered retakes, they found that in first-attempt exams, female students slightly outperformed their male counterparts. But male students performed better than female students in retakes.


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Exploring the divide
The gender gap in exam results has been shown to be much larger in the high-stakes classes that do not allow retakes.

This, the researchers argue, discounts the notion that retakes close the gender gap by allowing female students to improve their grades. Instead, they suggest that the benefit of retakes is that they lower the stakes of the first exam.

The researchers then compared the classes that offered retakes with those that did not, which they called high-stakes courses. They found that the gender gap in exam results was much larger in the high-stakes classes than the lower-stakes classes that allowed retakes.

"This suggests that high-stakes exams give a benefit to men, on average, [and] lowering the stakes of each exam can remove that bias," Webb told *Physics World*. He thinks that as well as allowing students to retake exams, physics might benefit from not having comprehensive high-stakes final exams but instead "use final exam time to let students retake earlier exams".

Michael Allen

Jim Al-Khalili celebrates Quantum Year at the Royal Institution

Matin Durrani

Author, physicist and broadcaster Jim Al-Khalili gave a public lecture at the Royal Institution (RI) in central London on 7 November as the final part of a week-long series of events in the UK organized by the Institute of Physics to mark the International Year of Quantum Science and Technology. A theorist based at the University of Surrey, Al-Khalili's lecture was titled "A new quantum world: 'spooky' physics to tech revolution". It formed part of the RI's famous Friday night "discourses", which this year celebrate their 200th anniversary. Al-Khalili, who also presents *A Life Scientific* on BBC Radio 4, is now the only person ever to have given three RI discourses. After the lecture, which was sold out, he took part in a panel discussion with fellow physicists Peter Knight from Imperial College and Elizabeth Cunningham, a former vice-president for membership at the IOP. Al-Khalili was later presented with a special bottle of "Glentanglement" whisky made by Glasgow-based Fraunhofer UK for the Scottish Quantum Technology cluster.
Matin Durrani

Funding

JPL lays off 10% of staff

NASA's Jet Propulsion Laboratory (JPL) is to lay off some 550 employees as part of a restructuring that began in July. The action affects about 11% of JPL's employees and represents the lab's third downsizing in the past 20 months. When the layoffs are complete by the end of the year, the lab will have roughly 4500 employees, down from about 6500 at the start of 2024. A further 4000 employees have already left NASA during the past six months via sacking, retirement or voluntary buyouts.

Managed by the California Institute of Technology in Pasadena, JPL oversees scientific missions such as the Psyche asteroid probe, the Europa Clipper and the Perseverance rover on Mars. JPL bosses already laid off about 530 staff – and 140 contractors – in February last year followed by another 325 people in November 2024.

JPL director Dave Gallagher insists, however, that the new layoffs are not related to the US government shutdown that ended on 12 November (see p3). "[They are] essential to securing JPL's future by creating a leaner infrastructure, focusing on our core technical capabilities, maintaining fiscal discipline, and positioning us to compete in the evolving space ecosystem," he says in a message to employees.

Judy Chu, Democratic Congresswoman for the constituency that includes JPL, is less optimistic. "Every layoff devastates the highly skilled and uniquely talented workforce that has made these accomplishments possible," she says. "Together with last year's layoffs, this will result in an untold loss of scientific knowledge and expertise."

John Logsdon, professor emeritus at George Washington University and founder of the university's Space Policy Institute, says that the cuts are a direct result of the Trump administration's approach to science and technology. "The administration gives low priority to robotic science and exploration, and has made draconic cuts to the science budget," he told *Physics World*.

Peter Gwynne
Boston, MA

Publishing

Chinese scientists lead more collaborations

International research collaborations will be increasingly led by scientists in China over the coming decade. That is according to a new study by researchers at the University of Chicago, which finds that the power balance in international science has shifted markedly away from the US and towards China over the last 25 years (*Proc. Natl Acad. Sci.* **122** e2414893122).

To explore China's role in global science, the team used a machine-learning model to predict the lead researchers of almost six million scientific papers that involved international collaboration listed by online bibliographic catalogue OpenAlex. The model was trained on author data from 80 000 papers published in high-profile journals that routinely detail author contributions, including team leadership.

Taking the lead Researchers predict that "leadership parity" between China and US scientists will be reached in the next few years.

iStock

The study found that between 2010 and 2012 there were only 4429 scientists from China who were likely to have led China–US collaborations. By 2023 this number had risen to 12 714, meaning that the proportion of team leaders affiliated with Chinese institutions had gone up from 30% to 45%.

If this trend continues, China will hit "leadership parity" with the US in chemistry, materials science and computer science by 2028, with maths, physics and engineering being level by 2031. The analysis also suggests that China will achieve leadership parity with the US in eight "critical technology" areas by 2030, including AI, semiconductors, communications, energy and high-performance computing. For China–UK partnerships, the model found that equality had already been reached in 2019, while EU–China leadership roles will be on par this year or next.

Michael Allen

Space

Shenzhou-20 return delayed by space debris

China delayed the return of a crewed mission to the country's space station last month after the astronaut's spacecraft was struck by space debris. The craft was supposed to return to Earth on 5 November but after an impact analysis and risk assessment, China Manned Space Agency brought the astronauts home on another craft nine days later.

The Shenzhou programme involves taking astronauts to and from China's Tiangong space station, which was constructed in 2022, for six-month stays. Shenzhou-20, carrying three crew, launched on 24 April from Jiuquan Satellite Launch Center on board a Long March 2F rocket. Once docked with Tiangong the three-member crew of Shenzhou-19 began handing over control of the station to the crew of Shenzhou-20 before they returned to Earth on 30 April.

Space delay The crewed Shenzhou-20 spacecraft was launched on 24 April for a six-month mission to China's Tiangong space station.

China Manned Space Agency

Shenzhou-21, which also had a crew of three, launched on 31 October and underwent the same hand-over process with the crew of Shenzhou-20 before they were set to return to Earth. But pre-operation checks revealed that the craft had been hit by "a small piece of debris" that resulted in "tiny cracks" in a window of the craft. The crew of Shenzhou-20 instead returned to Earth aboard Shenzhou-21 on 14 November.

Space debris is of increasing concern and this marks the first time that a crewed craft has been delayed due to a potential space debris impact. In 2021, for example, China noted that Tiangong had to perform two emergency avoidance manoeuvres to avoid fragments produced by Starlink satellites that were launched by SpaceX.

● Katherine Courtney, who chairs the Global Network on Sustainability in Space and Alice Gorman from Flinders University in Adelaide, Australia, appeared on a Physics World Live panel discussion about the impact of space debris that was held on 10 November. A recording of the event is available at tinyurl.com/9symny67

Michael Banks

Nobel laureate Chen-Ning Yang dies aged 103

Influential theoretical physicist carried out pioneering work on parity violation and advanced US–China collaboration, as **Michael Banks** explains

The Chinese particle physicist Chen-Ning Yang died on 18 October at the age of 103. Yang shared half of the 1957 Nobel Prize for Physics with Tsung-Dao Lee for their theoretical work that overturned the notion that parity is conserved in the weak force – one of the four fundamental forces of nature.

Born on 22 September 1922 in Hefei, China, Yang competed a BSc at the National Southwest Associated University in Kunming in 1942. After finishing an MSc in statistical physics at Tsinghua University two years later, he moved to the University of Chicago in the US in 1945 as part of a government-sponsored programme. He received his PhD in physics in 1948 working under the guidance of Edward Teller.

The following year Yang moved to the Institute for Advanced Study in Princeton, where he made pioneering contributions to quantum field theory, working together with Robert Mills. In 1953 they proposed the Yang–Mills theory, which became a cornerstone of the Standard Model of particle physics. It was also at Princeton where Yang began a fruitful collaboration with Lee, who died last year aged 97. Their work on parity – a property of elementary particles that expresses their behaviour upon reflection in a mirror – led to the duo winning the Nobel prize.

Particle pioneer Chen-Ning Yang paved the way to our understanding that parity is violated in the weak force.


CUHK

Parity puzzle

In the early 1950s, physicists had been puzzled by the decays of two subatomic particles, known as tau and theta, which are identical except that the tau decays into three pions with a net parity of –1, while a theta particle decays into two pions with a net parity of +1. There were two possible explanations: either the tau and theta are different particles or that parity in the weak interaction is not conserved with Yang and Lee proposing various ways to test their ideas (*Phys. Rev.* **104** 254).

This "parity violation" was later proved experimentally by, among others, Chien-Shiung Wu at Columbia University. She carried out an experiment based on the radioactive decay of unstable cobalt-60 nuclei into nickel-60 – what became known as the "Wu experiment". For their work, Yang, who was 35 at the time, shared the 1957 Nobel Prize for Physics with Lee.

Influential physicist

In 1965 Yang moved to Stony Brook University, becoming the first director of the newly founded Institute for Theoretical Physics, which is now known as the C N Yang Institute for Theoretical Physics. During this time, he also contributed to advancing science and education in China, setting up the Committee on Educational Exchange with China – a programme that has sponsored some 100 Chinese scholars to study in the US. In 1997 Yang returned to Beijing where he became an honorary director of the Centre for Advanced Study at Tsinghua University. He retired from Stony Brook in 1999, becoming a professor at Tsinghua University. During his time in the US, Yang obtained US citizenship, but renounced it in 2015.

More recently, Yang was involved in debates over whether China should build the Circular Electron Positron Collider (CEPC) – a huge 100 km circumference underground collider that would study the Higgs boson in unprecedented detail and be a successor to CERN's Large Hadron Collider. Yang took a sceptical view calling it "inappropriate" for a developing country that is still struggling with "more acute issues like economic development and environment protection".

Yang also expressed concern that the science performed on the CEPC is just "guess" work and without guaranteed results. "I am not against the future of high-energy physics, but the timing is really bad for China to build such a super collider," he noted in 2016. "Even if they see something with the machine, it's not going to benefit the life of Chinese people any sooner." As well as the Nobel prize, Yang won many other awards such as the US National Medal of Science in 1986, the Einstein Medal in 1995, which is presented by the Albert Einstein Society in Bern, and the American Physical Society's Lars Onsager Prize in 1990.

"The world has lost one of the most influential physicists of the modern era," noted Stony Brook president Andrea Goldsmith in a statement. "His legacy will continue through his transformational impact on the field of physics and through the many colleagues and students influenced by his teaching, scholarship and mentorship."

Michael Banks is news editor of *Physics World*

Research updates

First room-temperature superconductor

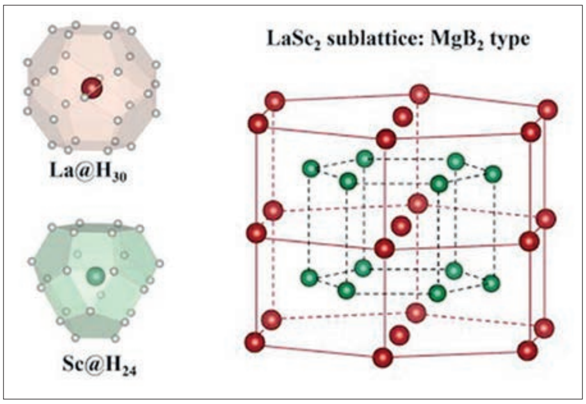
A ternary hydride shows signs of room-temperature superconductivity at high pressures, as **Isabelle Dumé** reports

Researchers in China claim to have made the first ever room-temperature superconductor by compressing an alloy of lanthanum-scandium (La-Sc) and the hydrogen-rich material ammonia borane (NH_3BH_3) together at pressures of 250–260 GPa, observing superconductivity with a maximum onset temperature of 298 K. While these high pressures are akin to those at the centre of the Earth, the work marks a milestone in the field of superconductivity, the physicists say (arXiv: 2510.01273).

Superconductors conduct electricity without resistance when cooled below a certain transition temperature, T_c. Researchers looking for superconductors that operate at high temperatures made considerable progress towards this goal in the 1980s and 1990s with the discovery of the "high-temperature" copper oxide superconductors, which have T_c values between 30 and 133 K. Fast-forward to 2015 and the maximum known critical temperature rose even higher thanks to the discovery of a sulphide material, H_3S, that has a T_c of 203 K when compressed to pressures of 150 GPa.

This result sparked much interest in solid materials containing hydrogen atoms bonded to other elements and in 2019, the record was broken again, this time by lanthanum decahydride (LaH_{10}), which was found to have a T_c of 250–260 K, albeit again at very high pressures. Then in 2021, researchers observed high-temperature superconductivity in the cerium hydrides, CeH_9 and CeH_{10}, which boast high-temperature superconductivity at lower pressures (about 80 GPa, or 0.8 million atmospheres) than the other so-called "superhydrides".

In recent years, researchers have started turning their attention to ternary hydrides – substances that comprise three different atomic species rather than just two. Compared with binary hydrides, ternary hydrides are more structurally complex, which may allow them to have higher T_c values. Indeed, Li_2MgH_{16} has been predicted to exhibit "hot" superconductivity with a T_c of 351–473 K under multimegabar pressures and several other high-T_c hydrides, including MB_xH_y, $MBeH_8$ and Mg_2IrH_{6-7}, have been predicted to be stable under comparatively lower pressures.



Under pressure The new high-T_c superconductor with the chemical formula $LaSc_2H_{24}$ has a transition temperature of 295 K at pressures of 250–260 GPa.

In the new work, a team led by physicist Yanming Ma of Jilin University studied $LaSc_2H_{24}$ – a compound that's made by doping scandium into the well-known La-H binary system. Ma and colleagues had already used a theoretical model to predict that this ternary material should feature a hexagonal *P6/mmm* symmetry. Introducing Sc into the La-H results in the formation of two novel interlinked H_{24} and H_{30} hydrogen clathrate "cages" with the H_{24} surrounding Sc and the H_{30} surrounding La.

The researchers calculated that these two novel hydrogen frameworks should produce an exceptionally large hydrogen-derived density of states at the Fermi level (the highest energy level that electrons can occupy in a solid at a temperature of absolute zero), as well as enhancing coupling between electrons and phonons in the material, leading to an exceptionally high T_c of up to 316 K at high pressure.

To create their material, the researchers placed it in a diamond-anvil cell while heating it with a laser. *In situ* X-ray diffraction experiments revealed that the compound crystallizes into a hexagonal structure, in excellent agreement with the predicted *P6/mmm* $LaSc_2H_{24}$ structure.

A key piece of experimental evidence for superconductivity in the La-Sc-H ternary system came from measurements that repeatedly demonstrated the onset of zero electrical resistance below the T_c. Another significant proof, co-author Guangtao Liu adds, is that the T_c decreases monotonically with the application of an external magnetic field in a number of independently synthesized samples. "This behaviour is consistent with the conventional theory of superconductivity since an external magnetic field disrupts Cooper pairs – the charge carriers responsible for the zero-resistance state – thereby suppressing superconductivity," says Liu.

Sven Friedemann of the University of Bristol, who was not involved in this work, says that the study is "an important step forward" for superconductivity. "The new measurements show zero resistance and suppression in magnetic fields, thus strongly suggesting superconductivity," he comments. "It will be exciting to see future work probing other signatures of superconductivity. The X-ray diffraction measurements could be more comprehensive and leave some room for uncertainty as to whether it is indeed the claimed $LaSc_2H_{24}$ structure giving rise to the superconductivity."

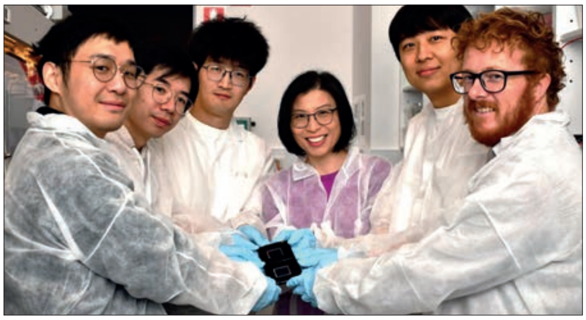
Ma and colleagues say they will continue to study the properties of this compound – such as the isotope effect and directly detect the Meissner effect – as well as synthesize new multinary superhydrides.

Materials

Triple-junction perovskite solar cell breaks efficiency records

An international research team has produced the largest and most efficient triple-junction perovskite–perovskite–silicon tandem solar cell to date. The finding shows that there could be potential for this triple-junction architecture in real-world settings in the near future, even though they are still far away from their theoretical efficiency limits (*Nat. Nanotechnol.* doi:10.1038/s41565-025-02015-x).

Multi-junction solar cells have a vertical stack of semiconductor materials with distinct bandgaps, with each layer converting a different part of the solar spectrum to maximize conversion of the Sun's energy to electricity. When there are no constraints on the choice of materials, triple-junction solar cells can outperform double-junction and single-junction solar cells, with a power conversion efficiency (PCE) of up to 51% theoretically possible. But material constraints – due to fabrication complexity, cost or other technical challenges – mean that many such devices still perform far from the theoretical limits.



The University of Sydney

Record breaker The team at the University of Sydney have created a 16 cm^2 triple-junction perovskite-based solar cell that achieves a power conversion efficiency of 23.3% – the highest reported for a large-area device.

Solar cells formed from metal halide perovskites could be commercially viable, being cheap, efficient, easy to make and able to be paired with silicon in multi-junction devices. The ease of fabrication means that the junctions can be directly fabricated on top of each other. However, these junctions can still contain surface defects.

To enhance the performance and resilience of their triple-junction cell, in which the top and middle are perovskite junctions on a bottom silicon cell, the researchers addressed surface defects in the top perovskite junction by replacing traditional lithium fluoride materials with piperazine-1,4-diium chloride (PDCl). They also replaced methylammonium – which is commonly used in perovskite cells – with rubidium.

With this design, Anita Ho-Baillie from the University of Sydney and colleagues developed a 16 cm^2 triple-junction cell that achieved an independently certified steady-state PCE of 23.3% – the highest reported for a large-area device. While triple-junction perovskite solar cells have exhibited higher PCEs – with all-perovskite triple-junction cells reaching 28.7% and perovskite–perovskite–silicon devices reaching 27.1% – these were all achieved on a 1 cm^2 cell, not on a large-area cell.

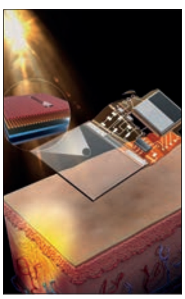
In the study, the researchers also developed a 1 cm^2 cell that had a PCE of 27.06% and passed the International Electrotechnical Commission's 61215 thermal cycling test, which exposes the cell to 200 cycles under extreme temperature swings, ranging from −40 to 85 °C. During this test, the 1 cm^2 cell retained 95% of its initial efficiency after 407 h of continuous operation.

Liam Critchley

Wearable UVA sensor monitors overexposure to sunlight

A flexible and wearable sensor that allows the user to monitor their exposure to ultraviolet (UV) radiation has been unveiled by researchers in South Korea. Based on a heterostructure of four different oxide semiconductors, the sensor's flexible, transparent design could vastly improve the real-time monitoring of skin health (*Sci. Adv.* 11 eaea7218).

UV light in the A band has wavelengths of 315–400 nm and comprises about 95% of UV radiation that reaches the surface of the Earth. Because of its relatively long wavelength, UVA can penetrate deep into the skin, where it can alter biological molecules, damage tissue and even cause cancer. Materials used for traditional UV sensors, such as gallium nitride and zinc oxide, are opaque and rigid – making them completely unsuitable for use in wearable sensors, which could monitor UVA levels in real time and alert users when their UVA exposure reaches a certain level.



Innovation Studio

Warning sign The researchers integrated their heterostructure of oxide semiconductors into a wearable detector that enabled the real-time display of UVA intensity as well as warning alerts.

In their study, Seong Jun Kang at Kyung Hee University and colleagues addressed these challenges by introducing a multi-junction heterostructure, made by stacking multiple ultrathin layers of different oxide semiconductors. The four semiconductors they selected each had wide bandgaps, which made them more transparent in the visible spectrum but responsive to UV light.

The structure included zinc and tin oxide layers as n-type semiconductors (doped with electron-donating atoms) and cobalt and hafnium oxide layers as p-type semiconductors (doped with electron-accepting atoms) – creating positively charged holes. Within the heterostructure, this selection created three types of interface: p–n junctions between hafnium and tin oxide; n–n junctions between tin and zinc oxide; and p–p junctions between cobalt and hafnium oxide.

When the team illuminated their heterostructure with UVA photons, the electron–hole charge separation was enhanced by the p–n junction, while the n–n and p–p junctions allowed for more efficient transport of electrons and holes respectively, improving the design's response speed. When the illumination was removed, the electron–hole pairs could quickly decay, avoiding any false detections.

To test their design's performance, the researchers integrated their heterostructure into a wearable detector that enabled real-time display of UVA intensity and warning alerts. The team believes its design could push the capabilities of oxide semiconductors beyond their typical use in displays and into the fast-growing field of smart personal health monitoring.

Sam Jarman

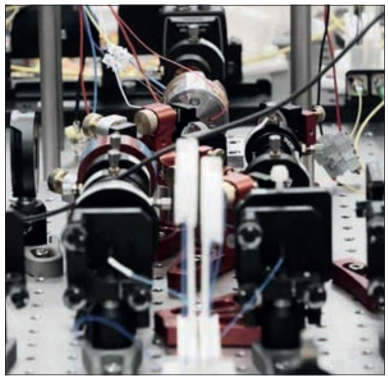
Quantum physics

Entangled light leads to quantum advantage

Physicists at the Technical University of Denmark (DTU) have demonstrated what they call "strong and unconditional" quantum advantage in a photonic platform for the first time. Using entangled light, they were able to reduce the number of measurements required to characterize their system by a factor of 10^{11}, reducing the time it would take a conventional scheme from 20 million years to just 15 minutes using entanglement (*Science* 389 1332).

Quantum devices are hard to isolate from their environment, which makes it a challenge to learn about their behaviour. To get around this problem, researchers have tried various "quantum learning" strategies that replace individual measurements with collective, algorithmic ones. These strategies have already been shown to reduce the number of measurements required to characterize certain quantum systems, such as superconducting electronic platforms containing tens of qubits, by as much as a factor of 10^5.

In the new study, the researchers obtained a quantum advantage in an alternative "continuous-variable" photonic platform. The team's experiment works with conventional, "imperfect" optical components and consists of a channel containing multiple light pulses that share the same pattern, or signature, of noise.



Jonas Schou Neergaard-Nielsen

Bench test
The researchers say that their next step is to demonstrate quantum advantage in a more practical set-up.

The researchers began by performing a procedure known as quantum squeezing on two beams of light in their system, which caused the beams to become entangled. The team then measured the properties of one of the beams (the "probe" beam) in an experiment known as a 100-mode bosonic displacement process. According to DTU physicist Romain Brunel, the experiment is like tweaking the properties of 100 independent light modes, which are packets or beams of light. "A 'bosonic displacement process' means you slightly shift the amplitude and phase of each mode, like nudging each one's brightness and timing," he explains. "So, you then have 100 separate light modes, and each one is shifted in phase space according to a specific rule or pattern."

By comparing the probe beam to the second ("reference") beam in a single joint measurement, Brunel explains that they were able to cancel out many of the uncertainties in these measurements. This meant they could extract more information per trial than they could have by characterizing the probe beam alone. This information boost, in turn, allowed them to significantly reduce the number of measurements – in this case, by a factor of 10^{11}.

While the researchers acknowledge that they have not yet studied a practical, real-world system, they emphasize that their platform is capable of "doing something that no classical system will ever be able to do", which is the definition of a quantum advantage. "Our next step will therefore be to study a more practical system in which we can demonstrate a quantum advantage," Brunel told *Physics World*.

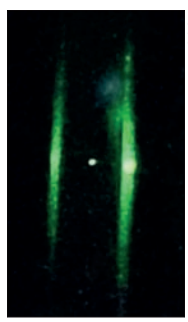
Isabelle Dumé

Physicists 'quantum squeeze' a nanoparticle for the first time

Physicists at the University of Tokyo in Japan have performed quantum mechanical squeezing on a nanoparticle for the first time. The feat, which they achieved by levitating the particle and rapidly varying the frequency at which it oscillates, could allow for a better understanding of how very small particles transition between classical and quantum behaviours as well as lead to improvements in quantum sensors (*Science* **389** 1225).

Oscillating objects that are smaller than a few microns in diameter have applications in optical clocks and quantum sensors. Such objects are small enough to be affected by Heisenberg's uncertainty principle, which places a limit on how precisely the position and momentum of a quantum object can be measured simultaneously. In this case, the only way to decrease the uncertainty in one variable is to boost the uncertainty in the other. This process has no classical equivalent and is called squeezing because reducing uncertainty along one axis of position–momentum space creates a "bulge" in the other, like squeezing a balloon.

In the new work, the researchers studied a single, charge-neutral nanoparticle levitating in an optical lattice created by lasers. After levitating the particle and cooling it to its motional ground state, the team rapidly varied the intensity of the lattice laser. This had the effect of changing the particle's oscillation frequency, which in turn changed the uncertainty in its momentum. To measure this change – and prove they had demonstrated quantum squeezing – the researchers then released the nanoparticle from the trap and let it propagate for a short time before measuring its velocity. By repeating these time-of-flight measurements many times, they were able to obtain the particle's velocity distribution.



Kamba et al 2025

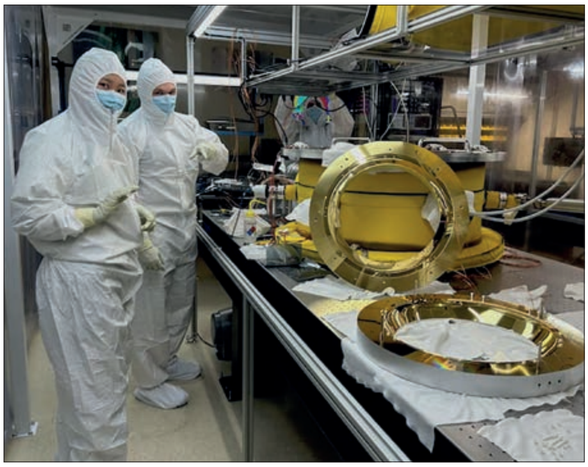
A squash and a squeeze
The team demonstrated quantum squeezing via a single, charge-neutral nanoparticle levitating in an optical lattice.

The tell-tale sign of quantum squeezing, the physicists say, is that the velocity distribution they measured for the nanoparticle was narrower than the uncertainty in velocity for the nanoparticle at its lowest energy level. Indeed, the measured velocity variance was narrower than that of the ground state by 4.9 dB, which they say is comparable to the largest mechanical quantum squeezing obtained thus far. "Our system will enable us to realize further exotic quantum states of motions and to elucidate how quantum mechanics should behave at macroscopic scales and become classical," Kiyotaka Aikawa told *Physics World*.

Isabelle Dumé

Optics

Adaptive optics technique boosts the power of gravitational wave detectors


J Richardson

Worth a shot
A novel adaptive optics device is designed to reduce quantum shot noise on gravitational-wave detectors to open up new detection frequencies.

Future versions of the Laser Interferometer Gravitational Wave Observatory (LIGO) will be able to run at much higher laser powers thanks to a sophisticated new system that compensates for temperature changes in optical components. Known as the FROnt Surface Type Irradiator (FROSTI) and developed by physicists at the University of California Riverside, US, the system will enable next-generation machines to detect gravitational waves emitted when the universe was just 0.1% of its current age, before the first stars had even formed (*Optica* **12** *1569*).

Detecting and studying gravitational waves is done via measuring differences in distance via a laser with an accuracy of 10^{-19} m. Despite this challenge, for the past decade, LIGO and two smaller facilities, KAGRA and VIRGO, have observed gravitational waves at frequencies ranging from 30–2000 Hz. Yet observing waves at lower and higher frequencies in the gravitational wave spectrum remains challenging. At lower frequencies (around 10–30 Hz), the problem stems from vibrational noise in the 40 kg mirrors. The incredible precision required to detect gravitational waves at these frequencies means that even the minute amount of energy the mirrors absorb from the laser beam can affect them.

At higher frequencies (150–2000 Hz), measurements are instead limited by quantum shot noise. Caused by the random arrival time of photons at LIGO's output photodetectors, it is a fundamental consequence of the fact that the laser field is quantized. FROSTI is designed to reduce quantum shot noise by allowing the mirrors to cope with much higher levels of laser power. At its heart is a novel adaptive optics device that is designed to precisely reshape the surfaces of LIGO's main mirrors under laser powers exceeding 1 megawatt (MW), which is nearly five times the power used at LIGO today. FROSTI uses heat to restore the mirror's surface to its original shape. It does this by projecting infrared radiation onto test masses in the interferometer to create a custom heat pattern that "smooths out" distortions and so allows for fine-tuned, higher-order corrections.

Jonathan Richardson, who led the study, says that FROSTI will be a critical component of future LIGO upgrades as well as in the design of future gravitational-wave detectors, such as Cosmic Explorer. "The current prototype has been tested on a 40 kg LIGO mirror, but the technology is scalable and will eventually be adapted to the 440 kg mirrors envisioned for Cosmic Explorer," he says.

Isabelle Dumé

Fluid dynamics

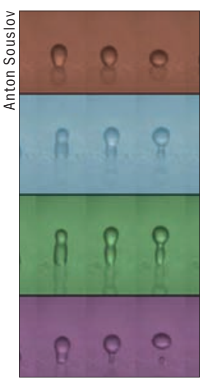
Here's how fast-moving droplets stick to hydrophobic surfaces

Researchers in the UK have discovered a velocity-dependent condition for when microscopic droplets of water land on a water-repelling surface. The work could have applications when spraying crops with pesticides or studying the spread of disease-causing aerosols (*Proc. Natl. Acad. Sci.* 122 e2507309122).

While single-droplet impact has been widely studied, a lot of previous work focused on millimetre-sized drops taking place on millisecond timescales. Previous research had also shown that on perfectly non-wetting surfaces, bouncing does not depend on velocity. The researchers wanted to study droplet sizes between 30–50 μm as they strike water-repelling surfaces at speeds of 1–10 m/s, where higher surface-to-volume ratios make interfacial effects critical.

To produce the droplets, they used a piezoelectric droplet generator capable of dispensing fluid via tiny 30 μm nozzles. The team then compared its findings with calculations based on a simple mathematical model that treats a droplet like a tiny spring, taking into account its speed; the stickiness of the surface; the viscosity of the droplet liquid; and the droplet's surface tension. The team found that if a droplet moves either very slowly or quickly it tends to stick, but for velocities in between it will bounce given there is enough momentum to detach from the surface but not so much that it collapses back onto it.

They also discovered a size effect in which droplets that are too small cannot bounce, no matter what their speed. This size limit, they say, is set by the droplets' viscosity, which prevents the tiniest droplets from leaving the surface once they land on it.


Anton Souslov

Sticky issue
Whether a micron-sized droplet sticks or bounces when landing on a hydroscopic surface depends on its size and speed.

Jamie McLauchlan at the University of Bath, UK, who led the new research, thinks that by linking bouncing to droplet velocity, size and surface properties, the new framework could make it easier to engineer microdroplets for specific purposes. "In agriculture, for example, understanding how spray velocities interact with plant surfaces with different hydrophobicity could help determine when droplets deposit fully versus when they bounce away, improving the efficiency of crop spraying," he says. Such a framework could also be useful for studying airborne diseases, since exhaled droplets frequently bump into surfaces while floating around indoors. The researchers now plan to expand their work on aqueous droplets to droplets with more complex soft-matter properties.

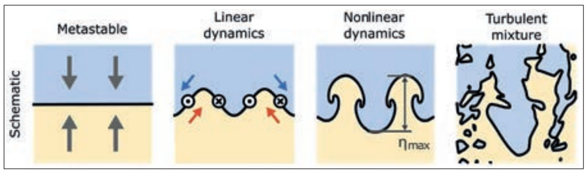
Isabelle Dumé

Fluid dynamics

Quantum fluids found to mix like oil and water

Researchers in the US have replicated a well-known fluid-dynamics process called the Rayleigh–Taylor instability on a quantum scale for the first time. The work opens the hydrodynamics of quantum gases to further exploration and could even create a new platform for understanding gravitational dynamics in the early universe (*Sci. Adv.* 11 eadw9752).

Due to their different molecular structures and the nature of the forces between their molecules, water and oil do not mix well. After some time, they separate, forming a clear interface between oil and water. Scientists have studied the dynamics of this interface via perturbations – disturbances of the system – for nearly 150 years. Under specific conditions related to the buoyant force of the fluid and the perturbative force causing the disturbance, they showed that this interface becomes unstable. Rather than simply oscillating, the system deviates from its initial state, leading to an instability and the formation of interesting geometric patterns such as mushroom clouds.



Mixing it up To study the Rayleigh–Taylor instability on a quantum scale, the team created a two-state quantum system using a Bose–Einstein condensate of sodium atoms.

To show that such dynamics occur not only in macroscopic structures, but also at a quantum scale, Ian Spielman from the University of Maryland and colleagues created a two-state quantum system using a Bose–Einstein condensate (BEC) of sodium-23 atoms. This state of matter is so cold that the sodium atoms behave as a single coherent system, giving researchers precise control of their parameters.

The team confined this BEC in a 2D optical potential before applying a microwave pulse that excites half of the atoms from the spin-down to the spin-up state. By adding a small magnetic field gradient along one of the horizontal axes, the researchers induce a force that acts on the two spin components in opposite directions due to the differing signs of their magnetic moments. This creates a clear interface between the spin-up and the spin-down atoms.

To initiate the Rayleigh–Taylor instability, the scientists perturbed the two-component BEC by reversing the magnetic field gradient, which consequently reverses the direction of the induced force. For a small differential force, they initially observed a sinusoidal modulation of the interface. After some time, the interface enters a nonlinear dynamics regime where the instability manifests through the formation of mushroom clouds. Finally, it becomes a turbulent mixture – and the larger the differential force, the more rapidly the system evolves.

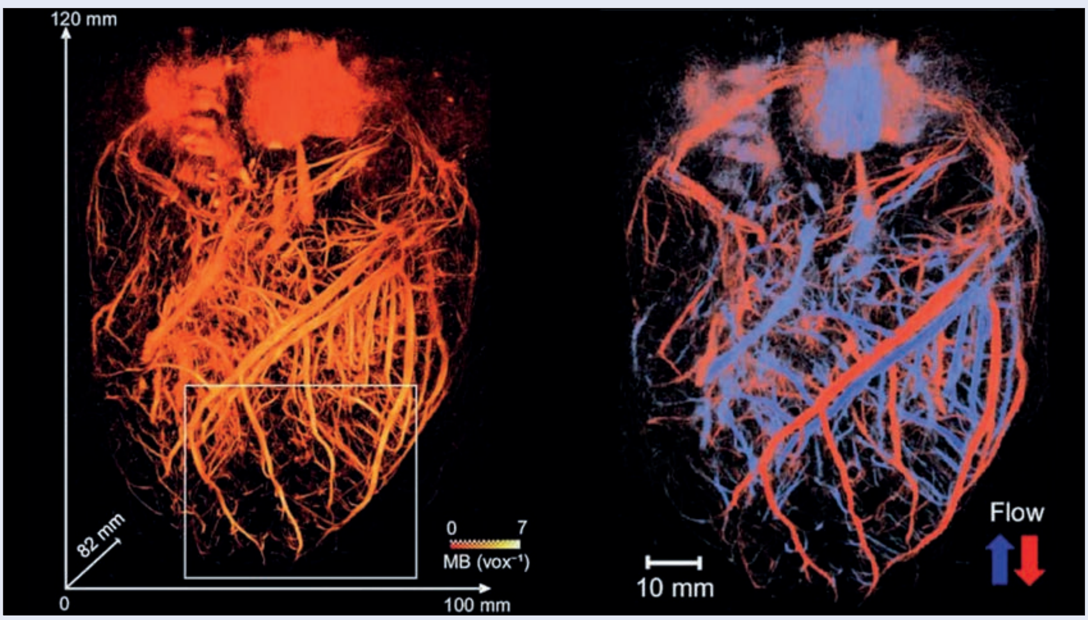
While Rayleigh–Taylor instability dynamics were expected to occur in quantum fluids, Spielman says that cold atoms are a great tool for studying the instability with the team now working to create a cleaner interface in its two-component BEC, which would allow a wider range of experiments.

Ali Lezeik

Ultrasound probe maps real-time blood flow across entire organs

Researchers in France have combined 3D ultrasound localization microscopy (ULM) with a multi-lens array method to image blood flow dynamics in entire organs with micron resolution (*Nat. Commun.* **16** 9317). 3D ULM has a spatial resolution roughly 10 times finer than conventional ultrasound and can map and quantify micro-scale vascular structures.

To enable a wide field of view, the team developed a multi-lens array probe that comprises 252 large (4.5 mm²) ultrasound transducer elements. The team used the probe to perform 3D dynamic ULM on an entire explanted porcine heart that was perfused with microbubble solution. This enabled the probe to visualize the whole coronary microcirculation network over 120 x 100 x 82 mm with a spatial resolution of around 125 μm. The probe could also assess flow dynamics across all vascular scales with the researchers estimating the absolute flow velocities ranging from 10 mm/s in small vessels to over 300 mm/s in the largest. The team now plans to begin a clinical trial and suggest s that the technique could evaluate kidney transplants as well as coronary microcirculation disorders.



Tami Freeman

Opinion

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A quantum future

A strong pipeline of skilled people is vital to maintain the UK's lead in quantum

As we enter the final stretch of the International Year of Quantum Science and Technology (IYQ), I hope you've enjoyed our extensive quantum coverage over the last 12 months. We've tackled the history of the subject, explored some of the unexplained mysteries of quantum physics, and examined many of the commercial applications of quantum technology. You can find most of our coverage collected into two free-to-read digital *Quantum Briefings*, available on the *Physics World* website.

One of my own highlights of IYQ was attending the Helgoland 2025 conference in June, which saw more than 300 physicists gather on the North Sea island where Werner Heisenberg made his pioneering breakthroughs 100 years ago.

Shutterstock/prawest; Shutterstock/VasylYurlov

Quantum mechanics has had immense practical ramifications in the form of "quantum 1.0" technologies – lasers, semiconductors and electronics. But as was clear from the UK National Quantum Technologies Showcase in London last month, the "quantum 2.0" revolution is in full swing. Attended by over 3000 people, the event featured over 110 exhibitors, including many firms exploiting basic quantum concepts such as entanglement and superposition for computing, sensing and communication.

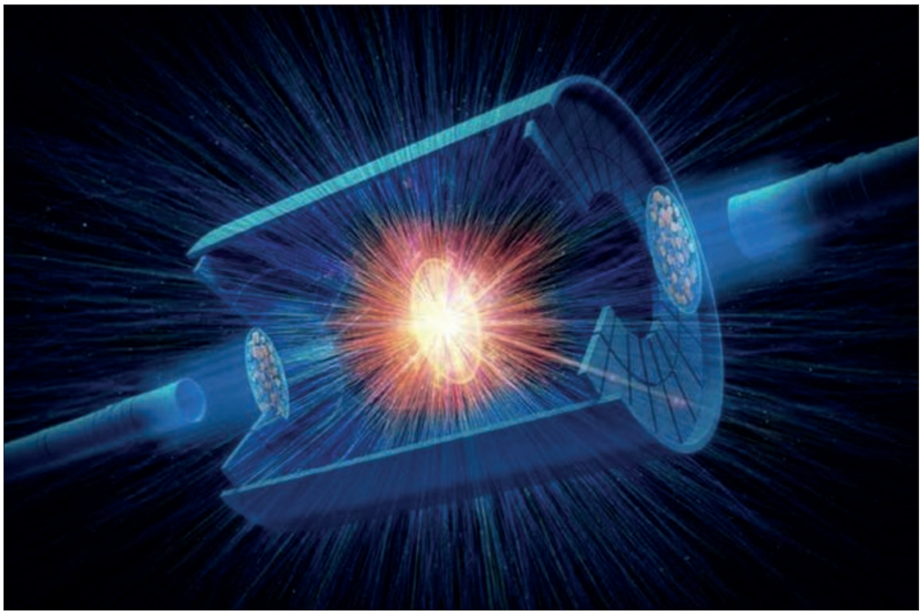
Last month also saw a two-day conference at the historic Royal Institution in central London that was a centrepiece of a week-long series of events organized by the Institute of Physics (IOP) to mark IYQ. The first day, focusing on the foundations of quantum mechanics, ended with a panel discussion – chaired by my colleague Tushna Commissariat and Daisy Shearer from the UK's National Quantum Computing Centre – with physicists Fay Dowker (Imperial College), Jim Al-Khalili (University of Surrey) and Peter Knight.

The second day included a discussion I chaired between four future leaders: Mehul Malik (Heriot-Watt University) and Sarah Malik (University College London) plus industry insiders Nicole Gillett (Riverlane) and Muhammad Hamza Waseem (Quantinuum). As well as outlining the technical challenges in their fields, the four speakers highlighted why physicists must work closely with industrialists, government officials and venture capitalists to ensure we reap the benefits of quantum tech. They also stressed the importance of developing a "skills pipeline" so that the quantum sector has enough talented people to meet its needs. By many measures, the UK is at the forefront of quantum tech – and it is a lead it should not let slip.

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

Critical Point Trump's 'blitzkrieg'?

Robert P Crease wonders if the Trump administration's sudden closure of many long-standing science advisory panels amounts to what one academic calls a "blitzkrieg"



Chunjian Zhang/Fudan University and Jiangyong Jia/Stony Brook University

Crunch time The US High Energy Physics Advisory Panel, which offered community-led scientific advice to the US government on topics such as particle colliders, has been abruptly terminated.

"Drain the swamp!"

In the intense first few months of his second US presidency, Donald Trump has been enacting his old campaign promise with a vengeance. He's ridding all the muck from the American federal bureaucracy, he claims, and finally bringing it back under control.

Scientific projects and institutions are particular targets of his, with one recent casualty being the High Energy Physics Advisory Panel (HEPAP). Outsiders might shrug their shoulders at a panel of scientists being axed. Panels come and go. Also, any development in Washington these days is accompanied by confusion, uncertainty, and the possibility of reversal.

But HEPAP's dissolution is different. Set up in 1967, it's been a valuable and long-standing advisory committee of the Office of Science at the US Department of Energy (DOE). HEPAP has a distinguished track record of developing, supporting and reviewing high-energy physics programmes, setting priorities and balancing different areas. Many scientists are horrified by its axing.

The terminator

Since taking office in January 2025, Trump has issued a flurry of executive orders – presidential decrees that do not need Congressional approval, legislative review, or public debate. One order, which he signed in February, was entitled "Commencing the Reduction of the Federal Bureaucracy".

It sought to reduce parts of the government "that the President has determined are unnecessary", seeking to eliminate "waste and abuse, reduce inflation, and promote American freedom and innovation". While supporters see those as laudable goals, opponents believe the order is driving a stake into the heart of US science.

Hugely valuable, long-standing scientific advisory committees have been axed at key federal agencies, including NASA, the National Science Foundation, the Environmental Protection Agency, the National Oceanic and Atmospheric Administration, the US Geological Service, the National Institute of Health, the Food and Drug Administration, and the Centers for Disease Control and Prevention.

What's more, the committees were terminated without warning or debate, eliminating load-bearing pillars of the US science infrastructure. It was, as the Columbia University sociologist Gil Eyal put it in a recent talk, the "Trump 2.0 Blitzkrieg".

Then, on 30 September, Trump's enablers took aim at advisory committees at the DOE Office of Science. According to the DOE's website, a new Office of Science Advisory Committee (SCAC) will take over functions of the six former discretionary (non-legislatively mandated) Office of Science advisory committees.

"Any current charged responsibilities of these former committees will be transferred to the SCAC," the website states matter-of-factly. The committee will provide "independent, consensus advice regarding complex scientific and technical issues" to the entire Office of Science. Its members will be appointed by under secretary for science Dario Gil – a political appointee.

Apart from HEPAP, others axed without warning were the Nuclear Science Advisory Committee, the Basic Energy Sciences Advisory Committee, the Fusion Energy Sciences Advisory Committee, the Advanced Scientific Computing Advisory Committee, and the Biological and Environmental Research Advisory Committee.

Over the years, each committee served a different community and was represented by prominent research scientists who were closely in touch with other researchers. Each committee could therefore assemble the awareness of – and technical knowledge about – emerging promising initiatives and identify the less promising ones.

Many committee members only learned of the changes when they received letters or e-mails out of the blue informing them that their committee had been dissolved, that a new committee had replaced them, and that they were not on it. No explanation was given.

Physicists whom I have spoken to are appalled for two main reasons. One is that closing HEPAP and the other Office of Science committees will hamper both the technical support and community input that it has relied on to promote the efficient, effective and robust growth of physics.

"Speaking just for high-energy physics, HEPAP gave feedback on the DOE and NSF funding strategies and priorities for the high-energy physics experiments", says Kay Kinoshita from the University of Cincinnati, a former HEPAP member. "The panel system provided a conduit for information between the agencies and the community, so the community felt heard and the

The elimination of the advisory committees spreads the expertise so thinly as to increase the likelihood of political pressure on decisions

agencies were (mostly) aligned with the community consensus".

As Kinoshita continued: "There are complex questions that each panel has to deal with, even within the topical area. It's hard to see how a broader panel is going to make better strategic decisions, 'better' meaning in terms of scientific advancement. In terms of community buy-in I expect it will be worse."

Other physicists cite a second reason for alarm. The elimination of the advisory committees spreads the expertise so thinly as to increase the likelihood of political pressure on decisions. "If you have one committee you are not going to get the right kind of fine detail," says Michael Lubell, a physicist and science-policy expert at the City College of New York, who has sat in on meetings of most of the Office of Science advisory committees.

"You'll get opinions from people outside that area and you won't be able to get information that you need as a policy maker to decide how the resources are to be allocated," he adds. "A condensed-matter physicist for example, would probably have insufficient knowledge to advise DOE on particle physics. Instead, new committee members would be expected to vet programs based on ideological conformity to what the Administration wants."

The critical point

At the end of the Second World War, the US began to construct an ambitious long-range plan to promote science that began with the establishment of the National Science Foundation in 1950 and developed and extended ever since. The plan aimed to incorporate both the ability of elected politicians to direct science towards social needs and the independence of scientists to explore what is possible.

US presidents have, of course, had pet scientific projects: the War on Cancer (Nixon), the Moon Shot (Kennedy), promoting renewable energy (Carter), to mention a few. But it is one thing for a president to set science to producing a socially desirable product and another to manipulate the scientific process itself.

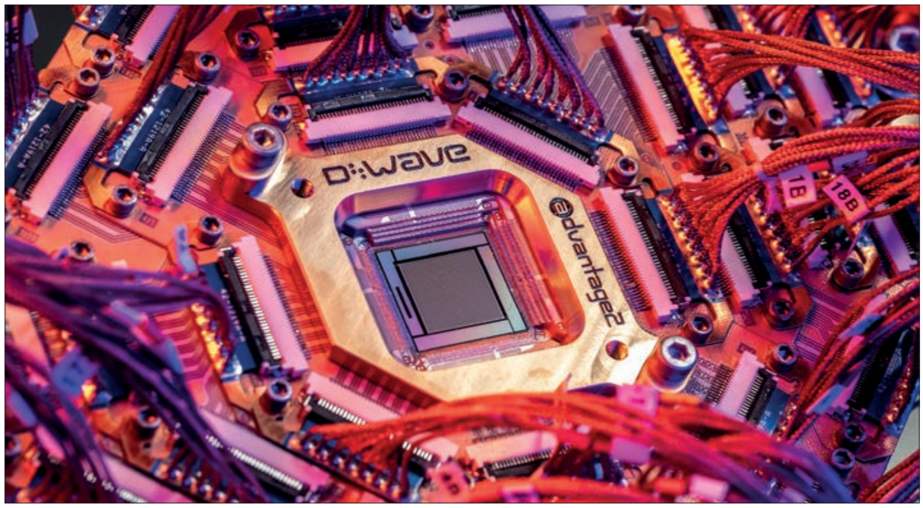
"This is another sad day for American science," says Lubell. "If I were a young person just embarking on a career, I would get the hell out of the country. I would not want to waste the most creative years of my life waiting for things to turn around, if they ever do. What a way to destroy a legacy!"

The end of HEPAP is not draining a swamp but creating one.

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 Quantum computing: hype or hope?

Are you baffled by quantum computers and bemused by what they could do? **Honor Powrie** offers her personal perspective about these devices and their current potential



D-Wave Quantum Inc.

Out in front D-Wave is one of the companies in the burgeoning quantum-computing sector.

Unless you've been living under a stone, you can't have failed to notice that 2025 marks the first 100 years of quantum mechanics. A massive milestone, to say the least, about which much has been written in *Physics World* and elsewhere in what is the International Year of Quantum Science and Technology (IYQ). However, I'd like to focus on a specific piece of quantum technology, namely quantum computing.

I keep hearing about quantum computers, so people must be using them to do cool things, and surely they will soon be as commonplace as classical computers. But as a physicist-turned-engineer working in the aerospace sector, I struggle to get a clear picture of where things are really at. If I ask friends and colleagues when they expect to see quantum computers routinely used in everyday life, I get answers ranging from "in the next two years" to "maybe in my lifetime" or even "never".

Before we go any further, it's worth reminding ourselves that quantum computing relies on several key quantum properties, including superposition, which gives rise to the quantum bit, or qubit. The basic building block of a quantum computer – the qubit – exists as a combination of 0 and 1 states at the same time and is represented by a probabilistic wave function. Classical computers, in contrast, use binary digital bits that are either 0 or 1.

Also vital for quantum computers is the notion of entanglement, which is when two or more qubits are co-ordinated, allowing them to share their quantum information. In a highly correlated system, a quantum computer can explore many paths simultaneously. This "massive scale" parallel processing is how quantum may solve certain problems exponentially faster than a classical computer.

The other key phenomenon for quantum computers is quantum interference. The wave-like nature of qubits means that when different probability amplitudes are in phase, they combine constructively to increase the likelihood of the right solution. Conversely, destructive interference occurs when amplitudes are out of phase, making it less likely to get the wrong answer.

Quantum interference is important in quantum computing because it allows quantum algorithms to amplify the probability of correct answers and suppress incorrect ones, making calculations much faster. Along with superposition and entanglement, it means that quantum computers could process and store vast numbers of probabilities at once, outstripping even the best classical supercomputers.

Towards real devices

To me, it all sounds exciting, but what have quantum computers ever done for us so far? It's clear that quantum computers are not ready to be deployed in the real world. Significant technological challenges need to be overcome before they become fully realisable. In any case, no-one is expecting quantum computers to displace classical computers "like for like": they'll both be used for different things.

Yet it seems that the very essence of quantum computing is also its Achilles heel. Superposition, entanglement and interference – the quantum properties that will make it so powerful – are also incredibly difficult to create and maintain. Qubits are also extremely sensitive to their surroundings. They easily lose their quantum state due to interactions with the environment, whether via stray particles, electromagnetic fields, or thermal fluctuations. Known as decoherence, it makes quantum computers prone to error.

That's why quantum computers need specialized – and often cryogenically controlled – environments to maintain the quantum states necessary for accurate computation. Building a quantum system with lots of interconnected qubits is therefore a major, expensive engineering challenge, with complex hardware and extreme operating conditions. Developing "fault-tolerant" quantum hardware and robust error-correction techniques will be essential if we want reliable quantum computation.

As for the development of software and algorithms for quantum systems, there's a long way to go, with a lack of mature tools and frameworks. Quantum algorithms require fundamentally different programming paradigms to those used for classical computers. Put simply, that's why building reliable, real-world deployable quantum computers remains a grand challenge.

What does the future hold?

Despite the huge amount of work that still lies in store, quantum computers have already demonstrated some amazing potential. The US firm D-Wave, for example, claimed earlier this year to have carried out simulations of quantum magnetic phase transitions that wouldn't be possible with the most powerful classical devices. If true, this was the first time a quantum computer had achieved "quantum advantage" for a practical physics problem (whether the problem was worth solving is another question).

There is also a lot of research and development going on around the world into solving the qubit stability problem. At some stage, there will likely be a breakthrough design for robust and reliable quantum computer architecture. There is probably a lot of technical advancement happening right now behind closed doors.

The first real-world applications of quantum computers will be akin to the giant classical supercomputers of the past. If you were around in the 1980s, you'll remember Cray supercomputers: huge, inaccessible beasts owned by large corporations, government agencies and academic institutions to enable vast amounts of calculations to be performed (provided you had the money).

> Quantum computing poses a major threat to existing encryption methods

And, if I believe what I read, quantum computers will not replace classical computers, at least not initially, but work alongside them, as each has its own relative strengths. Quantum computers will be suited for specific and highly demanding computational tasks, such as drug discovery, materials science, financial modelling, complex optimization problems and increasingly large artificial intelligence and machine-learning models.

These are all things beyond the limits of classical computer resource. Classical computers will remain relevant for everyday tasks like web browsing, word processing and managing databases, and they will be essential for handling the data preparation, visualization and error correction required by quantum systems.

And there is one final point to mention, which is cyber security. Quantum computing poses a major threat to existing encryption methods, with potential to undermine widely used public-key cryptography. There are concerns that hackers nowadays are storing their stolen data in anticipation of future quantum decryption.

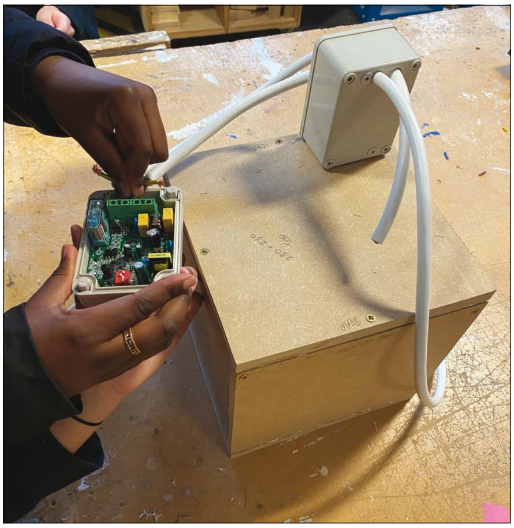
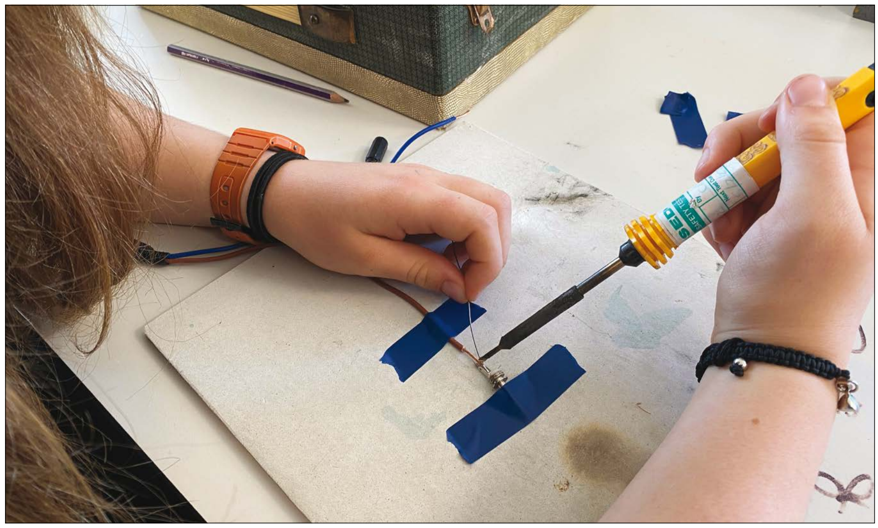
Having looked into the topic, I can now see why the timeline for quantum computing is so fuzzy and why I got so many different answers when I asked people when the technology would be mainstream. Quite simply, I still can't predict how or when the tech stack will pan out. But as IYQ draws to a close, the future for quantum computers is bright.

- More information about the quantum marketplace can be found in the feature by Philip Ball on pp28–32.

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

The ‘future of physics’ problem

Neil Downie believes that supporting students to devise, build and test their own projects can help to get them and their teachers interested in and enjoying physics

Calum Watterson and Tom Williams

Practical solutions Students who work on projects that they have devised can end up enjoying physics more as well as learning physics better and picking up important life skills such as team-working and giving presentations.

I hugely enjoyed physics when I was a youngster. I had the opportunity both at home and school to create my own projects, which saw me make electronic circuits, crazy flying models like delta-wings and autogiros, and even a gas chromatograph with a home-made chart recorder. Eventually, this experience made me good enough to repair TV sets, and work in an R&D lab in the holidays devising new electronic flow controls.

That enjoyment continued beyond school. I ended up doing a physics degree at the University of Oxford before working on the discovery of the gluon at the DESY lab in Hamburg for my PhD. Since then I have used physics in industry – first with British Oxygen/Linde and later with Air Products & Chemicals – to solve all sorts of different problems, build innovative devices and file patents.

While some students have a similarly positive school experience and subsequent career path, not enough do. Quite simply, physics at school is the key to so many important, useful developments, both within and beyond physics. But we have a physics education problem, or to put it another way – a “future of physics” problem.

There are just not enough school students enjoying and learning physics. On top of that there are not enough teachers enjoying physics and not enough students doing practical physics. The education problem is bad for physics and for many other subjects that draw on physics. Alas, it’s not a new problem but one that has been developing for years.

Problem solving

Many good points about the future of physics learning were made by the Institute of Physics in its 2024 report *Fundamentals of 11 to 19 Physics*. The report called for more physics lessons to have a practical element and encouraged more 16-year-old students in England, Wales and Northern Ireland to take AS-level physics at 17 so that they carry their GCSE learning at least one step further.

Doing so would furnish students who are aiming to study another science or a technical subject with the necessary skills and give them the option to take physics A-level. Another recommendation is to link physics more closely to T-levels – two-year vocational courses in England for 16–19 year olds that are equivalent to A-levels – so that students following that path get a background in key aspects of physics, for example in engineering, construction, design and health.

But do all these suggestions solve the problem? I don’t think they are enough and we need to go further. The key change to fix the problem, I believe, is to have student groups invent, build and test their own projects. Ideally this should happen before GCSE level so that students have the enthusiasm and background knowledge to carry them happily forward into A-level physics. They will benefit from “pull learning” – pulling in knowledge and active learning that they will remember for life. And they will acquire wider life skills too.

During my time in industry, I did outreach work with schools every few weeks and gave talks with demonstrations at the Royal Institution and the Franklin Institute. For many years I also ran a Saturday Science club in Guildford, Surrey, for pupils aged 8–15.

Developing skillsets

Based on this, I wrote four *Saturday Science* books about the many playful and original demonstrations and projects that came out of it. Then at the University of Surrey, as a visiting professor, I had small teams of final-year students who devised extraordinary engineering – designing superguns for space launches, 3D printers for full-size buildings and volcanic power plants inter alia. A bonus was that other staff working with the students got more adventurous too.

But that was working with students already committed to a scientific path. So lately I’ve been working with teachers to get students to devise and build their own innovative projects. We’ve had 14–15-year-old state-school students in groups of three or four, brainstorming projects, sketching possible designs, and gathering background informa-


Calum Watterson and Tom Williams

Ingenuity and failure Students benefit from practical physics projects whether they are brilliant successes or riddled with mistakes.

tion. We help them and get A-level students to help too (who gain teaching experience in the process). Students not only learn physics better but also pick up important life skills like brainstorming, team-working, practical work, analysis and presentations.

We've seen lots of ingenuity and some great projects such as an ultrasonic scanner to sense wetness of cloth; a system to teach guitar by lighting up LEDs along the guitar neck; and measuring breathing using light passing through a band of Lycra around the patient below the ribs. We've seen the value of failure, both mistakes and genuine technical problems.

Best of all, we've also noticed what might be dubbed the "combination bonus" – students having to think about how they combine their knowledge of one area of physics with another. A project involving a sensor, for example, will often involve electronics as well the physics of the sensor and so student knowledge of both areas is enhanced.

Some teachers may question how you mark such projects. The answer is don't mark them! Project work and especially group work is difficult to mark fairly and accurately, and the enthusiasm and increased learning by students working on innovative projects will feed through into standard school exam results.

Not trying to grade such projects will mean more students go on to study physics further, potentially to do a physics-related extended project qualification – equivalent to half an A-level where students research a topic to university level – and do it well. Long term, more students will take physics with them into the world of work, from physics to engineering or medicine, from research to design or teaching.

Such projects are often fun for students and teachers. Teachers are often intrigued and amazed by students' ideas and ingenuity. So, let's choose to do student-invented project work at school and let's finally solve the future of physics problem.

Neil Downie works with the British Physics Olympiad in the UK and abroad, and is a co-founder of the charity Exovent, which promotes negative-pressure breathing machines

Feedback

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

Dalén's legacy

In response to the feature "The physics Nobel prizes you've never heard of" by Margaret Harris about the 1908 and 1912 prizes being awarded, respectively, to Gabriel Lippmann and Gustaf Dalén (November pp28–32).

I read Harris's article with interest since I was born and raised not far from Dalén's hometown of Stenstorp, Sweden. Although Dalén is a Nobel laureate, very little has been written about him. I have not been able to find any extensive biography in English at all, and only two in Swedish: one from 2016 by Anders Johnson and an older book from the 1920s. There is also an entry for Dalén in the *Svenskt Biografiskt Lexikon* (the Swedish version of *Who's Who*) from 1931.

This lack of good sources may be why errors about Dalén's life have propagated in other languages. While Harris's article correctly states that Dalén enrolled at what is now Chalmers University of Technology, it is inaccurate to say he earned a doctorate there, since it was then a technical school and did not award doctorates. The article also glosses over the fact that Dalén did not immediately join the company AGA after finishing his year at ETH Zürich. Instead, he went to work for his mentor, Gustaf de Laval, before co-founding a company with a Chalmers colleague.

Dalén's connection to AGA began via Svenska Karbid & Acetylén AB, which hired him as head engineer in 1901. He left that company in 1904, but after it was reorganized as AB Gasaccumulator later that year, he became its consulting engineer. He took a full-time position at AGA in 1906 and was appointed chief executive in 1909 following a reconstruction that rescued the company from near bankruptcy.

Apart from his Nobel prize, Dalén's legacy includes a museum and science centre in Stenstorp; lighthouses in Sweden and Finland named after him; a lecture hall at Chalmers; an award in his name; and a 1954 biopic titled *Seger i mörker* ("Victory in Darkness"). He also donated a large portion of his Nobel prize money to AGA employees as an extra week's pay.

Jonas Persson
Norwegian University of Science and Technology, Trondheim, Norway

Margaret Harris replies:
Thank you for pointing out that Dalén could not (despite statements to the contrary in reputable English-language sources) have received a doctorate from Chalmers in 1896. We are happy to correct this part of the record, and to add Dalén's generous gift to his employees to the English-language information about his life.

AI and fusion

In response to the Transactions article by Honor Powrie, which says that the success of artificial intelligence (AI) will depend on good input data (October p23).

Powrie concludes that we will need a collective vigilance to avoid AI being turned into "garbage in, garbage squared". After reading these wise words, I came across a recent interview on the BBC website with US energy secretary Chris Wright, which advised us not to "worry too much about planet-warming emissions… because within five years AI will have enabled the harnessing of nuclear fusion".

AI is especially unreliable when asked to make predictions outside its training domain, and the bigger the extrapolation the worse it gets. This is not good news for fusion reactor designers, since even the fusion world records in terms of energy gain and other key parameters fall very far short of the ultimate requirements. Real-world AI training data spanning the fusion reactor domain therefore remain woefully inadequate or non-existent.

AI has been usefully applied to fusion R&D for rapid first-pass analysis using well-validated training data from experiments – but there's no reason to believe that it will magically find a quick fix for the plethora of complex physics and engineering problems that await would-be fusion reactors, which lie well beyond the limits of current experimental data. As far as fusion is concerned, we will need a collective vigilance to avoid AI being turned into "garbage in, garbage cubed out".

Guy Matthews
Oxfordshire, UK

Way too sunny

In response to Robert P Crease's interview with US physicist Richard Muller about his book *Physics for Presidents*, based on lectures he once gave at the University of California, Berkeley (October pp21–22).

The article describes how someone called Liz, who'd once taken one of Muller's courses, recently showed up at his office. According to Muller, Liz told him that in California, sunshine provides a gigawatt in a square kilometre and added that this was "about the space of a nuclear-power plant". The implication is that solar takes up about the same area as a nuclear-power plant.

But that intensity of sunlight occurs only for a few hours in the day. On average, it is around only one fifth of that value – and that is before the efficiency of the solar panels is taken into account. Undoubtedly, solar electricity can play an important part in the low-carbon mix, but statements like Liz's, which grossly overstates its capability, do it no favours.

Norman Wilson
Lancaster, UK

Hello aliens

In response to Hamish Johnston's review of *Do Aliens Speak Physics?* by Daniel Whiteson and Andy Warner (October pp24–25).

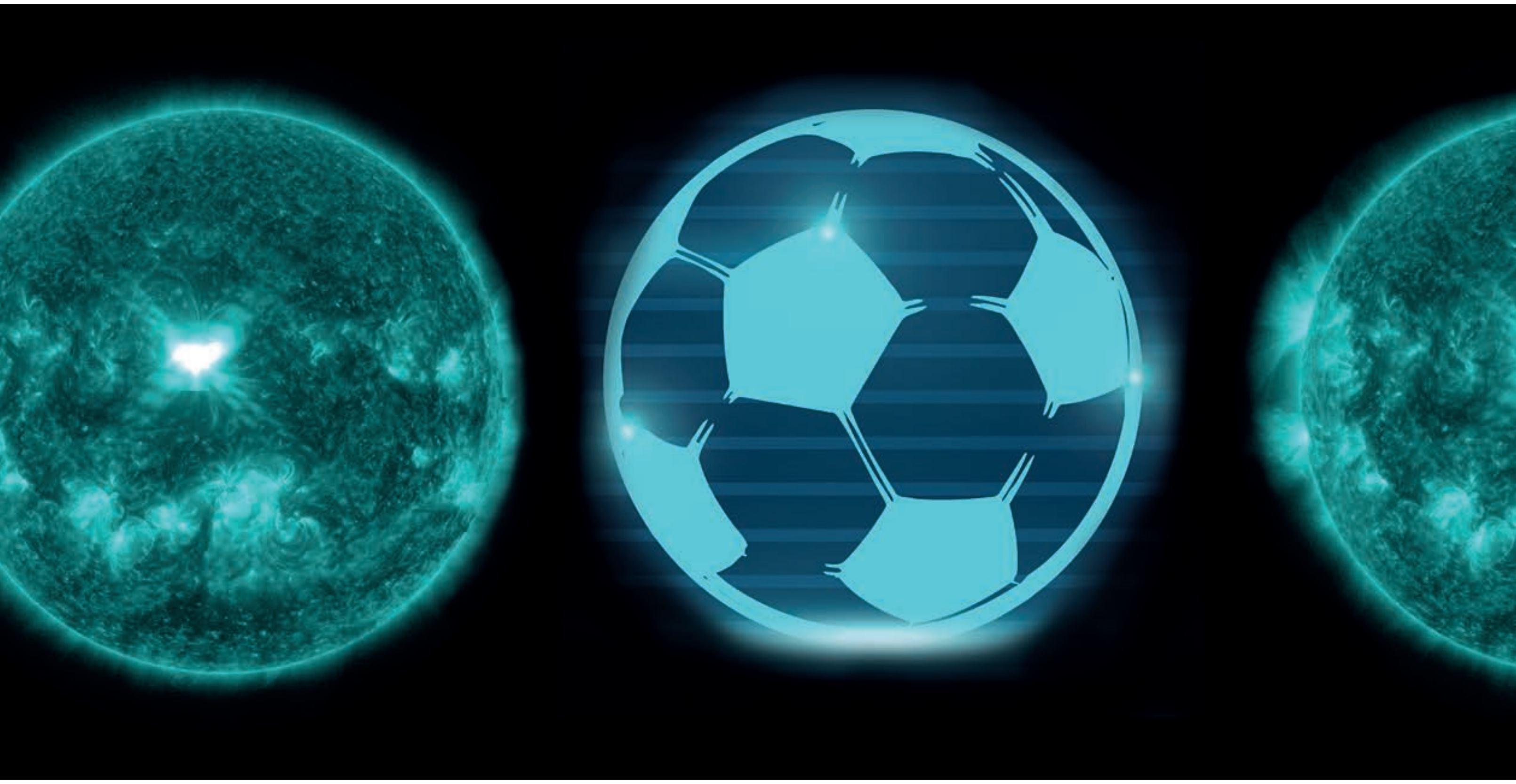
I wonder if readers are aware of an experiment supposedly proposed by Carl Friedrich Gauss in about 1820. He planned to buy a large tract of pine forest in the Siberian tundra, fell the trees, and lay out three vast squares in the pattern of the famous visual representation of the Pythagorean theorem. The idea was to plant wheat in the cleared areas to create a high-contrast image visible from space.

Any passing alien spacecraft, Gauss reasoned, would instantly recognize the mathematical proof and infer that intelligent life exists on Earth. In fact, Gauss believed that Mars harbours intelligent beings and calculated that, if the squares were "hundreds of miles in size", they would be visible to our planetary neighbours. Later scholarship has cast doubt on Gauss's authorship, suggesting the idea came from other astronomers, notably Joseph Johann von Littrow.

Attribution aside, it remains one of the most charmingly audacious attempts to say "hello" across the cosmos.

Colin White
Exeter, UK

Astrophysics and sports science:



David Jess and colleagues at Queen's University Belfast are joining the dots between the seemingly distant disciplines of solar physics and sports science. Joe McEntee assesses their game plan

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

If David Jess were a professional footballer – and not a professional physicist – he'd probably be a creative midfielder: someone who links defence and attack to set up goal-scoring opportunities for his team mates. Based in the Astrophysics Research Centre at Queen's University Belfast (QUB), Northern Ireland, Jess orchestrates his scientific activities in much the same way. Combining vision, awareness and decision-making, he heads a cross-disciplinary research team pursuing two very different and seemingly unconnected lines of enquiry.

Jess's research within the QUB's solar-physics groups centres on optical studies of the Sun's lower atmosphere. That involves examining how the Sun's energy travels through its near environment – in the form of both solar flares and waves. In addition, his group is developing instruments to support international research initiatives in astrophysics, including India's upcoming National Large Solar Telescope.

But Jess is also a founding member of the Predictive Sports Analytics (PSA) research group within QUB and Ulster University's AI Collaboration Centre – a £16m R&D facility supporting the adoption of AI and machine-learning technologies in local industry. PSA links researchers from a mix of disciplines – including physics, mathematics, statistics and computer science – with sports scientists in football, rugby, cycling and athletics. Its goal is to advance the fundamental science and application of predictive modelling in sports and health metrics.

Joined-up thinking

Astronomy and sports science might seem worlds apart, but they have lots in common, not least because both yield vast amounts of data. "We're lucky," says Jess. "Studying the closest star in the solar system means we are not photon-starved – there's no shortage of light – and we are able to make observations of the Sun's atmosphere at very high frame rates, which means we're accustomed to managing and manipulating really big data sets."

Similarly, big data also fuels the sports analytics industry. Many professional athletes wear performance-tracking sports vests with embedded GPS trackers that can generate tens of millions of data points over the course of, say, a 90-minute football match. The trackers capture information such as a player's speed, their distance travelled, and the number of sprints and high-intensity runs.

"Trouble is," says Jess, "you're not really getting the ebb and flow of all that data by just summing it all up into the 'one big number'." Researchers in the PSA group are therefore trying to understand how athlete

not worlds apart

NASA/Goddard/SDO; Shutterstock/E2.art.lab

data evolves over time – often in real-time – to see if there's some nuance or wrinkle that's been missed in the "big-picture" metrics that emerge at the end of a game or training session.

The group's work might, for example, make it possible not only to measure how tired a player becomes after a 90-minute game but also to pinpoint the rates and causes of fatigue during the match. "Insights like this have the power to better inform coaching staff so they can create bespoke training regimes to target these specific areas," adds Jess.

Work at PSA involves a mix of data mining, analysis, interpretation and visualization – teasing out granular insights from raw, unfiltered data streams by adapting and applying tried-and-tested statistical and mathematical methods from QUB's astrophysics research. Take, for example, observational studies of solar flares – large eruptions of electromagnetic radiation from the Sun's atmosphere lasting for a few minutes up to several hours.

"We might typically capture a solar-flare event at multiple wavelengths – optical, X-ray and UV, for example – to investigate the core physical processes from multiple vantage points," says Jess. In other words, they can see how one wavelength component differs from another or how the discrete spectral components correlate and influence each other. "Statistically, that's not so different from analysing the player data during a football match, with each player offering a unique vantage point in terms of the data points they generate," he adds.

Knowledge transfer between QUB's astrophysics and sports analytics programmes works in both directions and delivers high-impact research dividends David Jess from Queen's University Belfast

If that sounds like a stretch, Jess insists that PSA is not an indulgence or sideline. "We are experts in big data at PSA and, just as important, all of us have a passion for sports," says Jess, who is a big fan of Chelsea FC. "What's more, knowledge transfer between QUB's astrophysics and sports analytics programmes works in both directions and delivers high-impact research dividends."

The benefits of association

In-house synergies are all well and good, but the biggest operational challenge for PSA since it was set up in 2023 has been external. As a research group in QUB's School of Mathematics and Physics, Jess and colleagues need to find ways to "get in the door" with prospective clients and clubs in the professional sports community. Bridging that gap isn't straightforward for a physics lab that isn't established in the sports-analytics business.

It's all in the game for PSA

QUB

Set up in 2023, the Predictive Sports Analysis (PSA) research group in Belfast has developed collaborations with professional football teams, rugby squads and other sporting organizations across Northern Ireland and beyond. From elite-level to grassroots sports, real-world applications of PSA's research aim to give athletes and coaches a competitive edge. Current projects include:

- Player/squad speed distribution analyses to monitor strength and conditioning improvements with time (also handy for identifying growth and performance trajectories in youth sport)
- Longitudinal examination of acceleration intensity as a proxy for explosive strength, which correlates with heart-rate variability (a useful aid to alert coaching staff to potential underlying cardiac conditions)
- 3D force vectorization to uncover physics-based thresholds linked to concussion and musculoskeletal injury in rugby

QUB

Solar insights David Jess from Queen's University Belfast assembles a near-UV instrument for hyperspectral imaging at the Dunn Solar Telescope in New Mexico, US.

QUB

Fast-track physics Real-time monitoring of athlete performance by PSA PhD students Jack Brown (left) and Eamon McGleenan. The researchers capture acceleration and sprint metrics to provide feedback on sprint profiling and ways to mitigate injury risks.

> With so much data – whether astrophysics or sports analytics – we want to be at the cutting edge and deliver new advances
>
> David Jess from Queen's University Belfast

But clear communication as well as creative and accessible data visualization can help successful engagement. "Whenever we meet sports scientists at a professional club, the first thing we tell them is we're not trying to do their job," says Jess. "Rather, it's about making their job easier to do and putting more analytical tools at their disposal."

PSA's skill lies in extracting "hidden signals" from big data sets to improve how athlete performance is monitored. Those insights can then be used by coaches, physiotherapists and medical staff to optimize training and recovery schedules as well as to improve the fitness, health and performance of individual athletes and teams.

Validation is everything in the sports analytics business, however, and the barriers to entry are high. That's one reason why PSA's R&D collaboration with STATSports could be a game-changer. Founded in 2007 in Newry, Northern Ireland, the company makes wearable devices that record and transmit athlete performance metrics hundreds of times each second.

STATSports is now a global leader in athlete monitoring and GPS performance analysis. Its technology is used by elite football clubs such as Manchester City, Liverpool, Arsenal and Juventus, as well as national football teams (including England, Argentina, USA and Australia) and leading teams in rugby and American football.

Six physicists who also succeeded at sport

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- Quantum physicist Niels Bohr was a keen footballer, who played in goal for Danish side Akademisk Boldklub in the early 1900s. He once let a goal in because he was more focused on solving a maths problem mid-game by scribbling calculations on the goal post. His mathematician brother Harald Bohr also played for the club and won silver at the 1908 London Olympics for the Danish national team.
- Jonathan Edwards, who originally studied physics at Durham University, still holds the men's world record for the triple-jump. Edwards broke the record twice on 7 August 1995 at the World Athletics Championships in Gothenburg, Sweden, first jumping 18.16 m and then 18.29 m barely 20 minutes later.
- David Florence, who studied physics at the University of Nottingham, won silver in the single C1 canoe slalom at the Beijing Olympics in 2008. He also won silver in the doubles C2 slalom at the 2012 Olympics in London and in Rio de Janeiro four years later.
- Louise Shanahan is a middle-distance runner who competed for Ireland in the women's 800 m race at the delayed 2020 Summer Olympics while still doing a PhD in physics on the properties of nanodiamonds at the University of Cambridge. She has recently set up a sports website called TrackAthletes.
- US professional golfer Bryson DeChambeau is nicknamed "The Scientist" owing to his analytical, science-based approach to the sport – and the fact that he majored in physics at Southern Methodist University in Dallas, US. DeChambeau won the 2020 and 2024 US Open.
- In 2023 Harvard University's Jenny Hoffman, who studies the electronic properties of exotic materials, became the fastest woman to run across the US, completing the 5000 km journey in 47 days, 12 hours and 35 minutes. In doing so, she beat the previous record by more than a week.

Matin Durrani

The tie-up lets PSA work with an industry "name", while STATSports gets access to blue-sky research that could translate into technological innovation and commercial opportunities. "PSA is an academic research team first and foremost, so we don't want to just rest on our laurels," explains Jess. "With so much data – whether astrophysics or sports analytics – we want to be at the cutting edge and deliver new advances that loop back to enhance the big data techniques we're developing."

Right now, PhD physicist Eamon McGleenan provides the direct line from PSA into STATSports, which is funding his postgraduate work. The joint research project, which also involves sports scientists from Saudi Pro League football club Al Qadsiah, uses detailed data about player sprints during a game. The aim is to use force, velocity and acceleration curves – as well as the power generated by a player's legs – to evaluate the performance metrics that underpin athlete fatigue.

By reviewing these metrics during the course of a game, McGleenan and colleagues can model how an athlete's performance drops off in real-time, indicating their level of fatigue. The hope is that the research will lead to in-game modelling systems to help coaches and medical staff at pitch-side to make data-driven decisions about player substitutions (rather than just taking a player off because they "look leggy").

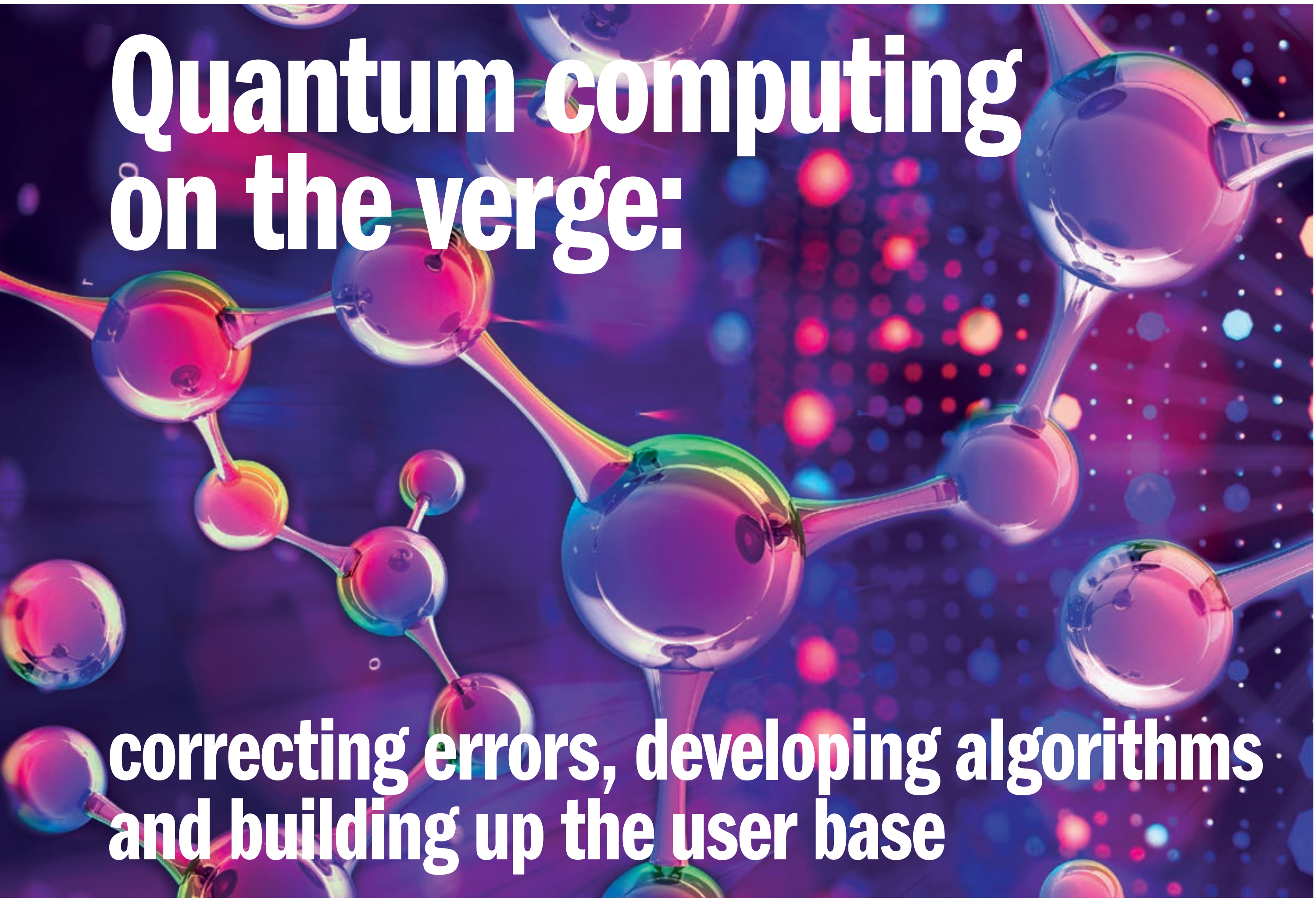
The transfer market

Jess says that the PSA group has been inundated with applications from physics students since it was set up. That's not surprising, argues Jess, given that a physics degree provides many transferable skills to suit PSA's broad scientific remit. Those skills include being able to manage, mine and interpret large data sets; disseminate complex results and actionable insights to a non-specialist audience; and work with industry partners in the sports technology sector.

"We're looking for multidisciplinarians at PSA," says Jess, with a nod to his group's ongoing PhD recruitment opportunities. "The ideal candidates will be keen to move beyond their existing knowledge base in physics and maths to develop skills in other specialist fields." There have also been discussions with QUB's research and enterprise department about the potential for a PSA spin-out venture – though Jess, for his part, remains focused on research.

"My priority is to ensure the sustainability of PSA," he concludes. "That means more grant funding – whether from the research councils or industry partners – while training up the next generation of early-career researchers. Longer term, though, I do think that PSA has the potential to be a 'disruptor' in the sports-analytics industry."

Quantum computing on the verge: correcting errors, developing algorithms and building up the user base



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In the second of a two-part article, Philip Ball looks the challenges of error correction to build truly useful quantum computing; how algorithms will need to be platform-independent; and finally how early users will adopt quantum technologies

Philip Ball is a science writer based in the UK, whose latest book is *How Life Works: a User's Guide to the New Biology* (2024), e-mail p.ball@btinternet.com

When it comes to building a fully functional "fault-tolerant" quantum computer, companies and government labs all over the world are rushing to be the first over the finish line. But a truly useful universal quantum computer capable of running complex algorithms would have to entangle millions of coherent qubits, which are extremely fragile. Because of environmental factors such as temperature, interference from other electronic systems in hardware, and even errors in measurement, today's devices would fail under an avalanche of errors long before reaching that point.

So the problem of error correction is a key issue for the future of the market. It arises because errors in qubits can't be corrected simply by keeping multiple copies, as they are in classical computers: quantum rules forbid the copying of qubit states while they are still entangled with others, and are thus unknown. To run quantum circuits with millions of gates, we therefore need new tricks to enable quantum error correction (QEC).

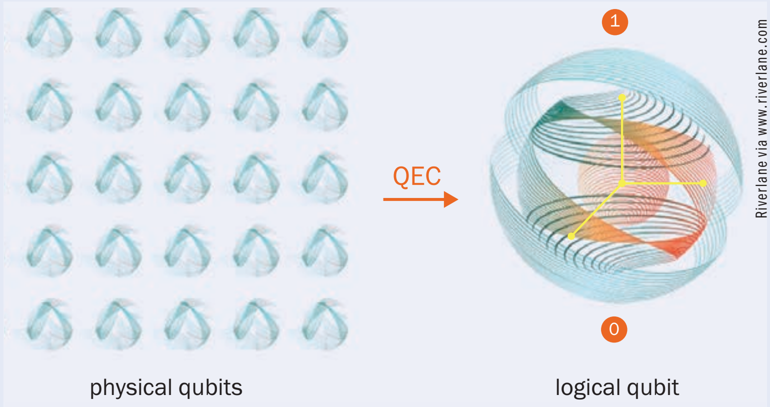
Protected states

The general principle of QEC is to spread the information over many qubits so that an error in any one of them doesn't matter too much. "The essential idea of quantum error correction is that if we want to protect a quantum system from damage then we should encode it in a very highly entangled state," says John Preskill, director of the Institute for Quantum Information and Matter at the California Institute of Technology in Pasadena.

There is no unique way of achieving that spreading, however. Different error-correcting codes can depend on the connectivity between qubits – whether, say, they are coupled only to their nearest neighbours or to all the others in the device – which tends to be determined by the physical platform being used. However error correction is done, it must be done fast. "The mechanisms for error correction need to be running at a speed that is commensurate with that of the gate operations," says Michael Cuthbert, founding director of the UK's National Quantum Computing Centre (NQCC). "There's no point in doing a gate operation in a nanosecond if it then takes 100 microseconds to do the error correction for the next gate operation."

At the moment, dealing with errors is largely about compensation rather than correction: patching up the problems of errors in retrospect, for example by using

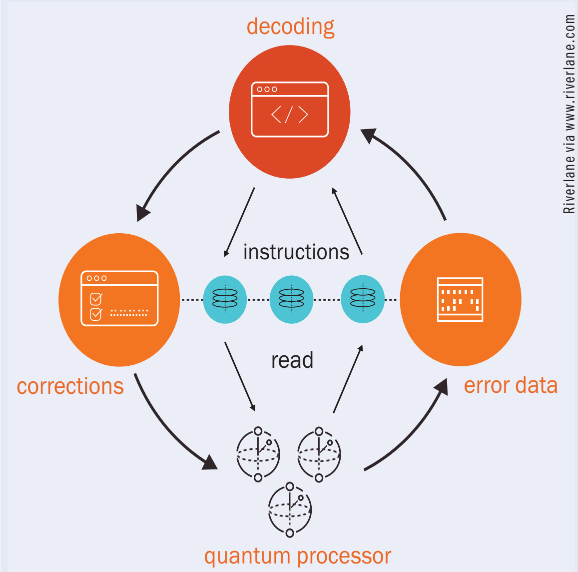
1 From many to few



Qubits are so fragile that their quantum state is very susceptible to the local environment and can easily be lost through the process of decoherence. Current quantum computers therefore have very high error rates – roughly one error in every few hundred operations. For quantum computers to be truly useful, this error rate will have to be reduced to the scale of one in a million especially as larger more complex algorithms would require one in a billion or even trillion error rates. This requires real-time quantum error correction (QEC).

To protect the information stored in qubits, a multitude of unreliable physical qubits have to be combined in such a way that if one qubit fails and causes an error, the others can help protect the system. Essentially, by combining many physical qubits (shown above on the left), one can build a few "logical" qubits that are strongly resistant to noise.

2 Error correction in action



The illustration gives an overview of quantum error correction (QEC) in action within a quantum processing unit. UK-based company Riverlane is building its Deltaflow QEC stack that will correct millions of data errors in real time, allowing a quantum computer to go beyond the reach of any classical supercomputer.

algorithms that can throw out some results that are likely to be unreliable (an approach called "post-selection"). It's also a matter of making better qubits that are less error-prone in the first place.

According to Maria Maragkou, commercial vice-president of quantum error-correction company Riverlane, the goal of full QEC has ramifications for the design of the machines all the way from hardware to workflow planning. "The shift to support error correction has a profound effect on the way quantum processors themselves are built, the way we control and operate them, through a robust software stack on top of which the applications can be run," she explains. The "stack" includes everything from programming languages to user interfaces and servers.

With genuinely fault-tolerant qubits, errors can be kept under control and prevented from proliferating during a computation. Such qubits might be made in principle by combining many physical qubits into a single "logical qubit" in which errors can be corrected (see figure 1). In practice, though, this creates a large overhead: huge numbers of physical qubits might be needed to make just a few fault-tolerant logical qubits. The question is then whether errors in all those physical qubits can be checked faster than they accumulate (see figure 2).

That overhead has been steadily reduced over the past several years, and at the end of last year researchers at Google announced that their 105-qubit Willow quantum chip passed the break-even threshold at which the error rate gets smaller, rather than larger, as more physical qubits are used to make a logical qubit. This means that in principle such arrays could be scaled up without errors accumulating.

Fault-tolerant quantum computing is the ultimate goal, says Jay Gambetta, director of IBM research at the company's centre in Yorktown Heights, New York. He believes that to perform truly transformative quantum calculations, the system must go beyond demonstrating a few logical qubits – instead, you need arrays of at least a 100 of them, that can perform more than 100 million quantum operations (10^8 QuOps). "The number of operations is the most important thing," he says.

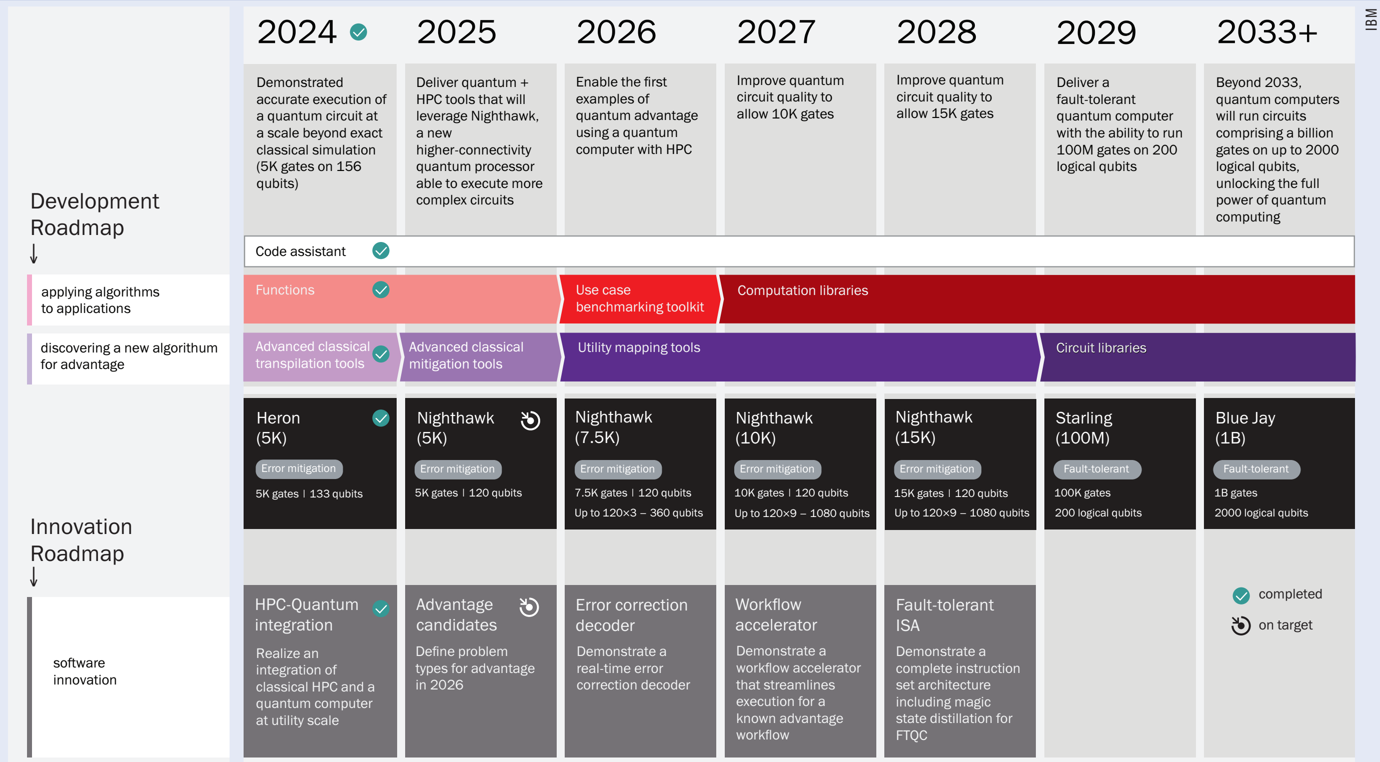
It sounds like a tall order, but Gambetta is confident that IBM will achieve these figures by 2029. By building on what has been achieved so far with error correction and mitigation, he feels "more confident than I ever did before that we can achieve a fault-tolerant computer." Jerry Chow, previous manager of the Experimental Quantum Computing group at IBM, shares that optimism. "We have a real blueprint for how we can build [such a machine] by 2029," he says (see figure 3).

Others suspect the breakthrough threshold may be a little lower: Steve Brierley, chief executive of Riverlane, believes that the first error-corrected quantum computer, with around 10 000 physical qubits supporting 100 logical qubits and capable of a million QuOps (a megaQuOp), could come as soon as 2027. Following on, gigaQuOp machines (10^9 QuOps) should be available by 2030–32, and teraQuOps (10^{12} QuOp) by 2035–37.

Platform independent

Error mitigation and error correction are just two of the challenges for developers of quantum software. Fundamentally, developing a truly quantum algorithm involves taking full advantage of the key quantum-mechanical properties such as superposition and entanglement.

3 The road ahead for IBM



IBM's current roadmap charts how the company plans on scaling up its devices to achieve a fault-tolerant device by 2029. Alongside hardware development, the firm will also focus on developing new algorithms and software for these devices.

Ultimately the goal will be to make software that is not platform-dependent and so doesn't require the user to think about the physics involved

Often, the best way to do that depends on the hardware used to run the algorithm. But ultimately the goal will be to make software that is not platform-dependent and so doesn't require the user to think about the physics involved.

"At the moment, a lot of the platforms require you to come right down into the quantum physics, which is a necessity to maximize performance," says Richard Murray of photonic quantum-computing company Orca. Try to generalize an algorithm by abstracting away from the physics and you'll usually lower the efficiency with which it runs. "But no user wants to talk about quantum physics when they're trying to do machine learning or something," Murray adds. He believes that ultimately it will be possible for quantum software developers to hide those details from users – but Brierley thinks this will require fault-tolerant machines.

"In due time everything below the logical circuit will be a black box to the app developers", adds Maragkou over at Riverlane. "They will not need to know what kind of error correction is used, what type of qubits are used, and so on." She stresses that creating truly efficient and useful machines depends on developing the requisite skills. "We need to scale up the workforce to develop better qubits, better error-correction codes and decoders, write the software that can elevate those machines and solve meaningful problems in a way that they can be adopted." Such skills won't come only from quantum physicists, she adds: "I would dare say it's mostly not!"

Yet even now, working on quantum software doesn't demand a deep expertise in quantum theory. "You can be someone working in quantum computing and solving problems without having a traditional physics training and knowing about the energy levels of the hydrogen atom and so on," says Ashley Montanaro, who co-founded the quantum software company Phasecraft.

On the other hand, insights can flow in the other direction too: working on quantum algorithms can lead to new physics. "Quantum computing and quantum information are really pushing the boundaries of what we think of as quantum mechanics today," says Montanaro, adding that QEC "has produced amazing physics breakthroughs."

Early adopters?

Once we have true error correction, Cuthbert at the UK's NQCC expects to see "a flow of high-value commercial uses" for quantum computers. What might those be?

In this arena of quantum chemistry and materials science, genuine quantum advantage – calculating something that is impossible using classical methods alone – is more or less here already, says Chow. Crucially, however, quantum methods needn't be used for the entire simulation but can be added to classical ones to give them a boost for particular parts of the problem.

For example, last year researchers at IBM teamed up with scientists at several RIKEN institutes in Japan to calculate the minimum energy state for the iron sulphide cluster (4Fe-4S) at the heart of the bacterial nitrogenase enzyme that fixes nitrogen. This cluster is too big and complex to be accurately simulated using the classical approximations of quantum chemistry. The researchers used a combination of both quantum computing (with IBM's 72-qubit Heron chip) and RIKEN's Fugaku high

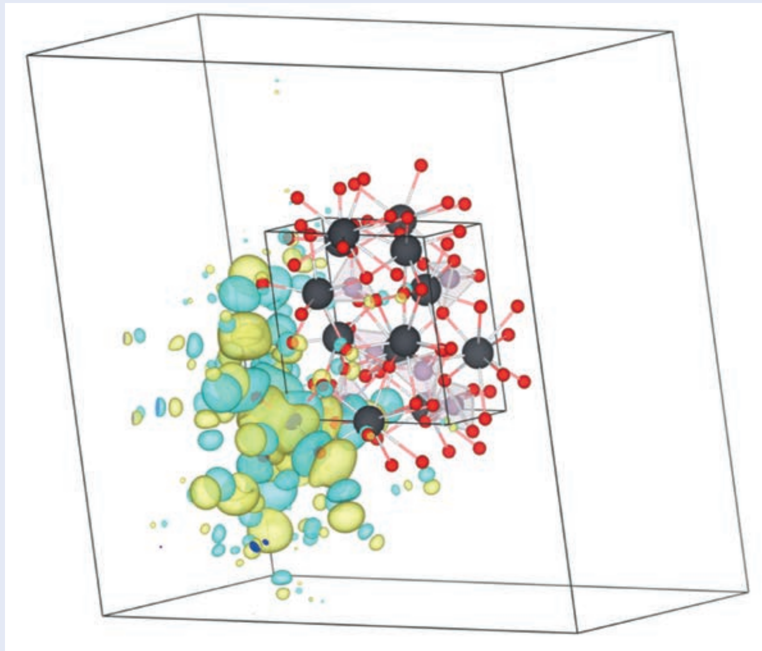
IBM

RIKEN

Joint effort In June 2025, IBM in the US and Japan's national research laboratory RIKEN, unveiled the IBM Quantum System Two, the first to be used outside the US. It involved IBM's 156-qubit IBM Heron quantum computing system (top) being paired with RIKEN's supercomputer Fugaku (bottom) – one of the most powerful classical systems on Earth. The computers are linked through a high-speed network at the fundamental instruction level to form a proving ground for quantum-centric supercomputing.

4 Structural insights

Phasecraft



A promising application of quantum computers is simulating novel materials. Researchers from the quantum algorithms firm Phasecraft, for example, have already shown how a quantum computer could help simulate complex materials such as the polycrystalline compound LK-99, which was purported by some researchers in 2024 to be a room-temperature superconductor.

Using a classical/quantum hybrid workflow, together with the firm's proprietary material simulation approach to encode and compile materials on quantum hardware, Phasecraft researchers were able to establish a classical model of the LK99 structure that allowed them to extract an approximate representation of the electrons within the material. The illustration above shows the green and blue electronic structure around red and grey atoms in LK-99.

performance computing (HPC). This idea of "improving classical methods by injecting quantum as a subroutine" is likely to be a more general strategy, says Gambetta. "The future of computing is going to be heterogeneous accelerators [of discovery] that include quantum."

Likewise, Montanaro says that Phasecraft is developing "quantum-enhanced algorithms", where a quantum computer is used, not to solve the whole problem, but just to help a classical computer in some way. "There are only certain problems where we know quantum computing is going to be useful," he says. "I think we are going to see quantum computers working in tandem with classical computers in a hybrid approach. I don't think we'll ever see workloads that are entirely run using a quantum computer." Among the first important problems that quantum machines will solve, according to Montanaro, are the simulation of new materials – to develop, for example, clean-energy technologies (see figure 4).

"For a physicist like me," says Preskill, "what is really exciting about quantum computing is that we have good reason to believe that a quantum computer would be able to efficiently simulate any process that occurs in nature."

Montanaro believes another likely near-term goal for useful quantum computing is solving optimization problems – both here and in quantum simulation, "we think genuine value can be delivered already in this NISQ era with hundreds of qubits." (NISQ, a term coined by Preskill, refers to noisy intermediate-scale quantum computing, with relatively small numbers of rather noisy, error-prone qubits.)

One further potential benefit of quantum computing is that it tends to require less energy than classical high-performance computing, which is notoriously high. If the energy cost could be cut by even a few percent, it would be worth using quantum resources for that reason alone. "Quantum has real potential for an energy advantage," says Chow. One study in 2020 showed that a particular quantum-mechanical calculation carried out on a HPC used many orders of magnitude more energy than when it was simulated on a quantum circuit. Such comparisons are not easy, however, in the absence of an agreed and well-defined metric for energy consumption.

Building the market

Right now, the quantum computing market is in a curious superposition of states itself – it has ample proof of principle, but today's devices are still some way from being able to perform a computation relevant to a practical problem that could not be done with classical computers. Yet to get to that point, the field needs plenty of investment.

The fact that quantum computers, especially if used with HPC, are already unique scientific tools should establish their value in the immediate term, says Gambetta. "I think this is going to accelerate, and will keep the funding going." It is why IBM is focusing on utility-scale

It's not clear, though, whether there will be a big demand for quantum machines that every user will own and run

systems of around 100 qubits or so and more than a thousand gate operations, he says, rather than simply trying to build ever bigger devices.

Montanaro sees a role for governments to boost the growth of the industry "where it's not the right fit for the private sector". One role of government is simply as a customer. For example, Phasecraft is working with the UK national grid to develop a quantum algorithm for optimizing the energy network. "Longer-term support for academic research is absolutely critical," Montanaro adds. "It would be a mistake to think that everything is done in terms of the underpinning science, and governments should continue to support blue-skies research."

It's not clear, though, whether there will be a big demand for quantum machines that every user will own and run. Before 2010, "there was an expectation that banks and government departments would all want their own machine – the market would look a bit like HPC," Cuthbert says. But that demand depends in part on what commercial machines end up being like. "If it's going to need a premises the size of a football field, with a power station next to it, that becomes the kind of infrastructure that you only want to build nationally." Even for smaller machines, users are likely to try them first on the cloud before committing to installing one in-house.

According to Cuthbert , the real challenge in the supply-chain development is that many of today's technologies were developed for the science community – where, say, achieving millikelvin cooling or using high-power lasers is routine. "How do you go from a specialist scientific clientele to something that starts to look like a washing machine factory, where you can make them to a certain level of performance," while also being much cheaper, and easier to use?

But Cuthbert is optimistic about bridging this gap to get to commercially useful machines, encouraged in part by looking back at the classical computing industry of the 1970s. "The architects of those systems could not imagine what we would use our computation resources for today. So I don't think we should be too discouraged that you can grow an industry when we don't know what it'll do in five years' time."

Montanaro too sees analogies with those early days of classical computing. "If you think what the computer industry looked like in the 1940s, it's very different from even 20 years later. But there are some parallels. There are companies that are filling each of the different niches we saw previously, there are some that are specializing in quantum hardware development, there are some that are just doing software." Cuthbert thinks that the quantum industry is likely to follow a similar pathway, "but more quickly and leading to greater market consolidation more rapidly."

However, while the classical computing industry was revolutionized by the advent of personal computing in the 1970s and 80s, it seems very unlikely that we will have any need for quantum laptops. Rather, we might increasingly see apps and services appear that use cloud-based quantum resources for particular operations, merging so seamlessly with classical computing that we don't even notice.

That, perhaps, would be the ultimate sign of success: that quantum computing becomes invisible, no big deal but just a part of how our answers are delivered. ■

FestiveReviews

The entangled histories of women in quantum physics

Jennifer Carter reviews *Women in the History of Quantum Physics: Beyond Knabenphysik* edited by Patrick Charbonneau, Michelle Frank, Margriet van der Heijden and Daniela Monaldi

Women in the History of Quantum Physics: Beyond Knabenphysik
Patrick Charbonneau, Michelle Frank, Margriet van der Heijden and Daniela Monaldi (eds)
2025 Cambridge University Press
486 pp £37.99hb

Women of quantum Clockwise from top left: Chien-Shiung Wu, Hertha Sponer, Grete Hermann, Carolyn Beatrice Parker, Katharine Way, Ana María Cetto Kramis.

Writing about women in science remains an important and worthwhile thing to do. That's the premise that underlies *Women in the History of Quantum Physics: Beyond Knabenphysik* – an anthology charting the participation of women in quantum physics, edited by Patrick Charbonneau, Michelle Frank, Margriet van der Heijden and Daniela Monaldi.

What does a history of women in science accomplish? This volume firmly establishes that women have for a long time made substantial contributions to quantum physics. It raises the profiles of figures like Chien-Shiung Wu, whose early work on photon entanglement is often overshadowed by her later fame in nuclear physics; and Grete Hermann, whose critiques of John von Neumann and Werner Heisenberg make her central to early quantum theory.

But in specifically recounting the work of these women in quantum, do we risk reproducing the same logic of exclusion that once kept them out – confining women to a specialized narrative? The answer is no, and this book is an especially compelling illustration of why.

A reference and a reminder

Two big ways this volume demonstrates its necessity are by its success as a reference, a place to look for the accomplishments and contributions of women in quantum physics; and as a reminder that we still have far to go before there is anything like true diversity, equality or the disappearance of prejudice in science.

The subtitle *Beyond Knabenphysik* – meaning "boys' physics" in German – points to one of the book's central aims: to move past a vision of quantum physics as a purely male domain. Originally a nickname for quantum mechanics given because of the youth of its pioneers, Knabenphysik comes to be emblematic of the collaboration and mentorship that welcomed male physicists and consistently excluded women.

The exclusion was not only symbolic but material. Hendrika Johanna van Leeuwen, who co-developed a key theorem in classical magnetism, was left out of the camaraderie and recognition extended to her male colleagues. Similarly, credit for Laura Chalk's research into the Stark effect – an early confirmation of Schrödinger's wave equation – was under-acknowledged in favour of that of her male collaborator's.

Something this book does especially well is combine the sometimes conflicting aims of history of science and biography. We learn not only about the trajectories of these women's careers, but also about the scientific developments they were a part of. The chapter on Hertha Sponer, for instance, traces both her personal journey and her pioneering role in quantum spectroscopy. The piece on Freda Friedman Salzman situates her theoretical contributions within the professional and social networks that both enabled and constrained her. In so doing, the book treats each of these women as not only whole human beings, but also integral players in a complex history of one of the most successful and debated physical theories in history.

Lost physics

Because the history is told chronologically, we trace quantum physics from some of the early astronomical images suggesting discrete quantized elements to later developments in quantum electrodynamics. Along the way, we encounter women like Maria McEachern, who revisits Williamina Fleming's spectral work; Maria Lluïsa Canut, whose career spanned crystallography and feminist activism; and Sonja Ashauer, a Brazilian physicist whose PhD at Cambridge placed her at the heart of theoretical developments but whose story remains little known.

This history could lead to a broader reflection on how credit, networking and even theorizing are accomplished in physics. Who knows how many discoveries in quantum physics, and science more broadly, could have been made more quickly or easily without the barriers and prejudice women and other marginalized persons faced then and still face today? Or what discoveries still lie latent?

The book critiques the idea of a "leaky pipeline" as this metaphor minimizes how educational and institutional investments in women often translate into contributions both inside and outside formal science

Not all the women profiled here found lasting professional homes in physics. Some faced barriers of racism as well as gender discrimination, like Carolyn Parker who worked on the Manhattan Project's polonium research and is recognized as the first African American woman to have earned a postgraduate degree in physics. She died young without having received full recognition in her lifetime. Others – like Elizabeth Monroe Boggs who performed work in quantum chemistry – turned to policy work after early research careers. Their paths reflect both the barriers they faced and the broader range of contributions they made.

Calculate, don't think

The book makes a compelling argument that the heroic narrative of science doesn't just undermine the contributions of women, but of the less prestigious more broadly. Placing these stories side by side yields something greater than the sum of its parts. It challenges the idea that physics is the work of lone geniuses by revealing the collective infrastructures of knowledge-making, much of which has historically relied not only on women's labour – and did they labour – but on their intellectual rigour and originality.

Many of the women highlighted were at times employed "to calculate, not to think" as "computers", or worked as teachers, analysts or managers. They were often kept from more visible positions even when they were recognized by colleagues for their expertise. Katharine Way, for instance, was praised by peers and made vital contributions to nuclear data, yet was rarely credited with the same prominence as her male collaborators. It shows clearly that those employed to support from behind the scenes could and did contribute to theoretical physics in foundational ways.

The book also critiques the idea of a "leaky pipeline", showing that this metaphor oversimplifies. It minimizes how educational and institutional investments in women often translate into contributions both inside and outside formal science. Ana María Cetto Kramis, for example, who played a foundational role in stochastic electrodynamics, combined research with science diplomacy and advocacy.

Should women's accomplishments be recognized in relation to other women's, or should they be integrated into a broader historiography? The answer is both. We need inclusive histories that acknowledge all contributors, and specialized works like this one that repair the record and show what emerges specifically and significantly from women's experiences in science. Quantum physics is a unique field, and women played a crucial and distinctive role in its formation. This recognition offers an indispensable lesson: in physics and in life it's sometimes easy to miss what's right in front of us, no less so in the history of women in quantum physics.

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Optimistic, idealistic and naïve

Tara Shears reviews *This is for Everyone: the Captivating Memoir from the Inventor of the World Wide Web* by Tim Berners-Lee

Outward focus Tim Berners-Lee's memoir reveals less about himself and more about his vision for the future of the Web.

This is for Everyone: the Captivating Memoir from the Inventor of the World Wide Web
Tim Berners-Lee
2025 Macmillan
400pp
£25.00/$30.00hb

It's rare to come across someone who's been responsible for enabling a seismic shift in society that has affected almost everyone and everything. Tim Berners-Lee, who invented the World Wide Web, is one such person. His new memoir *This is for Everyone* unfolds the history and development of the Web and, in places, of the man himself.

Berners-Lee was born in London in 1955 to parents, originally from Birmingham, who met while working on the Ferranti Mark 1 computer and knew Alan Turing. Theirs was a creative, intellectual and slightly chaotic household. His mother could maintain a motorbike with fence wire and pliers, and was a crusader for equal rights in the workplace. His father – brilliant and absent minded – taught Berners-Lee about computers and queuing theory. A childhood of camping and model trains, it was, in Berners-Lee's view, idyllic.

Berners-Lee had the good fortune to be supported by a series of teachers and managers who recognized his potential and unique way of working. He studied physics at the University of Oxford (his tutor "going with the flow" of Berners-Lee's unconventional notation and ability to approach problems from oblique angles) and built his own computer. After graduating, he married and, following a couple of jobs, took a six-month placement at the CERN particle-physics lab in Geneva in 1985.

This placement set "a seed that sprouted into a tool that shook up the world". Berners-Lee saw how difficult it was to share information stored in different languages in incompatible computer systems and how, in contrast, information flowed easily when researchers met over coffee, connected semi-randomly and talked. While at CERN, he therefore wrote a rough prototype for a program to link information in a type of web rather than a structured hierarchy.

The placement ended and the program was ignored, but four years later Berners-Lee was back at CERN. Now divorced and soon to remarry, he developed his vision of a "universal portal" to information. It proved to be the perfect time. All the tools necessary to achieve the Web – the Internet, address labelling of computers, network cables, data protocols, the hypertext language that allowed cross-referencing of text and links on the same computer – had already been developed by others.

Berners-Lee saw the need for a user-friendly interface, using hypertext that could link to information on other computers across the world. His excitement was "uncontainable", and according to his line manager "few of us if any could understand what he was talking about". But Berners-Lee's managers supported him and freed his time away from his actual job to become the world's first web developer.

Having a vision was one thing, but getting others to share it was another. People at CERN only really started to use the Web properly once the lab's internal phone book was made available on it. As a student at the time, I can confirm that it was much, much easier to use the Web than log on to CERN's clunky IBM mainframe, where phone numbers had previously been stored.

Wider adoption relied on a set of volunteer developers, working with open-source software, to make browsers and platforms that were attractive and easy to use. CERN agreed to donate the intellectual property for web software to the public domain, which helped. But the path to today's Web was not smooth: standards risked diverging and companies wanted to build applications that hindered information sharing.

Feeling that "the Web was outgrowing my institution" and "would be a distraction" to a lab whose core mission was physics, Berners-Lee moved to the Massachusetts Institute of Technology in 1994. There he founded the World Wide Web Consortium (W3C) to ensure consistent, accessible standards were followed by everyone as the Web developed into a global enterprise. The progression sounds straightforward although earlier accounts, such as James Gillies and Robert Cailliau's 2000 book *How the Web Was Born*, imply some rivalry between institutions that is glossed over here.

The rest is history, but not quite

the history that Berners-Lee had in mind. By 1995 big business had discovered the possibilities of the Web to maximize influence and profit. Initially inclined to advise people to share good things and not search for bad things, Berners-Lee had reckoned without the insidious power of "manipulative and coercive" algorithms on social networks. Collaborative sites like Wikipedia are closer to his vision of an ideal Web; an emergent good arising from individual empowerment. The flip side of human nature seems to come as a surprise.

The rest of the book brings us up to date with Berners-Lee's concerns (data, privacy, misuse of AI, toxic online culture), his hopes (the good use of AI), a third marriage and his move into a data-handling business. There are some big awards and an impressive amount of name dropping; he is excited by Order of Merit lunches with the Queen and by sitting next to Paul McCartney's family at the opening ceremony to the London Olympics in 2012. A flick through the index reveals names ranging from Al Gore and Bono to Lucien Freud. These are not your average computing technology circles.

> Berners-Lee had reckoned without the insidious power of "manipulative and coercive" algorithms on social networks

There are brief character studies to illustrate some of the main players, but don't expect much insight into their lives. This goes for Berners-Lee too, who doesn't step back to particularly reflect on those around him, or indeed his own motives beyond that vision of a Web for all enabling the best of humankind. He is firmly future focused.

Still, there is no-one more qualified to describe what the Web was intended for, its core philosophy, and what caused it to develop to where it is today. You'll enjoy the book whether you want an insight into the inner workings that make your web browsing possible, relive old and forgotten browser names, or see how big tech wants to monetize and monopolize your online time. It is an easy read from an important voice.

The book ends with a passionate statement for what the future could be, with businesses and individuals working together to switch the Web from "the attention economy to the intention economy". It's a future where users are no longer distracted by social media and manipulated by attention-grabbing algorithms; instead, computers and services do what users want them to do, with the information that users want them to have.

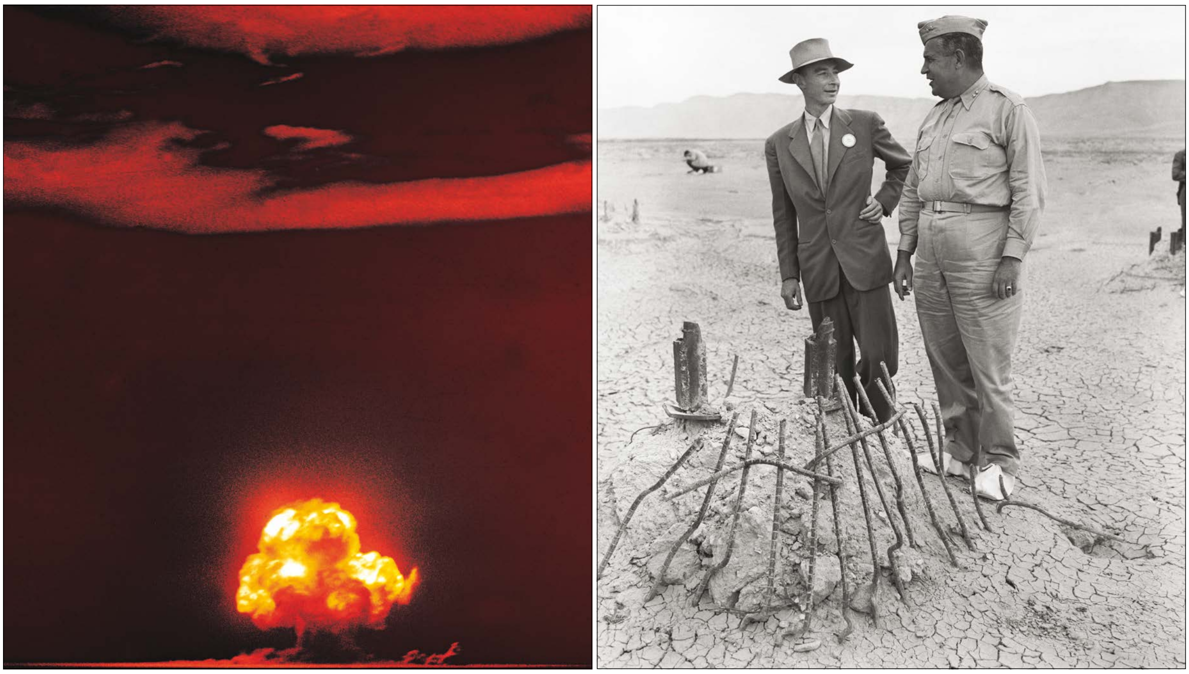
Berners-Lee is still optimistic, still an incurable idealist, still driven by vision. And perhaps still a little naïve too in believing that everyone's values will align this time.

Tara Shears is a professor of particle physics at the University of Liverpool, UK

Builders of the bomb

Andrew Robinson reviews *Destroyer of Worlds: the Deep History of the Nuclear Age 1895–1965* by Frank Close

Destroyer of Worlds: the Deep History of the Nuclear Age 1895–1965
Frank Close
2025 Allen Lane
£25.00hb 321pp



Dark destroyers This photo of the Trinity test was taken by Jack W Aeby, a Los Alamos employee, on 16 July 1945. Two months later many Manhattan Project participants returned to the Trinity test site for news crews, including Robert J Oppenheimer and General Leslie Groves, who are shown here examining the remains of a base of the steel test tower.

The title of particle physicist Frank Close's engaging new book, *Destroyer of Worlds*, refers to Robert Oppenheimer's famous comment after he witnessed the first detonation of an atomic bomb, known as the Trinity test, in July 1945. Quoting the Hindu scripture *Bhagavad Gita*, he said "Now I am become death, the destroyer of worlds." But although Close devotes much space to the Manhattan Project, which Oppenheimer directed between 1942 and 1945, his book has a much wider remit.

Aimed at non-physicist readers with a strong interest in science, though undoubtedly appealing to physicists too, the book seeks to explain the highly complex physics and chemistry that led to the atomic bomb – a term first coined by H G Wells in his 1914 science-fiction novel *The World Set Free*. It also describes the contributions of numerous gifted scientists to the development of those weapons.

Close draws mainly on numerous published sources from this deeply analysed period, including Richard Rhodes's seminal 1988 study *The Making of the Atomic Bomb*. He starts with Wilhelm Röntgen's discovery of X-rays in 1895, before turning to the discovery of radioactivity by Henri Becquerel in 1896 – described by Close as "the first pointer to nuclear energy [that was] so insignificant that it was almost missed". Next, he highlights the work on radium by Marie and Pierre Curie in 1898.

After discussing the emergence of nuclear physics, Close goes on to talk about the Allies' development of the nuclear bomb. A key figure in this history was Enrico Fermi, who abandoned Fascist Italy in 1938 and emigrated to the US, where he worked on the Manhattan Project and built the first nuclear reactor, in Chicago, in 1942.

Within seconds of seeing Trinity's blast in the desert in 1945, Fermi showed his legendary ability to estimate a physical phenomenon's magnitude by shredding a sheet of paper into small pieces and throwing them into the air. The bomb's shock wave blew this "confetti" (Close's word) a few metres away. After measuring the exact distance, Fermi immediately estimated that the blast was equivalent to about 10 000 tonnes of TNT. This figure was not far off the 18 000 tonnes determined a week later following a detailed analysis by the project team.

The day after the Trinity test, a group of 70 scientists, led by Leo Szilard, sent a petition to US President Harry Truman, requesting him not to use the bomb against Japan. Albert Einstein agreed with the petition but did not sign it, having been excluded from the Manhattan Project on security grounds (though in 1939 he famously backed the bomb's development, fearing that Nazi Germany might build its own device). Despite the protests, atomic bombs were dropped on Hiroshima and Nagasaki less than a month later – a decision that Close neither defends nor condemns.

Other key figures in the Manhattan Project were emigrants to the UK, who had fled Germany in the mid-1930s because of Nazi persecution of Jews, and later joined the secret British Tube Alloys bomb project. The best known are probably the nuclear physicists Otto Frisch and Rudolf Peierls, who initially worked together at the University of Birmingham for Tube Alloys before joining the Manhattan Project. They both receive their due from Close.

Oddly, however, he neglects to mention their fellow émigré Franz (Francis) Simon by name, despite acknowledging the importance of his work in demonstrating a technique to separate fissionable uranium-235 from the more stable uranium-238. In 1940 Simon, then working at the Clarendon Laboratory in wartime Oxford, showed that separation could be achieved by gaseous diffusion of uranium hexafluoride through a porous barrier, which he initially demonstrated by hammering his wife's kitchen sieve flat to make the barrier.

As Close ably documents and explains, numerous individuals and groups eventually ensured the success of the Manhattan Project. In addition to ending the Second World War and preserving freedom against Fascism, there is an argument that it also set an example for the future of science as a highly collaborative, increasingly international albeit sometimes dangerous adventure.

A fusion of minds

Close finishes the book with a shorter discussion of the two decades of Cold War rivalry between scientists from the US and the Soviet Union to develop and test the hydrogen bomb. It features physicists such as Edward Teller and Andrei Sakharov, who led the efforts to build the American "Super Bomb" and the Soviet "Tsar Bomba", respectively.

The book ends in around 1965, after the 1963 partial test-ban treaty signed by the US, Soviet Union and the UK, preventing further tests of the hydrogen bomb for fear of their likely devastating effects on Earth's atmosphere. As Close writes, the Tsar Bomba was more powerful than any recorded explosion other than the meteorite impact 65 million years ago that wreaked global change and killed the dinosaurs, which had ruled for 150 million years.

"Within just one per cent of that time, humans have produced nuclear arsenals capable of replicating such levels of destruction," Close warns. "The explosion of a gigaton weapon would signal the end of history. Its mushroom cloud ascending towards outer space would be humanity's final vision."

Andrew Robinson is the author of *Einstein on the Run* and *Einstein in Oxford*

Condensed natter: bite-size reviews of recent books


iStock/Cavan Images

Cereal conundrums Michael Banks' new book explores, among other things, the science of why Cheerios tend to stick together when floating in milk.

Physics Around the Clock

By Michael Banks

Why do Cheerios tend to stick together while floating in a bowl of milk? Why does a runner's ponytail swing back and forth? These might not be the most pressing questions in physics, but getting to the answers is both fun and provides insights into important scientific concepts. These are just two examples of everyday physics that *Physics World* news editor Michael Banks explores in his book *Physics Around the Clock: Adventures in the Science of Everyday Living*, which begins with the physics (and chemistry) of your morning coffee and ends with a formula for predicting the winner of those cookery competitions that are mainstays of evening television. **Hamish Johnston**

- 2025 The History Press

AUDIO Hamish Johnston talks to Michael Banks about his new book *Physics Around the Clock*

Quantum 2.0

By Paul Davies

You might wonder why the world needs yet another book about quantum mechanics, but for physicists there's no better guide than Paul Davies. Based for the last two decades at Arizona State University in the US, in *Quantum 2.0: the Past, Present and Future of Quantum Physics* Davies tackles the basics of quantum physics – along with its mysteries, applications and philosophical implications – with great clarity and insight. The book ends with truly strange topics such as quantum Cheshire cats and delayed-choice quantum erasers – see if you prefer his descriptions to those we've attempted in *Physics World* this year. **Matin Durrani**

- 2025 Pelican

Can You Get Music on the Moon?

By Sheila Kanani, illustrated by Liz Kay

Why do dogs bark but wolves howl? How do stars "sing"? Why does thunder rumble? This delightful, fact-filled children's book answers these questions and many more, taking readers on an adventure through sound and space. Written by planetary scientist Sheila Kanani and illustrated by Liz Kay, *Can you get Music on the Moon? the Amazing Science of Sound and Space* reveals not only how sound is produced but why it can make us feel certain things. Each of the 100 or so pages brims with charming illustrations that illuminate the many ways that sound is all around us. **Michael Banks**

- 2025 Puffin Books

A Short History of Nearly Everything 2.0

By Bill Bryson

Alongside books such as Stephen Hawking's *A Brief History of Time* and Carl Sagan's *Cosmos*, British-American author Bill Bryson's *A Short History of Nearly Everything* is one of the bestselling popular-science books of the last 50 years. First published in 2003, the book became a fan favourite of readers across the world and across disciplines as Bryson wove together a clear and humorous narrative of our universe. Now, 22 years later, he has released an updated and revised volume – *A Short History of Nearly Everything 2.0* – that covers major updates in science from the past two decades. This includes the discovery of the Higgs boson and the latest on dark-matter research. The new edition is still imbued with all the wit and wisdom of the original, making it the perfect Christmas present for scientists and anyone else curious about the world around us. **Tushna Commissariat**

- 2025 Doubleday

A rocky road to success

Kate Gardner reviews *If I Am Right, and I Know I Am: Inge Lehmann, the Woman Who Discovered Earth's Innermost Secret* by Hanne Strager

GEUS

Intrepid
Inge Lehmann at the Ittoqqortoormiit (Scoresbysund) seismic station in Greenland c. 1928. A keen hiker, Lehmann was comfortable in cold and remote environments.

If I Am Right, and I Know I Am: Inge Lehmann, the Woman Who Discovered Earth's Innermost Secret
Hanne Strager
2025 Columbia University Press
308 pp, £25hb

In the 1930s a little-known Danish seismologist calculated that the Earth has a solid inner core, within the liquid outer core identified just a decade earlier. The international scientific community welcomed Inge Lehmann as a member of the relatively new field of geophysics – yet in her home country, Lehmann was never really acknowledged as more than a very competent keeper of instruments.

It was only after retiring from her seismologist job aged 65 that Lehmann was able to devote herself full time to research. For the next 30 years, Lehmann worked and published prolifically, finally receiving awards and plaudits that were well deserved. However, this remarkable scientist, who died in 1993 aged 104, rarely appears in short histories of her field.

In a step to address this, we now have a biography of Lehmann: *If I Am Right, and I Know I Am* by Hanne Strager, a Danish biologist, science museum director and science writer. Strager pieces together Lehmann's life in great detail, as well as providing potted histories of the scientific areas that Lehmann contributed to.

A brief glance at the chronology of Lehmann's education and career would suggest that she was a late starter. She was 32 when she graduated with a bachelor's degree in mathematics from the University of Copenhagen, 40 when she received her master's degree in geodosy and was appointed state geodesist for Denmark. Lehmann faced a litany of struggles in her younger years, from health problems and money issues to the restrictions placed on most women's education in the first decades of the 20th century.

The limits did not come from her family. Lehmann and her sister were sent to good schools, she was encouraged to attend university, and was never pressed to get married, which would likely have meant the end of her education. When she asked her father's permission to go to the University of Cambridge, his objection was the cost – though the money was found and Lehmann duly went to Newnham College in 1910. While there she passed all the preliminary exams to study for Cambridge's legendarily tough mathematical tripos but then her health forced her to leave.

Lehmann was suffering from stomach pains; she had trouble sleeping; her hair was falling out. And this was not her first breakdown. She had previously studied for a year at the University of Copenhagen before then, too, dropping out and moving to the countryside to recover her health.

The cause of Lehmann's recurrent breakdowns is unknown. They unfortunately fed into the prevailing view of the time that women were too fragile for the rigours of higher learning. Strager attempts to unpick these historical attitudes from Lehmann's very real medical issues. She posits that Lehmann had severe anxiety or a physical limitation to how hard she could push herself. But this conclusion fails to address the hostile conditions Lehmann was working in.

In Cambridge Lehmann formed firm friendships that lasted the rest of her life. But women there did not have the same access to learning as men. They were barred from most libraries and laboratories; could not attend all the lectures; were often mocked and belittled by professors and male students. They could sit exams but, even if they passed, would not be awarded a degree. This was a contributing factor when after the First World War Lehmann decided to complete her undergraduate studies in Copenhagen rather than Cambridge.

More than meets the eye

Lehmann is described as quiet, shy, reticent. But she could be eloquent in writing and once her career began she established connections with scientists all over the world by writing to them frequently. She was also not the wallflower she initially appeared to be. When she was hired as an assistant at Denmark's Institute for the Measurement of Degrees, she quickly complained that she was being using as an office clerk, not a scientist, and she would not have accepted the job had she known this was the role. She was instead given geometry tasks that she found intellectually stimulating, which led her to seismology.

Unfortunately, soon after this Lehmann's career development

GEUS

Valued colleague A farewell party held for Inge Lehmann in 1954 at Lamont Geological Observatory after one of her research stays.

stalled. While her title of "state geodesist" sounds impressive, she was the only seismologist in Denmark for decades, responsible for all the seismographs in Denmark and Greenland. Her days were filled with the practicalities of instrument maintenance and publishing reports of all the data collected.

Despite repeated requests Lehmann didn't receive an assistant, which meant she never got round to completing a PhD, though she did work towards one in her evenings and weekends. Time and again opportunities for career advancement went to men who had the title of doctor but far less real experience in geophysics. Even after she co-founded the Danish Geophysical Society in 1934, her native country overlooked her.

The breakthrough that should have changed this attitude from the men around her came in 1936, when she published "P′". This innocuous sounding paper was revolutionary, but based firmly in the P wave and S wave measurements that Lehmann routinely monitored.

In *If I Am Right, and I Know I Am*, Strager clearly explains what P and S waves are. She also highlights why they were being studied by both state seismologist Lehmann and Cambridge statistician Harold Jeffreys, and how they led to both scientists' biggest breakthroughs.

After any seismological disturbance, P and S waves propagate through the Earth. P waves move at different speeds according to the material they encounter, while S waves cannot pass through liquid or air. This knowledge allowed Lehmann to calculate whether any fluctuations in seismograph readings were earthquakes, and if so where the epicentre was located. And it led to Jeffreys' insight that the Earth must have a liquid core.

Lehmann's attention to detail meant she spotted a "discontinuity" in P waves that did not quite match a purely liquid core. She immediately wrote to Jeffreys that she believed there was another layer to the Earth, a solid inner core, but he was dismissive – which led to her writing the statement that forms the title of this book. Undeterred, she published her discovery in the journal of the International Union of Geodesy and Geophysics.

In 1951 Lehmann visited the institution that would become her second home: the Lamont Geological Observatory in New York state. Its director Maurice Ewing invited her to work there on a sabbatical, arranging all the practicalities of travel and housing on her behalf.

Time and again opportunities for career advancement went to men who had the title of doctor but far less real experience in geophysics

Here, Lehmann finally had something she had lacked her entire career: friendly collaboration with colleagues who not only took her seriously but also revered her. Lehmann took retirement from her job in Denmark and began to spend months of every year at the Lamont Observatory until well into her 80s.

Though Strager tells us this "second phase" of Lehmann's career was prolific, she provides little detail about the work Lehmann did. She initially focused on detecting nuclear tests during the Cold War. But her later work was more varied, and continued after she lost most of her vision. Lehmann published her final paper aged 99.

If I Am Right, and I Know I Am is bookended with accounts of Strager's research into one particular letter sent to Lehmann, an anonymous (because the final page has been lost) declaration of love. It's an insight into the lengths Strager went to – reading all the surviving correspondence to and from Lehmann; interviewing living relatives and colleagues; working with historians both professional and amateur; visiting archives in several countries.

But for me it hit the wrong tone. The preface and epilogue are mostly speculation about Lehmann's love life. Lehmann destroyed a lot of her personal correspondence towards the end of her life, and chose what papers to donate to an archive. To me those are the actions of a woman who wants to control the narrative of her life – and does not want her romances to be written about. I would have preferred instead another chapter about her later work, of which we know she was proud.

But for the majority of its pages, this is a book of which Strager can be proud. I came away from it with great admiration for Lehmann and an appreciation for how lonely life was for many women scientists even in recent history.

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

Careers

From an attic laboratory to the heart of galaxies

Thaisa Storchi Bergmann, who won the L'Oréal-UNESCO For Women in Science prize in 2015, talks to **Meghie Rodrigues** about extragalactic astronomy, doing high-impact international research, and being a woman in South American physics

Lifelong curiosity Thaisa Storchi Bergmann won the L'Oréal-UNESCO For Women in Science prize in 2015 "for her outstanding work on supermassive black holes in the centres of galaxies and their associated regions of dense gas, dust and young stars surrounding them, as well as their role in the evolution of galaxies".

As a teenager in her native Rio Grande do Sul, a state in Southern Brazil, Thaisa Storchi Bergmann enjoyed experimenting in an improvised laboratory her parents built in their attic. They didn't come from a science background – her father was an accountant, her mother a primary school teacher – but they encouraged her to do what she enjoyed. With a friend from school, Storchi Bergmann spent hours looking at insects with a microscope and running experiments from a chemistry toy kit. "We christened the lab Thasi-Cruz after a combination of our names," she chuckles.

At the time, Storchi Bergmann could not have imagined that one day this path would lead to cosmic discoveries and international recognition at the frontiers of astrophysics. "I always had the curiosity inside me," she recalls. "It was something I carried since adolescence."

That curiosity almost got lost to another discipline. By the time Storchi Bergmann was about to enter university, she was swayed by a cousin living with her family who was passionate about architecture. By 1974 she began studying architecture at the Federal University of Rio Grande do Sul (UFRGS). "But I didn't really like technical drawing. My favourite part of the course were physics classes," she says. Within a semester, she switched to physics.

There she met Edemundo da Rocha Vieira, the first astrophysicist UFRGS ever hired – who later went on to structure the university's astronomy department. He nurtured Storchi Bergmann's growing fascination with the universe and introduced her to research.

In 1977, newly married after graduation, Storchi Bergmann followed her husband to Rio de Janeiro, where she did a master's degree and worked with William Kunkel, an American astronomer who was in Rio to help establish Brazil's National Astrophysics Laboratory. She began working on data from a photometric system to measure star radiation. "But Kunkel said galaxies were a lot more interesting to study, and that stuck in my head," she says.

Three years after moving to Rio, she returned to Porto Alegre, in Rio Grande do Sul, to start her doctoral research and teach at UFRGS. Vital to her career was her decision to join the group of Miriani Pastoriza, one of the pioneers of extragalactic astrophysics in Latin America. "She came from Argentina, where [in the late 1970s and early 1980s] scientists were being strongly persecuted [by the country's military dictatorship] at the time," she recalls. Pastoriza studied galaxies with "peculiar nuclei" – objects later known to harbour supermassive black holes. Under Pastoriza's guidance, she moved from stars to galaxies, laying the foundation for her career.

Between 1986 and 1987, Storchi Bergmann often travelled to Chile to make observations and gather data for her PhD, using some of the largest telescopes available at the time. Then came a transformative period – a postdoc fellowship in Maryland, US, just as the Hubble Space Telescope was launched in 1990. "Each Thursday, I would drive to Baltimore for informal bag-lunch talks at the Space Telescope Science Institute, absorbing new results on active galactic nuclei (AGN) and supermassive black holes," Storchi Bergmann recalls.

Discoveries and insights

In 1991, during an observing campaign, she and a collaborator saw something extraordinary in the galaxy NGC 1097: gas moving at immense speeds, captured by the galaxy's central black hole. The work, published in 1993, became one of the earliest documented cases of what are now called "tidal disruption events", in which a star or cloud gets too close to a black hole and is torn apart.

Her research also contributed to one of the defining insights of the Hubble era: that every massive galaxy hosts a central black hole. "At first, we didn't know if they were rare," she explains. "But gradually it became clear: these objects are fundamental to galaxy evolution."

Another collaboration brought her into contact with Daniela Calzetti, whose work on the effects of interstellar dust led to the formulation of the widely used "Calzetti law". These and other contributions placed Storchi Bergmann among the most cited scientists worldwide, recognition of which came in 2015 when she received the L'Oréal-UNESCO Award for Women in Science.

Her scientific achievements, however, unfolded against personal and structural obstacles. As a young mother, she often brought her baby to observatories and conferences so she could breastfeed. This kind of juggling is no stranger to many women in science. "It was never easy," Storchi Bergmann reflects. "I was always running, trying to do 20 things at once." The lack of childcare infrastructure in universities compounded the challenge. She recalls colleagues who succeeded by giving up on family life altogether. "That is not sustainable," she insists. "Science needs all perspectives – male, female and everything in-between. Otherwise, we lose richness in our vision of the universe."

When she attended conferences early in her career, she was often the only woman in the room. Today, she says, the situation has greatly improved, even if true equality remains distant.

Now a tenured professor at UFRGS and a member of the Brazilian Academy of Sciences, Storchi Bergmann continues to push at the cosmic frontier. Her current focus is the Legacy Survey of Space and Time (LSST), about to begin at the Vera Rubin Observatory in Chile.

Her group is part of the AGN science collaboration, developing methods to analyse the characteristic flickering of accreting black holes. With students, she is experimenting with automated pipelines and artificial intelligence to make sense of and manage the massive amounts of data.

Challenges ahead

Yet this frontier science is not guaranteed. Storchi Bergmann is frustrated by the recent collapse in research scholarships. Historically, her postgraduate programme enjoyed a strong balance of grants from both of Brazil's federal research funding agencies, CNPq (from the Ministry of Science) and CAPES (from the Ministry of Education). But cuts at CNPq, she says, have left students without support, and CAPES has not filled the gap.

"The result is heartbreaking," she says. "I have brilliant students ready to start, including one from Piauí (a state in north-eastern Brazil), but without a grant, they simply cannot continue. Others are forced to work elsewhere to support themselves, leaving no time for research."

She is especially critical of the policy of redistributing scarce funds away from top-rated programmes to newer ones without expanding the overall budget. "You cannot build excellence by dismantling what already exists," she argues.

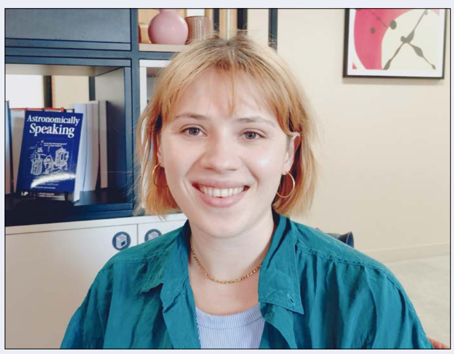
For her, the consequences go beyond personal frustration. They risk undermining decades of investment that placed Brazil on the international astrophysics map. Despite these challenges, Storchi Bergmann remains driven and continues to mentor master's and PhD students, determined to prepare them for the LSST era.

At the heart of her research is a question as grand as any in cosmology: which came first – the galaxy or its central black hole? The answer, she believes, will reshape our understanding of how the universe came to be. And it will carry with it the fingerprint of her work: the persistence of a Brazilian scientist who followed her curiosity from a home-made lab to the centres of galaxies, overcoming obstacles along the way.

Meghie Rodrigues is a Brazil-based science and environment journalist covering mainly earth and physical sciences, climate change and environmental policy

Ask me anything: Kirsty McGhee

Kirsty McGhee did a PhD in condensed-matter physics at the University of Sheffield, UK, and a postdoc at the University of Leipzig, Germany, before becoming a science writer at the quantum-software company Qruise. She was previously part of the *Physics World* student-contributor network.



AUDIO Kirsty McGhee speaks to *Physics World*'s Hamish Johnston about her career

What skills do you use every day in your job?

Obviously, I write: I wouldn't be a very good science writer if I couldn't. So communication skills are vital. Recently, for example, Qruise launched a new magnetic-resonance product for which I had to write a press release, create a new webpage and do social-media posts. That meant co-ordinating with lots of different people, finding out the key features to advertise, identifying the claims we wanted to make – and if we have the data to back those claims up. I'm not an expert in quantum computing or magnetic-resonance imagining or even marketing so I have to pick things up fast and then translate technically complex ideas from physics and software into simple messages for a broader audience. Thankfully, my colleagues are always happy to help. Science writing is a difficult task but I think I'm getting better at it.

What do you like best and least about your job?

I love the variety and the fact that I'm doing so many different things all the time. If there's a day I feel I want something a little bit lighter, I can do some social media or the website, which is more creative. On the other hand, if I feel I could really focus in detail on something then I can write some documentation that is a little bit more technical.

I also love the flexibility of remote working, but I do miss going to the office and socialising with my colleagues on a regular basis. You can't get to know someone as well online, it's nicer to have time with them in person.

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

That's a hard one. It would be easy to say I wish I'd known earlier that I could combine science and writing and make a career out of that. On the other hand, if I'd known that, I might not have done my PhD – and if I'd gone into writing straight after my undergraduate degree, I perhaps wouldn't be where I am now.

My point is, it's okay not to have a clear plan in life. As children, we're always asked what we want to be – in my case, my dream from about the age of four was to be a vet. But then I did some work experience in a veterinary practice and I realized I'm really squeamish. It was only when I was 15 or 16 that I discovered I wanted to do physics because I liked it and was good at it. So just follow the things you love. You might end up doing something you never even thought was an option.

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Spider webs, jumping worms, cutting onions

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

Spider webs are a marvel of bioengineering, but there is still more to understand about these sticky structures. Many spider species build spiral orb webs to capture prey, and some incorporate so-called "stabilimenta" into their web structure. These "extra touches" look like zig-zagging threads that span the gap between two adjacent "spokes," or threads arranged in a circular "platform" around the web centre. The purpose of stabilimenta is unknown and proposed functions include as a deterrence for predatory wasps or birds. To find out more, Gabriele Greco of the Swedish University of Agricultural Sciences and colleagues observed different stabilimentum geometries that were constructed by wasp spiders, *Argiope bruennichi* (*PLOS One* **20** e0332593). The researchers then performed numerical simulations to explore how stabilimenta affect the propagation of web vibrations triggered by the impact of captured prey. For waves generated at angles perpendicular to the threads spiralling out from the web centre, stabilimenta caused negligible delays in wave propagation. However, for waves generated in the same direction as the spiral threads, vibrations in webs with stabilimenta propagated to a greater number of potential detection points across the web – where a spider might sense them – than in webs without stabilimenta. This suggests that stabilimenta may boost a spider's ability to pinpoint the location of unsuspecting prey caught in its web.

Flight of the nematode

From arachnids to nematodes as researchers in the US have discovered that a tiny jumping worm uses static electricity to increase its chances of attaching to unsuspecting prey. The parasitic roundworm *Steinernema carpocapsae* can leap some 25 times its body length by curling into a loop and springing in the air. If the nematode lands successfully on a victim, it releases bacteria that kills the insect within a couple of days upon which the worm feasts and lays its eggs. To investigate whether static electricity aids their flight, a team at Emory University and the University of California, Berkeley, used high-speed microscopy to film the worms as they leapt onto a fruit fly that was tethered with a copper wire connected to a high-voltage power supply (*Proc. Natl Acad. Sci.* **122** e2503555122). The researchers found that a charge of a few hundred volts – similar to that generated in the wild by an insect's wings rubbing against ions in the air – fosters a negative charge on the worm, creating an attractive force with the positively charged fly. They discovered that without any electrostatics, only 1 in 19 worm trajectories successfully reached their target. The greater the voltage, however, the greater the chance of landing with 880 V resulting in an 80% probability of success. "We're helping to pioneer the emerging field of electrostatic ecology," notes Emory physicist Ranjiangshang Ran.

Tear-jerking result

While it is known that volatile chemicals released from onions irritate the nerves in the cornea to produce tears, how such chemical-laden droplets reach the eyes and whether they are influenced by the knife or cutting technique remain less clear. To investigate, Sunghwan Jung from Cornell University and colleagues built a guillotine-like apparatus and used high-speed video to observe the droplets released from onions as they were cut by steel blades (*Proc. Natl Acad. Sci.* **122** e2512779122). They found that droplets, which can reach up to 60 cm high, were released in two stages – the first being a fast mist-like outburst that was followed by threads of liquid fragmenting into many droplets. The most energetic droplets were released during the initial contact between the blade and the onion's skin. When they began varying the sharpness of the blade and the cutting speed, they discovered that a greater number of droplets were released by blunter blades and faster cutting speeds. "That was even more surprising," notes Jung. "Blunter blades and faster cuts – up to 40 m/s – produced significantly more droplets with higher kinetic energy." Another surprise was that refrigerating the onions prior to cutting also produced an increased number of droplets of similar velocity, compared to room-temperature vegetables.


Pierluigi Rizzo

Hanging by a thread Wasp spiders, *Argiope bruennichi*, are known to incorporate zig-zagging threads known as "stabilimenta" into their web structure.

It is harder to be a parent than to be a Space Shuttle commander

Astronaut **Eileen Collins**, who in 1995 became the first woman to pilot and command a NASA spacecraft, notes in a new feature-length documentary – *Spacewoman* – about her life and career that the best commander training she ever had "was being a parent because you have to learn how to say no to people". (Source: BBC)

This is like *The Kardashians* for physicists – I love it

Podcaster **Chris Williamson**, host of the show *Modern Wisdom*, was commenting on the rise of "conspiracy physics", in which people build huge audiences of millions of viewers or listeners by proclaiming that physics is in crisis, despite concerns from scientists that it is damaging the field. (Source: *Wall Street Journal*)

Michael Banks is news editor of *Physics World*