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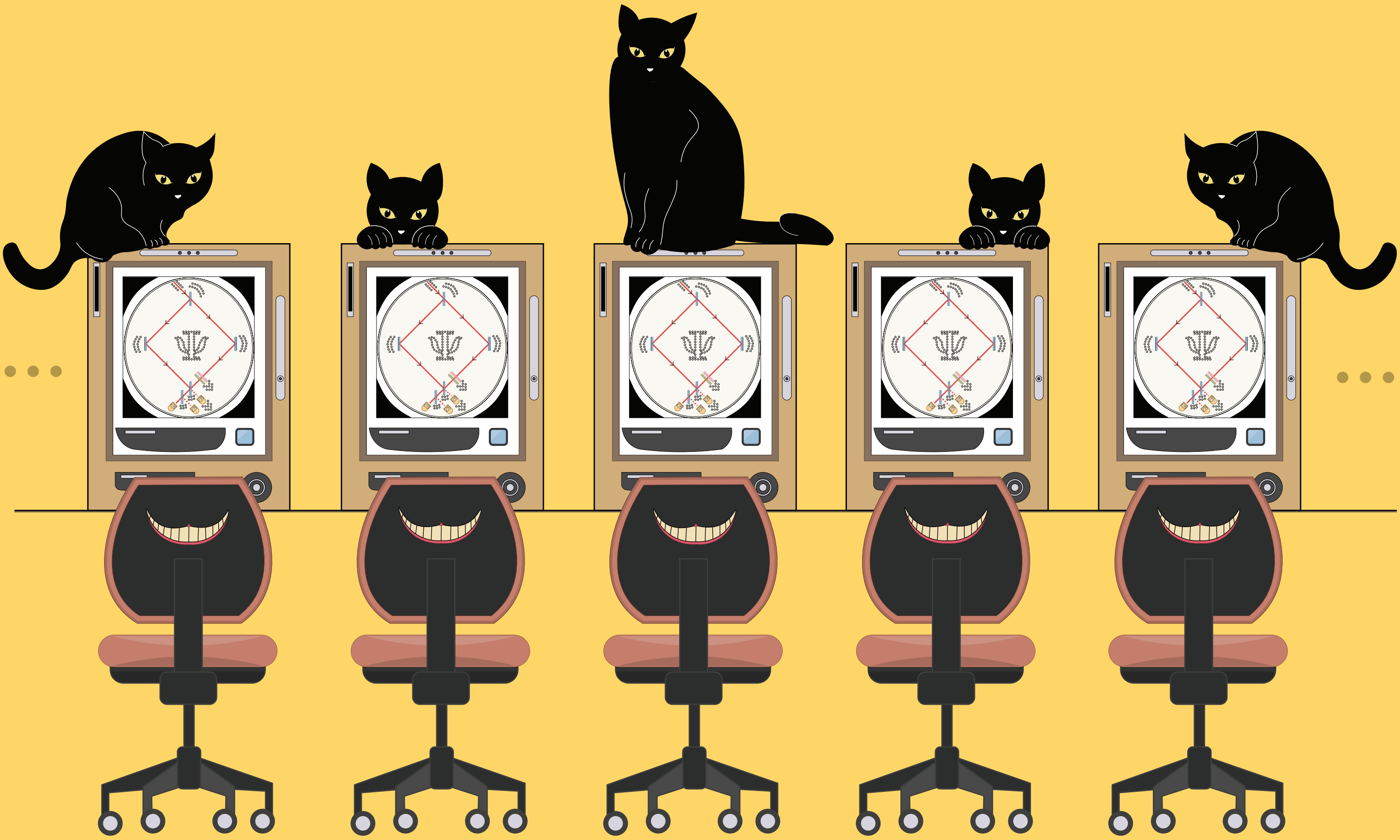
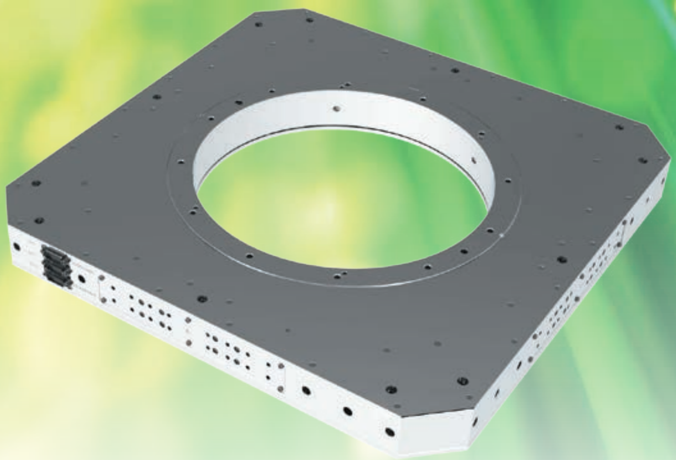
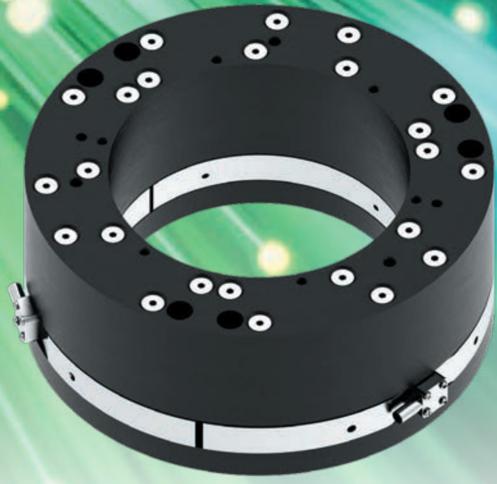
June 2025



Curiouser and curiouser

The strange case of quantum Cheshire cats





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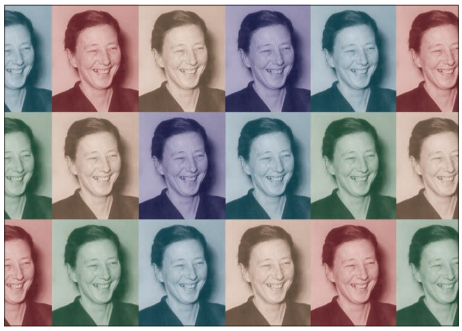

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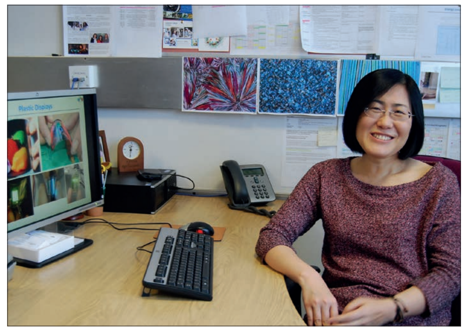

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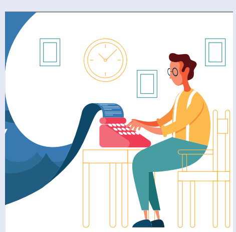


25 years of Critical Point

To celebrate a quarter century of our monthly column by science historian and philosopher Robert P Crease, we've put together a special collection of the best Critical Point articles from our archives. Check it out now

News & Analysis

Harvard sues Trump administration

Amid deep cuts to American science, Harvard University is suing the US government over its plan to block up to $9bn of government research grants to the institution. **Peter Gwynne** reports

Harvard University is suing the Trump administration over its plan to block up to $9bn of government research grants to the institution. The suit, filed in a federal court on 21 April, claims that the administration's "attempt to coerce and control" Harvard violates the academic freedom protected by the first amendment of the US constitution.

The action comes in the wake of the US administration claiming that Harvard and other universities have not protected Jewish students during pro-Gaza campus demonstrations. Columbia University has already agreed to change its teaching policies and clamp down on demonstrations in the hope of regaining some $400 000 of government grants. Harvard president Alan Garber also sought negotiations with the administration on ways that it might satisfy its demands. But a letter sent to Garber dated 11 April, signed by three Trump administration officials, asserted that the university had "failed to live up to both the intellectual and civil rights conditions that justify federal investments".

The letter demanded that Harvard reform and restructure its governance, stop all diversity, equality and inclusion (DEI) programmes, and change how it hires staff and students. It also said that Harvard must stop recruiting international students who are "hostile to American values" and provide an audit on "viewpoint diversity" on admissions and hiring. Some administration sources suggested that the letter, which effectively insists on government oversight of Harvard's affairs, was an internal draft sent to Harvard by mistake. Nevertheless, Garber decided to end negotiations, leading Harvard to instead sue the government over the blocked funds.

A letter on 14 April from Harvard's lawyers states that the university is "committed to fighting antisemitism and other forms of bigotry in its community". It adds that it is "open to dialogue" about what it has done, and is planning to do, to "improve the experience of every member" of its community but concludes that Harvard "is not prepared to agree to demands that go beyond the lawful authority of this or any other administration".

Kris Snibbe/Harvard University

Fighting back Harvard University is at loggerheads with the US government over research funding.

In an open letter to the community dated 22 April, Garber notes that "we stand for the values that have made American higher education a beacon for the world". The administration hit back by threatening to withdraw Harvard's non-profit status, tax its endowment, and jeopardize its ability to enrol overseas students, who currently make up more than 27% of its intake.

On 12 May, US education secretary Linda McMahon said that the university should not bother to apply for federal grant money "since none will be provided". Yet Harvard's leadership refused to back down. It announced that it will "reaffirm the university's commitment to the research enterprise" by providing $250m of central funding to support research affected by the government's withdrawals. Garber also announced that he would take a voluntary pay cut of 25%.

Budget woes

Research is also on the chopping block at the Environmental Protection Agency (EPA). According to reports, a reorganization of the agency will block funding for, and close the laboratories of, its research arm, the Office of Research and Development – and will do so despite an agreement to maintain the office's funding until the financial year's end on 30 September. The EPA's leadership has cancelled hundreds of grants intended to help communities deal with the impacts of climate change.

The Trump administration is also planning swingeing cuts to government science agencies. If its budget request for 2026 is approved by Congress, funding for NASA's Science Mission Directorate would be almost halved from $7.3bn to $3.9bn. The Nancy Grace Roman Space Telescope, a successor to the Hubble and James Webb space telescopes, would be axed. Two missions to Venus – the DAVINCI atmosphere probe and the VERITAS surface-mapping project – as well as the Mars Sample Return mission would lose their funding too. "The impacts of these proposed funding cuts would not only be devastating to the astronomical sciences community, but they would also have far-reaching consequences for the nation," says Dara Norman, president of the American Astronomical Society. "These cuts will derail not only cutting-edge scientific advances, but also the training of the nation's future STEM workforce."

The National Oceanic and Atmospheric Administration also stands to lose key programmes, with the budget for its Ocean and Atmospheric Research Office slashed from $485m to just over $170m. Its research into tornado warning and ocean acidification, meanwhile, would move to the National Weather Service and National Ocean Service. "This administration's hostility toward research and rejection of climate science will have the consequence of eviscerating the weather forecasting capabilities that this plan claims to preserve," says Zoe Lofgren, a senior Democrat who sits on the House of Representatives' Science, Space, and Technology Committee.

Nor will the Department of Energy escape the axe. The budget of its Office of Science is slated to fall by 14%, while its Advanced Research Projects Agency–Energy faces a loss of 55% of its annual income.

The National Science Foundation (NSF), meanwhile, is unlikely to receive $234m for major building projects this financial year, which could spell the end of the Horizon supercomputer being built at the University of Texas at Austin. The NSF has already halved the number of graduate students in its research fellowship programme, while *Science* magazine says the NSF is calling back all grant proposals that had been approved but not signed off, apparently to check that awardees conform to Trump's stance on DEI. The administration's current plans envision a drop in the agency's annual budget from the current $9bn to $4bn.

This hostility toward research and rejection of climate science will have the consequence of eviscerating weather forecasting capabilities

In other news, Sethuraman Panchanathan resigned as NSF director five years into his six-year term, which began in 2020. "I believe that I have done all I can to advance the mission of the agency and feel that it is time to pass the baton to new leadership," Panchanathan said in a statement. "This is a pivotal moment for our nation in terms of global competitiveness. We must not lose our competitive edge."

In early May, the NSF became the third government agency – after the National Institutes of Health and the Department of Energy – to restrict indirect costs attached to government grants to 15%. The Massachusetts Institute of Technology (MIT), Brown University, and three university-supporting organizations responded by mounting a joint lawsuit filed in US District Court in Massachusetts. MIT noted that it had received $97m in such costs last financial year, while Brown had used $34.4m to support 250 NSF grants during the same time.

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

Quantum

India must boost investment in quantum tech, says report

India must intensify its efforts in quantum technologies and boost private investment if it is to become a leader in the burgeoning field. That is according to the first report from India's National Quantum Mission (NQM), which also warns that the country must improve its quantum security and regulation to make its digital infrastructure quantum-safe.

Approved by the Indian government in 2023, the NQM is an eight-year $750m (60bn INR) initiative that aims to make the country a leader in quantum tech. Its new report focuses on four aspects of the NQM's mission: quantum computing; communication; sensing and metrology; and materials and devices. The report finds that India's research interests include error-correction algorithms for quantum computers. It is also involved in building quantum hardware with superconducting circuits, trapped atoms/ions and engineered quantum dots.

Ajay Sood, principal scientific adviser to the Indian government, told *Physics World* that while India is strong in "software-centric, theoretical and algorithmic aspects of quantum computing, work on completely indigenous development of quantum computing hardware is…at a nascent stage". The NQM-supported Bengaluru-based start-up QPiAI, for example, has made a 25-superconducting qubit quantum computer called "Indus", although the qubits were fabricated abroad.

iStock/Quardia

Quantum focus The report by the National Quantum Mission warns that India needs to improve its quantum security and regulation.

Sood, who is a physicist by training, adds that while there are a few groups working on different platforms, these are at less than 10-qubit stage. "[It is] important for [India] to have indigenous capabilities for fabricating qubits and other ancillary hardware for quantum computers," he says. India is also developing secure protocols and satellite-based systems and implementing quantum systems for precision measurements. QNu Labs – another Bengalaru start-up – is, for example, developing a quantum-safe communication-chip module to secure satellite and drone communications with built-in quantum randomness and security micro-stack.

The report highlights the need for greater involvement of Indian industry in hardware-related activities. Unlike other countries, India struggles with limited industry funding, in which most comes from angel investors, with limited participation from institutional investors such as venture-capital firms, tech corporates and private equity funds. The report also calls for more indigenous development of single-photon detectors, quantum repeaters and associated electronics, with necessary testing facilities for quantum communication. "There is also room for becoming global manufacturers and suppliers for associated electronic or cryogenic components," says Sood. "Our industry should take this opportunity."

India must work on its quantum security and regulation as well, according to the report. It warns that the Indian financial sector, which is one of the major drivers for quantum tech applications, "risks lagging behind" in quantum security and regulation, with limited participation of Indian financial-service providers. India currently has about 50 educational programmes in various universities and institutions. Yet Arindam Ghosh, who runs the Quantum Technology Initiative at the Indian Institute of Science, Bangalore, says that the country faces a lack of people going into quantum-related careers. "In spite of [a] very large number of quantum-educated graduates, the human resource involved in developing quantum technologies is abysmally small," says Ghosh.

TV Padma
New Delhi

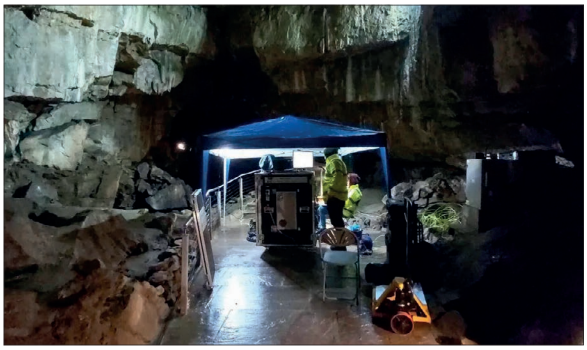
Awards

Birmingham's Delta.g wins qBIG prize for its gravity sensors

The UK-based company Delta.g has won the 2025 qBIG prize, which is awarded by the Institute of Physics (IOP). Initiated in 2023, qBIG celebrates and promotes the innovation and commercialization of quantum technologies in the UK and Ireland. Based in Birmingham, Delta.g makes quantum sensors that measure the local gravity gradient. This is done using atom interferometry, whereby laser pulses are fired at a cloud of cold atoms that is freefalling under gravity.

On the Earth's surface, this gradient is sensitive to the presence of buildings and underground voids such as tunnels. The technology was developed by physicists at the University of Birmingham who in 2022 showed how it could be used to map out a tunnel below a road on campus. The system has also been deployed in a cave and on a ship to test its suitability for use in navigation.

"Gravity is a fundamental force, yet its full potential remains largely untapped because it is so challenging to measure," explains Andrew Lamb, who is co-founder and chief technology officer at Delta.g. "As the first to take quantum technology gravity gradiometry from the lab to the field, we have set a new benchmark for high-integrity, noise-resistant data transforming how we understand and navigate the subsurface."



University of Birmingham © Crown Copyright

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

The qBIG prize is sponsored by Quantum Exponential – the UK's first enterprise venture capital fund focused on quantum technology. The winner was announced last month at the *Economist*'s Commercialising Quantum Global 2025 event in London. Delta.g receives a £10 000 prize; 10 months of mentoring from Quantum Exponential; and business support from the IOP.

"The IOP's role as UK and Ireland co-ordinator of the International Year of Quantum gives us a unique opportunity to showcase the exciting developments in the quantum sector," says Louis Barson, the IOP's director of science, innovation and skills. Runners-up are Glasgow-based Neuranics, which makes quantum sensors that detect tiny magnetic signals from the human body, and Southampton's Smith Optical, which makes an augmented-reality display based on quantum technology.

Hamish Johnston

Spectacular images of the cosmos released to celebrate Hubble's 35 years in orbit

NASA, ESA, STScI

A series of spectacular images of the cosmos has been released to celebrate the Hubble Space Telescope's 35 years in space. The images include pictures of Mars, planetary nebulae and a spiral galaxy. Hubble was launched into low-Earth orbit in April 1990, stowed in the payload bay of the Space Shuttle Discovery. During Hubble's operational life, the telescope has made nearly 1.7 million observations, studying approximately 55 000 astronomical targets. Its discoveries have resulted in more than 22 000 papers and over 1.3 million citations. Operating for three decades, Hubble has allowed astronomers to see astronomical changes such as seasonal variability on the planets in our solar system, black-hole jets travelling at nearly the speed of light as well as stellar convulsions, asteroid collisions and expanding supernova bubbles. Despite being 35 years in orbit around the Earth, Hubble is still one of the most sought-after observatories, with demand for observing time oversubscribed by 6:1. "[Hubble's] stunning imagery inspired people across the globe, and the data behind those images revealed surprises about everything from early galaxies to planets in our own solar system," notes Shawn Domagal-Goldman, acting director of NASA's astrophysics division. "The fact that it is still operating today is a testament to the value of our flagship observatories."

Michael Banks

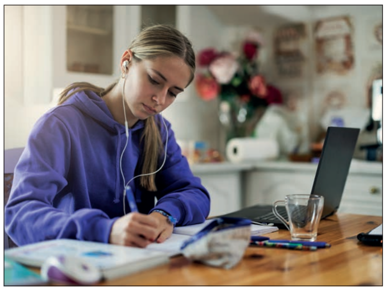
Education

‘Chatty’ AI could boost student interest in physics

Chatbots could improve students’ interest in maths and physics and make learning more enjoyable. So say researchers in Germany, who have compared the emotional response of students using artificial intelligence (AI) texts to learn physics compared with those who only read traditional textbooks. The team, however, found no difference in test performance between the two groups.

The study has been led by Julia Lademann, a physics-education researcher from the University of Cologne, who created a customized chatbot using OpenAI’s ChatGPT model. It was designed with a tone and language that was considered accessible to second-year high-school students in Germany.

After testing the chatbot for factual accuracy and for its use of motivating language, the researchers prompted it to generate explanatory text on proportional relationships in physics and mathematics. They then split 214 students, who had an average age of 11.7, into two groups. One group was given textbook material on the topic along with chatbot text, while the control group only got the textbook.



istock/imgorthand

Sweetening the pill Using a chatbot to learn about physics concepts was found to significantly enhance students’ positive emotions compared to those who only used a textbook.

The researchers first surveyed the students’ interest in mathematics and physics and then gave them 15 minutes to review the learning material. Their interest was assessed again afterwards along with the students’ emotional state and “cognitive load” – the mental effort required to do the work – through a series of questionnaires.

The chatbot was found to significantly enhance students’ positive emotions – including pleasure and satisfaction, interest in the learning material and self-belief in their understanding of the subject – compared with those who only used textbook text. “The text of the chatbot is more human-like, more conversational than texts you will find in a textbook,” explains Lademann. “It is more chatty.”

Chatbot text was also found to reduce cognitive load. “The group that used the chatbot explanation experienced higher positive feelings about the subject [and] they also had a higher confidence in their learning comprehension,” adds Lademann. Tests taken within 30 minutes of the “learning phase” of the experiment, however, found no difference in performance between students who received the AI-generated explanatory text and the control group, despite the former receiving more information. Lademann says this could be due to the short study time of 15 minutes.

The researchers say that further research is needed to assess AI’s impact on learning performance and long-term outcomes. Lademann would now like to see “longer term studies with a lot of participants and with children actually using the chatbot”. Such research would explore the potential key strength of chatbots; their ability to respond in real time to student’s queries and adapt their learning level to each individual student.

Michael Allen

UK

Ray Dolby Centre becomes new home for Cavendish Laboratory

A ceremony was held last month to officially open the Ray Dolby Centre at the University of Cambridge. Named after the Cambridge physicist and sound pioneer Ray Dolby, who died in 2013, the facility is the new home of the Cavendish Laboratory and has 173 labs as well as lecture halls, workshops, cleanrooms and offices.

Designed by the architecture and interior design practice Jestico + Whiles and constructed by Bouygues UK, the centre has been funded by £85m from Dolby’s estate as well as £75m from the UK’s Engineering and Physical Sciences Research Council (EPSRC).

Spanning 33 000 m² across five floors, the new centre will house 1100 staff members and students. The basement will feature microscopy and laser labs containing vibration-sensitive equipment as well as 2500 m² of cleanrooms. The Dolby centre will also serve as a national hub for physics, hosting the Collaborative R&D Environment – an EPSRC National Facility – that will foster collaboration between industry and university researchers.

University of Cambridge

Strong foundations The Ray Dolby Centre includes space for 173 labs, lecture halls, workshops, cleanrooms and offices.

Parts of the centre will be open to the public, including a café as well as outreach and exhibition spaces that are organized around six courtyards.

The centre also provides a new home for the Cavendish Museum. The ceremony last month was attended by Dagmar Dolby, president of the Ray and Dagmar Dolby Family Fund; Deborah Prentice, vice-chancellor of Cambridge; and physicist Mete Atatüre, current head of the Cavendish.

“The greatest impacts on society – including the Cavendish’s biggest discoveries – have happened because of that combination of technological capability and human ingenuity,” notes Atatüre. “Science is getting more complex and technically demanding with progress, but now we have the facilities we need for our scientists to ask those questions, in the pursuit of discovering creative paths to the answers – that’s what we hope to create with the Ray Dolby Centre.”

Michael Banks

Fifty years of ‘taking the weather’

As the European Centre for Medium-Range Weather Forecasts celebrates its 50th anniversary, research director **Andy Brown** talks to Joe McEntee about the growing impact of AI and machine-learning technologies in weather and climate modelling

What is the main role of the European Centre for Medium-Range Weather Forecasts (ECMWF)?

Making weather forecasts more accurate is at the heart of what we do at the ECMWF, working in close collaboration with our member states and their national meteorological services (see box on p8). That means enhanced forecasting for the weeks and months ahead as well as seasonal and annual predictions. We also have a remit to monitor the atmosphere and the environment – globally and regionally – within the context of a changing climate.

How does the ECMWF produce its weather forecasts?

Our task is to get the best representation, in a 3D sense, of the current state of the atmosphere versus key metrics like wind, temperature, humidity and cloud cover. We do this via a process of reanalysis and data assimilation: combining the previous short-range weather forecast, and its component data, with the latest atmospheric observations – from satellites, ground stations, radars, weather balloons and aircraft. Unsurprisingly, using all this observational data is a huge challenge, with the exploitation of satellite measurements a significant driver of improved forecasting over the past decade.

In what ways do satellite measurements help?

Consider the EarthCARE satellite that was launched in May 2024 by the European Space Agency (ESA) and is helping ECMWF to improve its modelling of clouds, aerosols and precipitation. EarthCARE has a unique combination of scientific instruments – a cloud-profiling radar, an atmospheric lidar, a multispectral imager and a broadband radiometer – to infer the properties of clouds and how they interact with solar radiation as well as thermal-infrared radiation emitted by different layers of the atmosphere.

ECMWF/Stephen Shepherd photography

On cloud nine Andy Brown, who originally studied physics at the University of Oxford before moving into meteorology.

A five-day forecast now is as good as a three-day forecast 20 years ago. A richer and broader mix of observational data underpins that improvement

How are you combining such data with modelling?

The ECMWF team is learning how to interpret and exploit the EarthCARE data to directly initiate our models. Put simply, mathematical models that better represent clouds and, in turn, yield more accurate forecasts. Indirectly, EarthCARE is also revealing a clearer picture of the fundamental physics governing cloud formation, distribution and behaviour. This is just one example of numerous developments taking advantage of new satellite data. We are looking forward, in particular, to fully exploiting next-generation satellite programmes from the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) – including the EPS-SG polar-orbiting system and the Meteosat Third Generation geostationary satellite for continuous monitoring over Europe, Africa and the Indian Ocean.

What other factors help improve forecast accuracy?

We talk of “a day, a decade” improvement in weather forecasting, such that a five-day forecast now is as good as a three-day forecast 20 years ago. A richer and broader mix of observational data underpins that improvement, with diverse data streams feeding into bigger supercomputers that can run higher-resolution models and better algorithms. Equally important is ECMWF’s team of multidisciplinary scientists, whose understanding of the atmosphere and climate helps to optimize our models and data assimilation methods. A case study in this regard is Destination Earth, an ambitious EU initiative to create a series of “digital twins” – interactive computer simulations – of our planet by 2030. Working with ESA and EUMETSAT, the ECMWF is building the software and data environment for Destination Earth as well as developing the first two digital twins.

What are these two twins?

Our Digital Twin on Weather-Induced and Geophysical Extremes will assess and predict environmental extremes to support risk assessment and management. Meanwhile, in collaboration with others, the Digital Twin on Climate Change Adaptation complements and extends existing capabilities for the analysis and testing of “what if” scenarios – supporting sustainable development and climate adaptation and mitigation policy-making over multidecadal timescales.

What kind of resolution will these models have?

Both digital twins integrate sea, atmosphere, land, hydrology and sea ice and their deep connections with a resolution currently impossible to reach. Right now, for example, the ECMWF’s operational forecasts cover the whole globe in a 9 km grid – effectively a localized forecast every 9 km. With Destination Earth, we’re experimenting with 4 km, 2 km, and even 1 km grids.

In February the ECMWF unveiled a 10-year strategy to accelerate the use of machine learning and AI. How will this be implemented?

The new strategy prioritizes growing exploitation of data-driven methods anchored on established physics-based modelling – rapidly scaling up our previous deployment of machine learning and AI. There are also a variety of hybrid approaches combining data-driven and physics-based modelling.

What will this help you achieve?

On the one hand, data assimilation and observations will help us to directly improve as well as initialize our physics-based forecasting models – for example, by optimizing uncertain parameters or learning correction terms. We are also investigating the potential of applying machine-learning techniques directly on observations – in effect, to make another step beyond the current state-of-the-art and produce forecasts without the need for reanalysis or data assimilation.

How is machine learning deployed?

Progress in machine learning and AI has been dramatic over the past couple of years – so much so that we launched our Artificial Intelligence Forecasting System (AIFS) back in February. Trained on many years of reanalysis and using traditional data assimilation, AIFS is already an important addition to our suite of forecasts, though still working off the coat-tails of our physics-based predictive models. Another notable innovation is our Probability of Fire machine-learning model, which incorporates multiple data sources beyond weather prediction to identify regional and localized hot-spots at risk of ignition. Those additional parameters – among them human presence, lightning activity as well as vegetation abundance and its dryness – help to pinpoint areas of targeted fire risk, improving the model's predictive skill by up to 30%.

What do you like most about working at the ECMWF?

Every day, the ECMWF addresses cutting-edge scientific problems – as challenging as anything you'll encounter in an academic setting – by applying its expertise in atmospheric physics, mathematical modelling, environmental science, big data and other disciplines. What's especially motivating, however, is that the ECMWF is a mission-driven endeavour with a straight line from our research outcomes to wider societal and economic benefits.

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

ECMWF at 50: new frontiers in weather and climate prediction

The European Centre for Medium-Range Weather Forecasts (ECMWF) is an independent intergovernmental organization supported by 35 states – 23 member states and 12 co-operating states. Established in 1975, the centre employs around 500 staff from more than 30 countries at its headquarters in Reading, UK, and sites in Bologna, Italy, and Bonn, Germany. As a research institute and 24/7 operational service, the ECMWF produces global numerical weather predictions four times per day and other data for its member/co-operating states and the broader meteorological community.

The ECMWF processes data from around 90 satellite instruments as part of its daily activities (yielding 60 million quality-controlled observations each day for use in its Integrated Forecasting System). The centre is a key player in Copernicus – the Earth observation component of the EU's space programme – by contributing information on climate change for the Copernicus Climate Change Service; atmospheric composition to the Copernicus Atmosphere Monitoring Service; as well as flooding and fire danger for the Copernicus Emergency Management Service.

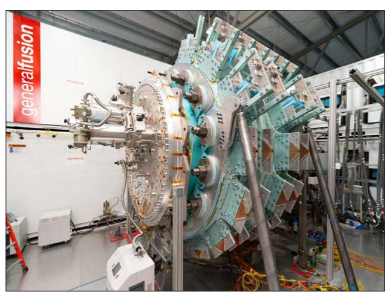
This year, the ECMWF is celebrating its 50th anniversary and has a series of celebratory events scheduled in Bologna (15–19 September) and Reading (1–5 December).

Fusion

General Fusion lays off staff due to 'financing constraints'

The Canadian firm General Fusion is to lay off about 25% of its 140-strong workforce and reduce the operation of its fusion device dubbed Lawson Machine 26 (LM26). The announcement was made in an open letter published on 5 May by the company's chief executive Greg Twinney. The moves follow what the firm says is an "unexpected and urgent financing constraint".

Founded in 2002 by the Canadian plasma physicist Michel Laberge, General Fusion is based in Richmond, British Columbia. It was one of the first private fusion companies and has attracted more than $325m of funding from both private investors, including Amazon boss Jeff Bezos, and the Canadian government. The firm is pursuing commercial fusion energy via magnetized target fusion (MTF) technology, based on the concept of an enclosed, liquid-metal vortex. Plasma is injected into the centre of the vortex before numerous pistons hammer on the outside of the enclosure, compressing the plasma and sparking a fusion reaction, with the resulting heat being absorbed by the liquid metal.



General Fusion

Turbulent times General Fusion's Lawson Machine 26 uses magnetized target fusion technology.

LM26 switched on in 2023 and is designed to achieve fusion conditions of over 100 million kelvin. Over the past couple of years, the machine has claimed a number of milestones, including generating a magnetized plasma in the machine's target chamber in March. Last month, General Fusion also said that LM26 had successfully compressed a large-scale magnetized plasma with lithium.

The firm was hoping to achieve "scientific breakeven equivalent" in the coming years with the aim of potentially building a commercial-scale machine with the technology in the 2030s. But that timescale now looks unlikely as General Fusion announced plans to downscale its efforts due to funding issues.

"Today's funding landscape is more challenging than ever as investors and governments navigate a rapidly shifting and uncertain political and market climate," says Twinney. "We are ready to execute our plan but are caught in an economic and geopolitical environment that is forcing us to wait." But he insists the firm, which is seeking new investors, remains an "attractive opportunity".

Andrew Holland, chief executive of the non-profit Fusion Industry Association, told *Physics World* that the "nature of private enterprise is that business cycles go up and go down" and claims that excitement about fusion is growing around the world.

Michael Banks

Research updates

Quantum computer makes random numbers

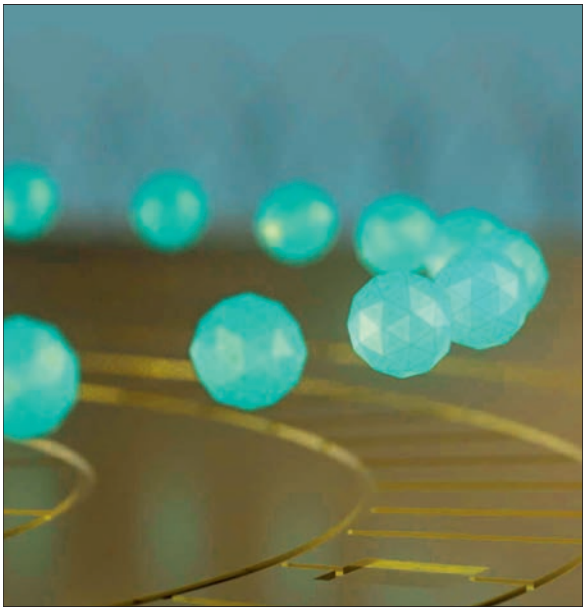
Quantinuum's trapped-ion quantum computer has generated strings of certifiably random numbers that could have applications in quantum cryptography, as **Tim Wogan** reports

A quantum computer has been used for the first time to generate strings of certifiably random numbers. The protocol, which was developed by a team at JPMorganChase and the quantum computing firm Quantinuum, could have applications ranging from lotteries to cryptography (*Nature* **640** 343).

Genuinely random numbers are important in several fields, but classical computers cannot create them. The best they can do is to generate apparently random or "pseudorandom" numbers. Randomness is inherent in the laws of quantum mechanics, however, so quantum computers are naturally suited to random number generation. In fact, random circuit sampling – in which all qubits are initialized in a given state and allowed to evolve via quantum gates before having their states measured at the output – is often used to benchmark their power.

Of course, not everyone who wants to produce random numbers will have their own quantum computer. However, in 2023 Scott Aaronson and Shi-Han Hung at the University of Texas at Austin suggested that a client could send a series of pseudorandomly chosen "challenge" circuits to a central server. There, a quantum computer could perform random circuit sampling before sending the readouts to the client. If these readouts are truly the product of random circuit sampling measurements performed on a quantum computer, they will be truly random numbers. "Certifying the 'quantumness' of the output guarantees its randomness," says Marco Pistoia, JPMorganChase's head of global technology applied research.

Importantly, this certification is something a classical computer can do. The way this works is that the client samples a subset of the bit strings in the readouts and performs a test called cross-entropy benchmarking. This test measures the probability that the numbers could have come from a non-quantum source. If the client is satisfied with this measurement, they can trust that the samples were genuinely the result of random circuit sampling. Otherwise, they may conclude that the data could have been generated by "spoofing" – that is, using a classical algorithm to mimic a quantum computer. The degree of confidence in this test, and the number of bits they are willing to settle for to achieve this confidence, is up to the client.



Quantinuum

That's guaranteed Quantinuum's 56-qubit trapped-ion quantum computer has been used to generate random numbers.

Game changer

In the new work, Pistoia, Aaronson, Hung and colleagues sent challenge circuits to the 56-qubit Quantinuum H2-1 quantum computer over the Internet. The team certified the randomness of the bits they got back by performing cross-entropy benchmarking using four of the world's most powerful supercomputers, including Frontier at the US Department of Energy's Oak Ridge National Laboratory. The results showed that it would have been impossible for a dishonest adversary with similar classical computing power to spoof a quantum computer – provided the client set a short enough time limit.

One drawback is that the computational cost of verifying that random numbers have not been spoofed is similar to the computational cost of spoofing them. "New work is needed to develop approaches for which the certification process can run on a regular computer," Pistoia says. "I think this will remain an active area of research in the future."

Quantinuum and its academic collaborators have also released the results of two scientific studies using Quantinuum H2-1. One examines a well-known problem in knot theory involving the Jones polynomial (arXiv: 2503.05625) while the other explores quantum magnetism (arXiv:2503.20870). Quantum information scientist Barry Sanders of the University of Calgary, Canada, is impressed by all three works. "The real game changer here is Quantinuum's really nice 56-qubit quantum computer," he says. "Instead of just being bigger in its number of qubits, it's hit multiple important targets."

In Sanders' view, the computer's fully digital architecture is important for scalability, although he notes that many in the field would dispute that. The most important development, he adds, is that the research frames the value of a quantum computer in terms of its accomplishments. "We've gone through a shift: when you buy a normal computer, you want to know what that computer can do for you, not how good is the transistor," he says. "In the old days, we used to say 'I made a quantum computer and my components are better than your components – my two-qubit gate is better'…Now we say, 'I made a quantum computer and I'm going to brag about the problem I solved'."

Quantum physics

Schrödinger cat states created in ‘hot’ environments

Superpositions of quantum states known as Schrödinger cat states can be created in “hot” environments with temperatures up to 1.8 K. By reducing the restrictions involved in obtaining ultracold temperatures, the researchers in Austria and Spain say the work could benefit fields such as quantum computing and quantum sensing (*Sci. Adv.* **11** eadr4492).

Creating superposition states, or Schrödinger cat states, requires quantum particles to be in their ground state. This, in turn, means cooling them to extremely low temperatures, which is challenging. Even marginally higher temperatures were thought to destroy the fragile nature of these states, rendering them useless for applications. Now, however, researchers have used thermally excited states to show that quantum superpositions can exist at temperatures of up to 1.8 K – an environment that might as well be an oven in the quantum world.

The experiment involved creating cat states inside a microwave cavity, which acts as a quantum harmonic oscillator. This cavity is coupled to a superconducting transmon qubit that behaves as a two-level system where the superposition is generated. While the overall set-up is cooled to 30 mK, the cavity mode itself is heated by equilibrating it with amplified Johnson-Nyquist noise from a resistor, making it 60 times hotter than its environment. To establish the existence of quantum correlations at this higher temperature, the team directly measured the Wigner functions of the states. Doing so revealed the characteristic interference patterns of Schrödinger cat states.

University of Innsbruck/Harald Ritsch

Some like it hot Researchers in Austria and Spain have created superpositions of quantum states at 1.8 K.

According to team leader Gerhard Kirchmair, a physicist at the University of Innsbruck and the Institute for Quantum Optics and Quantum Information in Austria, being able to realize cat states without ground-state cooling could bring benefits for quantum sensing. The mechanical oscillator systems used to sense acceleration or force, for example, are normally cooled to the ground state to achieve the necessary high sensitivity, but such extreme cooling may not be necessary.

Quantum error correction schemes could also benefit, as they rely on being able to create cat states reliably, with the team’s work showing that a residual thermal population places fewer limitations on this than previously thought. “For next steps we will use the system for what it was originally designed, i.e. to mediate interactions between multiple qubits for novel quantum gates,” says Kirchmair.

Martijn Boerkamp

Particle physics

KATRIN experiment sets tighter limit on neutrino mass

Researchers from the Karlsruhe Tritium Neutrino experiment (KATRIN) have announced the most precise upper limit yet on the neutrino’s mass. The new limit – 0.45 electron volts (eV) at 90% confidence – is half that of the previous tightest constraint, and marks a step toward answering one of particle physics’ longest-standing questions (*Science* 388 146).

KATRIN measures a process called tritium beta decay, where a tritium nucleus (a proton and two neutrons) decays into a helium-3 nucleus (two protons and one neutron) by releasing an electron and an electron antineutrino. Due to energy conservation, the total energy from the decay is shared between the electron and the antineutrino, with the neutrino’s mass determining the balance of the split. As the subtle effects of neutrino mass are most visible in decays where the antineutrino carries away very little energy (most of it bound up in mass), KATRIN concentrates on measuring electrons that have taken the lion’s share. From these measurements, physicists can calculate neutrino mass without having to detect these notoriously weakly-interacting particles directly.

The new neutrino mass limit is based on data taken between 2019 and 2021, with 259 days of operations yielding over 36 million electron measurements. “That’s six times more than the previous result,” explains KATRIN member Christoph Wiesinger, who is a physicist at the Technical University of Munich, Germany. At 0.45 eV, the new limit means the neutrino is at least a million times lighter than the electron. “This is a fundamental number,” Wiesinger adds. “It tells us that neutrinos are the lightest known massive particles in the universe, and maybe that their mass has origins beyond the Standard Model.”

Markus Breig, KIT

Weighty matters The Karlsruhe Tritium Neutrino experiment has set a new upper limit on the neutrino mass.

Despite the new tighter limit, however, definitive answers about the neutrino’s mass are still some way off. “Neutrino oscillation experiments tell us that the lower bound on the neutrino mass is about 0.05 eV,” says Patrick Huber, a theoretical physicist at Virginia Tech, US, who was not involved in the experiment. “That’s still about 10 times smaller than the new KATRIN limit.” KATRIN researchers are now aiming for 1000 days of operations by the end of 2025 and a final sensitivity approaching 0.3 eV.

Ananya Palivela

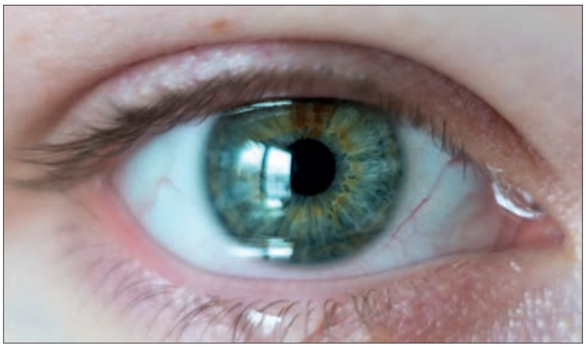
Biophysics

Retinal stimulation reveals colour never before seen by the human eye

A new retinal stimulation technique called Oz lets people see colours that lie beyond the natural range of human vision. Developed by researchers at the University of California, Berkeley, Oz works by stimulating individual cone cells in the retina with targeted microdoses of laser light, while compensating for the eye's motion (*Sci. Adv.* 11 eadu1052).

Colour vision is supported by cone cells in the retina. Most humans have three types of cone cells, known as L, M and S (long, medium and short), which respond to different wavelengths of visible light. During natural human vision, the spectral distribution of light reaching these cone cells determines the colours that we see. Some colours, however, simply cannot be seen. That's because the spectral sensitivity curves of the three cone types overlap – in particular, there is no wavelength of light that stimulates only the M cone cells without stimulating nearby L (and sometimes also S) cones as well.

Rather than being based on spectral distribution, colour perception in the Oz approach is controlled by shaping the spatial distribution of light on the retina. The Oz laser system uses adaptive optics scanning light ophthalmoscopy to simultaneously image and stimulate the retina with a raster scan of laser light. The device images the retina with infrared light to track eye motion in real time and targets pulses of visible laser light at individual cone cells, at 10 000 times per second. In their work the researchers tested a prototype Oz system on five volunteers, first using adaptive optics-based optical coherence tomography to classify the LMS spectral type of 1000 to 2000 cone cells in a region of each subject's retina.


iStock_leonovo

You won't believe what they've seen By stimulating the retina with a raster scan of laser light, volunteers reported seeing a new blue–green colour , dubbed "olo", that doesn't occur in natural vision.

Ren Ng from Berkeley and colleagues showed that targeting individual cone cells with a 543 nm laser enabled people to see a range of colours in both images and videos. Intriguingly, stimulating only the M cone cells sent a colour signal to the brain that never occurs in natural vision. When exclusively targeting M cone cells in these retinal regions, subjects reported seeing a new blue–green colour of unprecedented saturation – which the researchers named "olo".

They could also clearly perceive Oz hues in image and video form, reliably detecting the orientation of a red line and the motion direction of a rotating red dot on olo backgrounds. In colour matching experiments, the volunteers could only match olo with the closest monochromatic light by desaturating it with white light – demonstrating that olo lies beyond the range of natural vision. The technique could one day help to elicit full colour vision in people with colour blindness.

Tami Freeman

Medical physics

Light-activated pacemaker is smaller than a grain of rice

Researchers in the US have created the world's smallest pacemaker. Tinier than a single grain of rice, it is optically controlled and dissolves after it is no longer needed. The pacemaker could work in human hearts of all sizes that need temporary pacing, including those of newborn babies with congenital heart defects (*Nature* **640** 77).

As many as 1% of all children are born with congenital heart defects. The current clinical standard-of-care involves sewing pacemaker electrodes directly onto a patient's heart muscle during surgery. Wires from the electrodes protrude from the patient's chest and connect to an external pacing box. But placing and later removing the pacemakers can lead to infection, dislodgment, torn or damaged tissues, bleeding and blood clots.

In 2021, researchers developed a dissolvable pacemaker and by varying the composition and thickness of materials in the devices, they could control how long the pacemaker functions before dissolving. The dissolvable device also eliminates the need for bulky batteries and wires. Now the pacemaker has been paired with a small, soft, flexible, wireless device that is mounted onto the patient's chest. The skin-interfaced device continuously captures electrocardiogram data and when it detects an irregular heartbeat, it automatically shines a pulse of infrared light to activate the pacemaker and control the pacing.


Northwestern University

Tiny success The light-activated pacemaker is so small that it can be injected into the body via a syringe.

"The new device is self-powered and optically controlled – totally different than our previous devices in those two essential aspects of engineering design," says John Rogers from Northwestern University. "We moved away from wireless power transfer to enable operation, and we replaced RF wireless control strategies – both to eliminate the need for an antenna and to avoid the need for external RF power supply."

Measurements demonstrated that the pacemaker – which is 1.8 mm wide, 3.5 mm long and 1 mm thick – delivers as much stimulation as a full-sized pacemaker. Initial studies in animals and in the human hearts of organ donors suggest that the device could work in human infants and adults. The devices could also be used across different regions of the heart or the body – and even integrated with other implantable devices for applications in nerve and bone healing, treating wounds and blocking pain.

Catherine Steffel

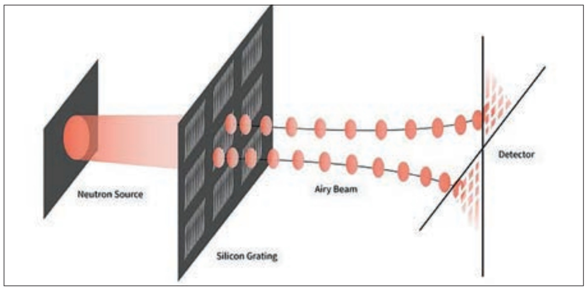
Particle physics

Neutron Airy beams make their debut

Physicists have succeeded in making neutrons travel in a curved parabolic waveform known as an Airy beam. This behaviour, which had previously been observed in photons and electrons but never in a non-elementary particle, could be exploited in fundamental quantum science and in advanced imaging techniques for materials characterization and development (*Phys. Rev. Lett.* **134** 153401).

In free space, beams of light propagate in straight lines. When they pass through an aperture, they diffract, becoming wider and less intense. Airy beams, however, are different. Named after the 19th-century British scientist George Biddell Airy, who developed the mathematics behind them while studying rainbows, they follow a parabola-shaped path – a property known as self-acceleration – and do not spread out as they travel. Airy beams are also "self-healing", meaning that they reconstruct themselves after passing through an obstacle that blocked part of the beam.

Researchers created the first Airy beams from light in 2007, followed by an electron Airy beam in 2013. Making such beams out of neutrons turned out to be challenging, however, because neutrons – being chargeless – cannot be shaped by electric field, while lenses that focus neutron beams do not exist. A team led by Dmitry Pushin, a physicist at the Institute for Quantum Computing (IQC) and the University of Waterloo, and Dusan Sarenac of the University at Buffalo in the US has now overcome these difficulties using a holographic approach based on a custom-microfabricated silicon diffraction grating. The team made this grating from an array of 6 250 000 micron-sized cubic phase patterns etched onto a silicon slab. "The grating modulates incoming neutrons into an Airy form and the resulting beam follows a curved trajectory, exhibiting the characteristics of a two-dimensional Airy profile at a neutron detector," Sarenac explains.



N Hanacek / NIST

Parabolic path An Airy beam of neutrons could be useful when investigating new drugs as well as in quantum computing.

The researchers say the self-acceleration and self-healing properties of Airy beams could improve existing neutron imaging techniques, potentially delivering sharper and more detailed images. The new beams might even allow for new types of neutron optics and could be particularly useful, for example, when targeting specific regions of a sample or navigating around structures. The researchers now plan to explore ways of combining neutron Airy beams with other structured neutron beams such as helical waves of neutrons or neutron vortices. This could make it possible to investigate complex properties such as the chirality, or handedness, of materials. Such work could be useful in drug development, spintronics and quantum computing.

Isabelle Dumé

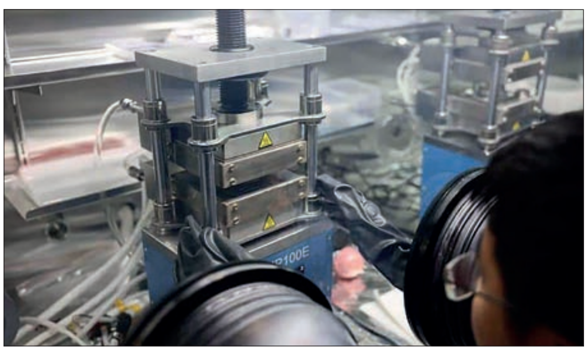
Materials

Scientists create two-dimensional sheets of metal

Researchers from the Institute of Physics of the Chinese Academy of Sciences have produced the first 2D sheets of metal. Barely a few angstroms thick, the metal sheets could be an ideal system for studying the fundamental physics of the quantum Hall effect, 2D superfluidity and superconductivity. They might also be used to make novel electronic devices such as ultrathin low-power transistors, high-frequency devices and transparent displays (*Nature* 639 354).

Since the discovery of graphene – a 2D sheet of carbon just one atom thick – in 2004, hundreds of other 2D materials have been fabricated and studied. In most of these, layers of covalently-bonded atoms are separated by gaps. The presence of these gaps mean that neighbouring layers are held together only by weak van der Waals (vdW) interactions, making it relatively easy to "shave off" single layers to make 2D sheets. Making atomically thin metals would expand this class of technologically important structures. However, because each atom in a metal is strongly bonded to surrounding atoms in all directions, thinning metal sheets to this degree has proved difficult. Indeed, many researchers thought it might be impossible.

The technique developed by Guangyu Zhang, Luojun Du and colleagues involves heating powders of pure metals between two monolayer molybdenum disulphide (MoS_2)/sapphire vdW anvils. The team used MoS_2/sapphire because both materials are atomically flat and lack dangling bonds that could react with the metals. Once the metal powders melted into a droplet, the researchers applied a pressure of 200 MPa. They then continued this "vdW squeezing" until the opposite sides of the anvils cooled to room temperature and 2D sheets of metal formed.



Chinese Academy of Sciences' Institute of Physics/Handout via Xinhua

Thin achievement Researchers in China have produced the first 2D sheets of metal.

The team produced five atomically thin 2D metals using this technique. The thinnest, at around 5.8 Å, was tin, followed by bismuth (~6.3 Å), lead (~7.5 Å), indium (~8.4 Å) and gallium (~9.2 Å). The researchers say this is just the "tip of the iceberg" for their method and they now intend to increase this number.

Isabelle Dumé

Opinion

physicsworld

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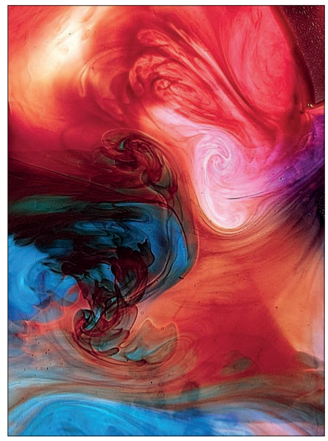
It's a quantum world

Explore all things quantum with the 2025 *Physics World Quantum Briefing*

As we reach the halfway point of the 2025 International Year of Quantum Science and Technology (IYQ), physicists from around the world will be travelling to Helgoland this month to commemorate the centenary of quantum mechanics. For it was on the windswept North Sea island in June 1925 that Werner Heisenberg – seeking refuge from a bout of hay fever – famously pioneered our mathematical framework of the quantum universe.

Over the following century, quantum mechanics has had a staggering impact on our lives – from lasers and MRI machines to the transistors and semiconductors in our phones. It's also transformed our understanding of the universe through seemingly bizarre and counter-intuitive concepts such as entanglement and superposition. They now underpin the technologies of the "second quantum revolution" – quantum computing, communication, cryptography and sensors.



Felicity Inkpen, oil on board, 2025

But the quantum universe encompasses even weirder phenomena, some of which *Physics World* is featuring this year. We've already tackled the "quantum Zeno effect" (May pp31–33), while this month we examine "quantum Cheshire cats" (pp21–23).

To mark IYQ the 2025 *Physics World Quantum Briefing* (tinyurl.com/2tx6tw29) is now out. The free-to-read online magazine examines the history, mystery and industry of quantum mechanics and includes a specially commissioned cover by the UK-based artist and scientist Felicity Inkpen. Entitled *Qubits, Duality*, it seeks to represent wave–particle duality (see above).

Inkpen created the image using sugar, water, expired printer cartridges, powdered paint, a glass oven dish and a re-purposed seasonal affective disorder lamp, capturing hundreds of images and hours of footage of pigments swirling and diffusing to create "spontaneous moments of colour". She then recreated the swirling images of dyes in water in oil paint on board to create the cover art.

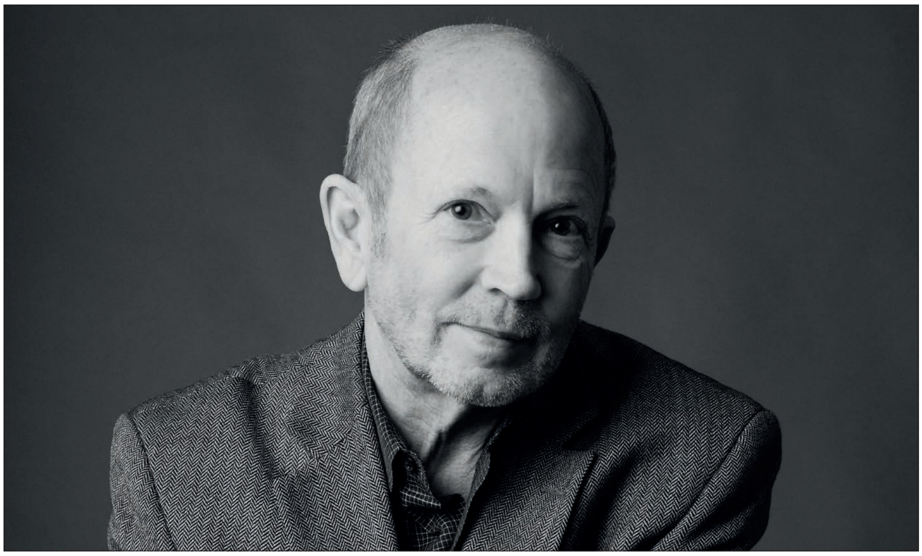
The *Physics World Quantum Briefing* is a celebration of how far we've come in 100 years – and offers a glimpse of the infinite impact of quantum technologies that lies ahead. Do take a look and share it widely: after all, the IYQ seeks to spread quantum resources equitably around the globe.

- Register now for the next Physics World Live event at 16:00 BST on 17 June to learn how quantum tech is boosting quantum fundamentals (tinyurl.com/3kbj75kd)

Tushna Commissariat, features editor, *Physics World*

Critical Point A science critic

A quarter of a century after he started writing this column, **Robert P Crease** reveals his underlying message



Still going strong The historian and philosopher Robert P Crease has been writing the Critical Point column in *Physics World* for the last 25 years.

A quarter of a century ago, in May 2000, I published an article entitled "Why science thrives on criticism". The article, which ran to slightly over a page in *Physics World* magazine, was the first in a series of columns called Critical Point. Periodicals, I said, have art and music critics as well as sports and political commentators, and book and theatre reviewers too. So why shouldn't *Physics World* have a science critic?

The implication that I had a clear idea of the "critical point" for this series was not entirely accurate. As the years go by, I have found myself improvising, inspired by politics, books, scientific discoveries, readers' thoughts, editors' suggestions and more. If there is one common theme, it's that science is like a workshop – or a series of loosely related workshops – as I argued in *The Workshop and the World*, a book that sprang from my columns.

Workshops are controlled environments, inside which researchers can stage and study special things – elementary particles, chemical reactions, plant uptakes of nutrients – that appear rarely or in a form difficult to study in the surrounding world. Science critics do not participate in the workshops themselves or even judge their activities. What they do is evaluate how workshops and worlds interact.

This can happen in three ways

Critical triangle

First is to explain why what's going on inside the workshops matters to outsiders. Sometimes, those activities can be relatively simple to describe, which leads to columns concerning all manner of everyday activities. I have written, for example, about the physics of coffee and breadmaking. I've also covered toys, tops, kaleidoscopes, glass and other things that all of us – physicists and non-physicists alike – use, value and enjoy.

Sometimes I draw out more general points about why those activities are important. Early on, I invited readers to nominate their most beautiful experiments in physics. (Spoiler alert: the clear winner was the double-slit experiment with electrons.) I later did something similar about the cultural impact of equations – inviting readers to pick their favourites and reporting on their results (second spoiler alert: Maxwell's equations came top). I also covered readers' most-loved literature about laboratories.

When viewing science as workshops, a second role is to explain why what's outside the workshops matters to insiders. That's because physicists often engage in activities that might seem inconsequential to them – they're "just what the rest the world does" – yet are an intrinsic part of the practice of physics. I've covered, for example, physicists taking out patents, creating logos, designing lab architecture, taking holidays, organizing dedications, going on retirement and writing memorials for the deceased.

Such activities I term "black elephants". That's because they're a cross between things physicists don't want to talk about ("elephants in the room") and things that force them to renounce cherished notions (just as "black swans" disprove that "all swans are white").

> Physicists often engage in activities that might seem inconsequential to them yet are an intrinsic part of the practice of physics

A third role of a science critic is to explain what matters that takes place both inside and outside the workshop. I'm thinking of things like competition, leadership, trust, surprise, workplace training courses, cancel culture and even jokes and funny tales. Interpretations of the meaning of quantum mechanics, such as "QBism", which I covered both in 2019 and 2022, are an ongoing interest. That's because they're relevant both to the structure of physics and to philosophy as they disrupt notions of realism, objectivity, temporality and the scientific method.

Being critical

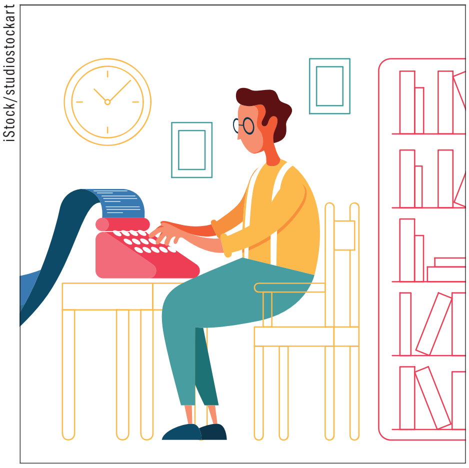
The term "critic" may suggest someone with a congenitally negative outlook, but that's wrong. My friend Fred Cohn, a respected opera critic, told me that, in a conversation after a concert, he criticized the performance of the singer Luciano Pavarotti. His remark provoked a woman to shout angrily at him: "Could you do better?" Of course not! It's the critic's role to evaluate performances of an activity, not to perform the activity oneself.

Having said that, sometimes a critic must be critical to be honest. In particular, I hate it when scientists try to delegitimize the experience of non-scientists by saying, for example, that "time does not exist". Or when they pretend they don't see rainbows but wavelengths of light or that they don't see sunrises or the plane of a Foucault pendulum move but the Earth spinning. Comments like that turn non-scientists off science by making it seem elitist and other-worldly. It's what I call "scientific gaslighting".

Most of all, I hate it when scientists pontificate that philosophy is foolish or worthless, especially when it's the likes of Steven Pinker, who ought to know better. Writing in *Nature* (**518** 300), I once criticized the great theoretical physicist Steven Weinberg, who I counted as a friend, for taking a complex and multivalent text, plucking out a single line, and misreading it as if the line were from a physics text.

The text in question was Plato's *Phaedo*, where Socrates expresses his disappointment with his fellow philosopher Anaxagoras for giving descriptions of heavenly bodies "in purely physical terms, without regard to what is best". Weinberg claimed this statement meant that Socrates "was not very interested in natural science". Nothing could be further from the truth.

At that moment in the *Phaedo*, Socrates is recounting his intellectual autobiography. He has just come to the point where, as a youth, he was entranced by materialism and was eager to hear Anaxagoras's opposing position. When Anaxagoras promised to describe the heavens both mechanically and as the product of a wise and divine mind but could do only the former, Socrates says he was disappointed.



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Working practices In his first Critical Point column for *Physics World*, Robert P Crease interrogated the role of the science critic.

Weinberg's jibe ignores the context. Socrates is describing how he had once embraced Anaxagoras's view of a universe ruled by a divine mind but later rejected that view. As an adult, Socrates learned to test hypotheses and other claims through putting them to the test, just as modern-day scientists do. Weinberg was misrepresenting Socrates by describing a position that he later abandoned.

The critical point of the critical point

Ultimately, the "critical point" of my columns over the last 25 years has been to provoke curiosity and excitement about what philosophers, historians and sociologists do for science. I've also wanted to raise awareness that these fields are not just fripperies but essential if we are to fully understand and protect scientific activity.

As I have explained several times – especially in the wake of the US shutting its High Flux Beam Reactor and National Tritium Labeling Facility – scientists need to understand and relate to the surrounding world with the insight of humanities scholars. Because if they don't, they are in danger of losing their workshops altogether.

● Explore the best of Robert P Crease's Critical Point articles at physicsworld.com/p/collections/best-of-critical-point

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 The art of overselling

There's a fine line between having a genuine enthusiasm for a product and not being entirely honest about what it can do. **Honor Powrie** warns of the danger of "overselling"

iStock/t:mikkelwilliam

Buyer beware It's wise to be careful of a product that a manufacturer claims does more than it really can.

What does the word "overselling" mean to you? At one level, it can just mean selling more of something than already exists or can be delivered. It's what happens when airlines overbook flights by selling more seats than physically exist on their planes. They assume a small fraction of passengers won't turn up, which is fine – until you can't fly because everyone else has rocked up ahead of you.

Overselling can also involve selling more of something than is strictly required. Also known as "upselling", you might have experienced it when buying a car or taking out a new broadband contract. You end up paying for extras and add-ons that were offered but you didn't really need or even want, which explains why you've got all those useless WiFi boosters lying around the house.

There's also a third meaning of "overselling", which is to exaggerate the merits of something. You see it when a pharmaceutical company claims its amazing anti-ageing product "will make you live 20 years longer", which it won't. Overselling in this instance means overstating a product's capability or functionality. It's pretending something is more mature than it is, or claiming a technology is real when it's still at proof-of-concept-stage.

From my experience in science and technology, this form of overselling often happens when companies and their staff want to grab attention or to keep customers or consumers on board. Sometimes firms do it because they are genuinely enthusiastic (possibly too much so) about the future possibilities of their product. I'm not saying overselling is necessarily a bad thing but just that there are reservations.

Fact and fiction

Before I go any further, let's learn the lingo of overselling. First off, there's "vapourware", which refers to a product that either doesn't exist or doesn't fulfil the stated technical capability. Often, it's something a firm wants to include in its product portfolio because they're sure people would like to own it. Deep down, though, the company knows the product simply isn't possible, at least not right now. Like a vapour, it's there but can't be touched.

Sometimes vapourware is just a case of waiting for product development to catch up with a genuine product plan. Sales staff know they haven't got the product at the right specification yet, and while the firm will definitely get there one day, they're pretending the hurdles have already been crossed. But genuine over-enthusiasm can sometimes cross over into wishful thinking – the idea that a certain functionality can be achieved with an existing technical approach.

Do you remember Google Glass? This was wearable tech, integrated into spectacle frames, that was going to become the ubiquitous portable computer. Information would be requested via voice commands, with the user receiving back the results, visible on a small heads-up display. Whilst the computing technology worked, the product didn't succeed. Not only did it look clunky, there were also deployment constraints and concerns about privacy and safety.

Google Glass failed on multiple levels and was discontinued in 2015, barely a year after it hit the market. Subsequent relaunches didn't succeed either and the product was pulled for a final time in 2023. Despite Google's best efforts, the product simply didn't capture the public's imagination or meet the needs of enough consumers.

Next up in our dictionary of overselling is "unobtanium", which is a material or material specification that we would like to exist, but simply doesn't. In the aerospace sector, where I work, we often dream of unobtanium. We're always looking for materials that can repeatedly withstand the operational extremes encountered during a flight, whilst also being sustainable without cutting corners on safety.

Like other engine manufacturers, my company – GE Aerospace – is pioneering multiple approaches to help develop such materials. We know that engines become more efficient when they burn at higher temperatures and pressures. We also know that nitrous-oxide (NOx) emissions fall when an engine burns more leanly. Unfortunately, there are no metals we know of that can survive to such high temperatures.

But the quest for unobtanium can drive innovative technical solutions. At GE, for example, we're making progress by looking instead at composite materials, such as carbon fibre and composite matrix ceramics. Stronger and more tolerant to heat and pressure than metals, they've already been included on the turbofan engines in planes such as the Boeing 787 Dreamliner.

We're also using "additive manufactur-

While unobtanium can never be reached, it's worth trying to get there to drive technology forward

ing" to build components layer by layer. This approach lets us make highly intricate components with far less waste than conventional techniques, in which a block of material is machined away. We're also developing innovative lean-burn combustion technologies, such as novel cooling and flow strategies, to reduce NOx emissions.

A further example is the single crystal turbine blade developed by Rolls-Royce in 2012. Each blade is cast to form a single crystal of super alloy, making it extremely strong and able to resist the intense heat inside a jet engine. According to the company, the single crystal turbine blades operate up to 200 degrees above the melting point of their alloy. So while unobtanium can never be reached, it's worth trying to get there to drive technology forward.

Lead us not into temptation

Now, here's the caveat. There's an unwelcome side to overselling, which is that it can easily morph into downright mis-selling. This was amply demonstrated by the Volkswagen diesel emissions scandal, which saw the German carmaker install "defeat devices" in its diesel engines. The software changed how the engine performed when it was undergoing emissions tests to make its NOx emissions levels appear much lower than they really were.

VW was essentially falsifying its diesel engine emissions to conform with international standards. After regulators worldwide began investigating the company, VW took a huge reputational and financial hit, ultimately costing it more than $33bn in fines, penalties and financial settlements. Senior chiefs at the company got the sack and the company's reputation took a serious hit.

It's tempting – and sometimes even fun – to oversell. Stretching the truth draws interest from customers and consumers. But when your product no longer does "what it says on the tin", your brand can suffer, probably more so than having something slightly less functional.

On the upside, the quest for unobtanium and, to some extent, the selling of vapourware can drive technical progress and lead to better technical solutions. I suspect this was the case for Google Glass. The underlying technology has had some success in certain niche applications such as medical surgery and manufacturing. So even though Google Glass didn't succeed, it did create a gap for other vendors to fill.

Google Glass was essentially a portable technology with similar functionality to smartphones, such as wireless Internet access and GPS connectivity. Customers, however, proved to be happier carrying this kind of technology in their hands than wearing it on their heads. The smartphone took off; Google Glass didn't. But the underlying tech – touchpads, cameras, displays, processors and so on – got diverted into other products.

Vapourware, in other words, can give a firm a competitive edge while it waits for its product to mature. Who knows, maybe one day even Google Glass will make a comeback?

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

Lessons in support

While supervisors have little training when it comes to helping students trying to balance their work and life, a few simple steps can go a long way, says **Caitlin Duffy**

Over the years, first as a PhD student and now as a postdoc, I have been approached by many students and early-career academics who have confided their problems in me. Their issues, which they struggled to deal with alone, ranged from anxiety and burnout to personal and professional relationships as well as mental-health concerns. Sadly, such discussions were not one-off incidents but seemed worryingly common in academia where people are often under pressure to perform, face uncertainty over their careers and need to juggle lots of different tasks simultaneously.

But it can be challenging to even begin to approach someone else with a problem. That first step can take days or weeks of mental preparation, so to those who are approached for help, it is our responsibility to listen and act appropriately when someone does finally open up. This is especially so given that a supervisor, mentor, teaching assistant, or anybody in a position of seniority, may be the first point of contact when a difficulty becomes debilitating.

I am fortunate to have had excellent relationships with my PhD and postdoc supervisors – providing great examples to follow. Even then, however, it was difficult to subdue the feeling of nausea when I knocked on their office doors to have a difficult conversation. I was worried about their response and reaction and how they would judge me. While that first conversation is challenging for both parties, fortunately it does gets easier from there.

Yet it can also be hard for the person who is trying to offer help, especially if they haven't done so before. In fact, when colleagues began to confide in me, I'd had no formal preparation or training to support them. But through experience and some research, I found a few things that worked well in such complex situations. The first is to set and maintain boundaries or where your personal limits lie. This includes which topics are off limits and to what extent you will engage with somebody. Someone who has recently experienced bereavement, for example, may not want to engage deeply with a student who is enduring the same and so should make it clear they can't offer help. Yet at the same time, that person may feel confident providing support for someone struggling with imposter syndrome – a feeling that you don't deserve to be there and aren't good at your work.

iStock/AzmanL

Support network It can be challenging for someone struggling to even discuss their problem so those who are approached for help must listen and act appropriately.

Time restrictions can also be used as boundaries. If you are working on a critical experiment, have an article deadline or are about to go on holiday, explain that you can only help them until a certain point, after which you will explore alternative solutions together. Setting boundaries can also be handy for mentors to prepare to help someone struggling. This could involve taking a mental-health first-aid course to support a person who experiences panic attacks or is relapsing into depression. It could also mean finding contact details for professionals, either on campus or beyond, who could help. While providing such information might sound trivial and unimportant, remember that for a person who is feeling overwhelmed, it can be hugely appreciated.

Following up

Sharing problems takes courage. It also requires trust because if information leaks out, rumours and accusations can spread quickly and worsen situations. It is, however, possible to ask more senior colleagues for advice without identifying anyone or their exact circumstances, perhaps in cases when dealing with less than amicable relationships with collaborators. It is also possible to let colleagues know that a particular person needs more support without explicitly saying why.

There are times, however, when that confidentiality must be broken. In my experience, this should always be first addressed with the person at hand and broken to somebody who is sure to have a concrete solution. For a student who is struggling with a particular subject, it could, for example, be the lecturer responsible for that course. For somebody not coping with divorce, say, it could be someone from HR or a supervisor for a colleague. It could even be a university's support team or the police for a student who has experienced sexual assault.

I have broken confidentiality at times and it can be nerve-wracking, but it is essential to provide the best possible support and take a situation that you cannot handle off your hands. Even if the issue has been handed over to someone else, it's important to follow up with the person struggling, which helps them know they're being heard and respected. Following up is not always a comfortable conversation, potentially invoking trauma or broaching sensitive topics. But it also allows them to admit that they are still looking for more support or that their situation has worsened.

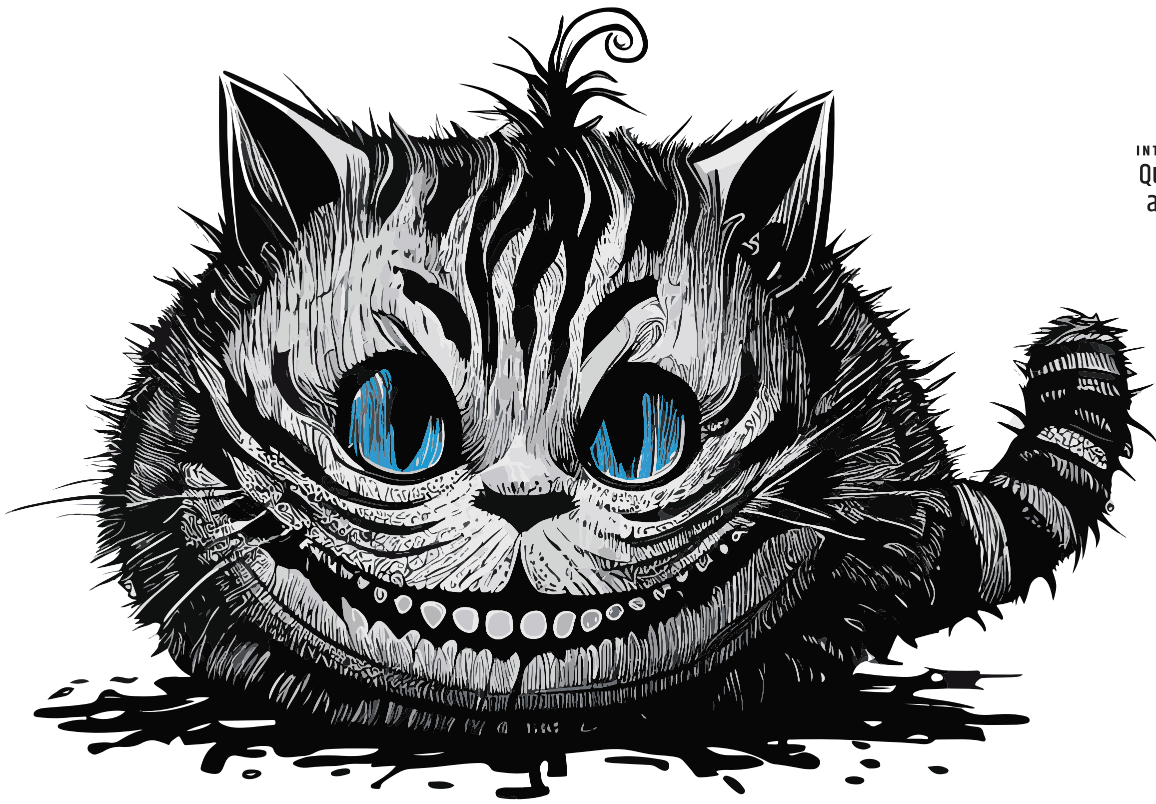
A follow-up conversation could also be held in a discrete environment with reassurance that nobody is obliged to go into detail. It may be as simple as asking "How are you feeling today?". Letting someone express themselves without judgement can help them come to terms with their situation, let them speak or have confidence to approach you again.

Regularly reflecting on your boundaries and limits as well as having a good knowledge of possible resources can help you prepare for unexpected circumstances. It gives students and colleagues immediate care and relief at what might be their lowest point. But perhaps the most important aspect when approached by someone is to ask yourself this: "What kind of person would I want to speak to if I were struggling?". That is the person you want to be.

Caitlin Duffy is a contributing columnist for *Physics World* and a postdoc researcher working on correlated electron systems at the Laboratoire National des Champs Magnétiques Intenses (LNCMI) in Toulouse, France

The curious case of quantum Cheshire cats

Shutterstock/aleksandr polle



INTERNATIONAL YEAR OF Quantum Science and Technology

For the International Year of Quantum Science and Technology, *Physics World* is shining a spotlight on quantum effects so "weird" they make superposition and entanglement seem almost ordinary. In the second of this series, **Iulia Georgescu** falls down the rabbit-hole to explore the curiosity that is a quantum Cheshire cat

Most of us have heard of Schrödinger's eponymous cat, but it is not the only feline in the quantum physics bestiary. Quantum Cheshire cats may not be as well known, yet their behaviour is even more insulting to our classical-world common sense.

These quantum felines get their name from the Cheshire cat in Lewis Carroll's *Alice's Adventures in Wonderland*, which disappears leaving its grin behind. As Alice says: "I've often seen a cat without a grin, but a grin without a cat! It's the most curious thing I ever saw in my life!"

Things are curiouser in the quantum world, where the property of a particle seems to be in a different place from the particle itself. A photon's polarization, for example, may exist in a totally different location from the photon itself: that's a quantum Cheshire cat.

While the prospect of disembodied properties might seem disturbing, it's a way of interpreting the elegant predictions of quantum mechanics. That at least was the thinking when quantum Cheshire cats were first put forward by Yakir Aharonov, Sandu Popescu, Daniel Rohrlich and Paul Skrzypczyk in an article published in 2013 (*New J. Phys.* **15** 113015).

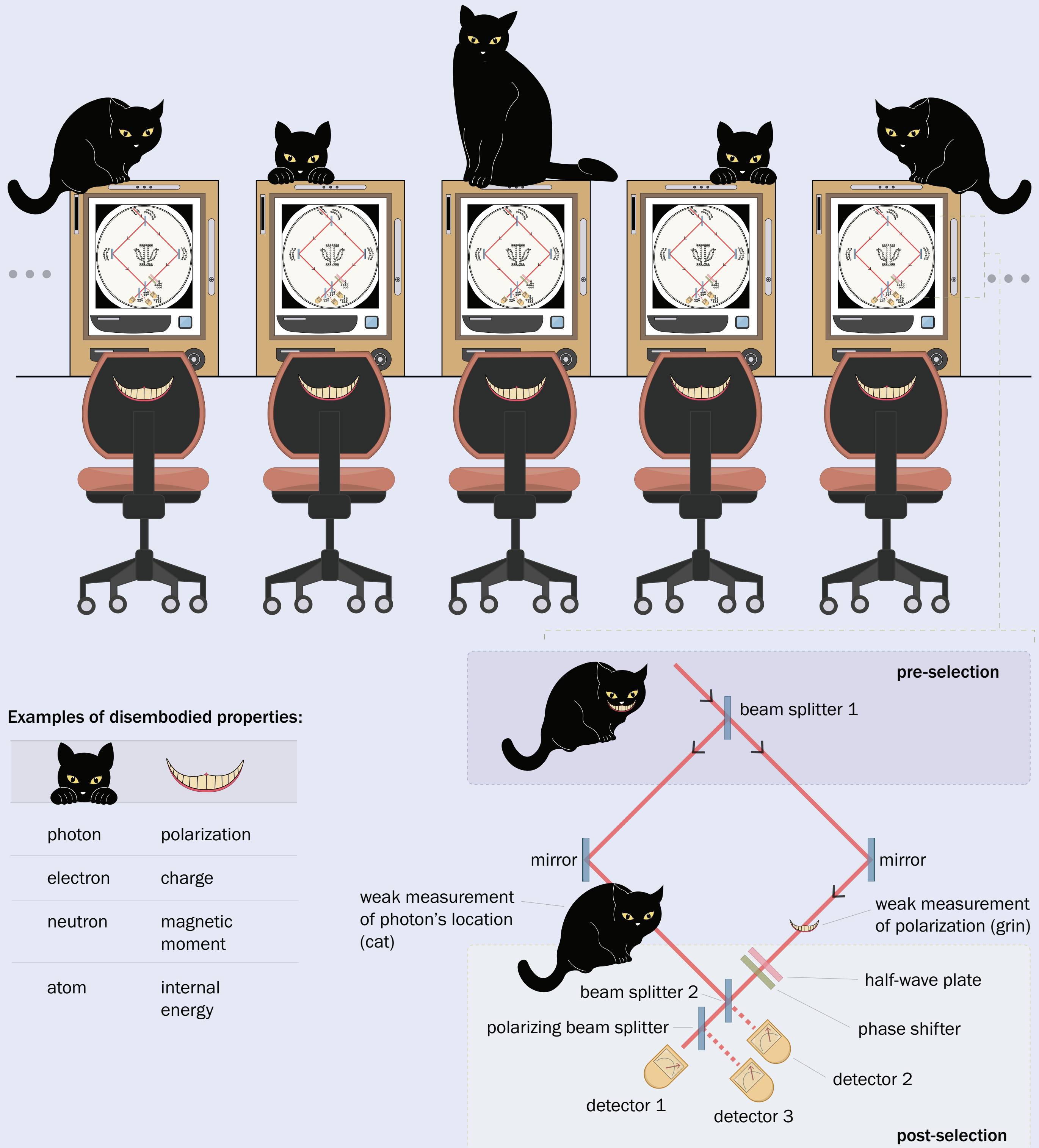
Strength of a measurement

To get to grips with the concept, remember that making a measurement on a quantum system will "collapse" it into one of its eigenstates – think of opening the box and finding Schrödinger's cat either dead or alive. However, by playing on the trade-off between the strength of a measurement and the uncertainty of the result, one can gain a tiny bit of information while disturbing the system as little as possible. If such a measurement is done many times, or on an ensemble of particles, it is possible to average out the results, to obtain a precise value.

First proposed in the 1980s, this method of teasing out information from the quantum system by a series

Iulia Georgescu is science and innovation manager at the Institute of Physics. She obtained her PhD from the University of Tokyo in 2008, having studied quantum information and simulation using trapped ions. She was a postdoctoral researcher at RIKEN Advanced Science Institute, Japan, and at the University of Basel, Switzerland

1 Split particle property



Mayank Shreshtha

Quantum Cheshire cats are a curious phenomenon, whereby the property of a quantum particle can be completely separate from the particle itself. A photon's polarization, for example, may exist at a location where there is no photon at all. In this illustration, our quantum Cheshire cats (the photons) are at a pachinko parlour. Depending on certain pre- and post-selection criteria, the cats end up in one location – in one arm of the detector or the other – and their grins in a different location, on the chairs.

of gentle pokes is known as weak measurement. While the idea of weak measurement in itself does not appear a radical departure from quantum formalism, "an entire new world appeared" as Popescu puts it. Indeed, Aharonov and his collaborators have spent the last four decades investigating all kinds of scenarios in which weak measurement can lead to unexpected consequences, with the quantum Cheshire cat being one they stumbled upon.

In their 2013 paper, Aharonov and colleagues imagined a simple optical interferometer set-up, in which the "cat" is a photon that can be in either the left or the right arm, while the "grin" is the photon's circular polarization. The cat (the photon) is first prepared in a certain superposition state, known as pre-selection. After it enters the set-up, the cat can leave via several possible exits. The disembodiment between particle and property appears in the cases in which the particle emerges in a particular exit (post-selection).

Certain measurements, analysing the properties of the particle, are performed while the particle is in the interferometer (in between the pre- and post-selection). Being weak measurements, they have to be carried out many times to get the average. For certain pre- and post-selection, one finds the cat will be in the left arm while the grin is in the right. It's a Cheshire cat disembodied from its grin.

The mathematical description of this curious state of affairs was clear, but the interpretation seemed preposterous and the original article spent over a year in peer review, with its eventual publication still sparking criticism. Soon after, experiments with polarized neutrons (*Nature Comms* **5** 4492) and photons (*Phys. Rev. A* **94** 012102) tested the original team's set-up. However, these experiments and subsequent tests, despite confirming the theoretical predictions, did not settle the debate – after all, the issue was with the interpretation.

A quantum of probabilities

To come to terms with this perplexing notion, think of the type of pre- and post-selected set-up as a pachinko machine, in which a ball starts at the top in a single pre-selected slot and goes down through various obstacles to end up in a specific point (post-selection): the jackpot hole. If you count how many balls hit the jackpot hole, you can calculate the probability distribution. In the classical world, measuring the position and properties of the ball at different points, say with a camera, is possible.

This observation will not affect the trajectory of the ball, or the probability of the jackpot. In a quantum version of the pachinko machine, the pre- and post-selection will work in a similar way, except you could feed in balls in superposition states. A weak measurement will not disturb the system so multiple measurements can tease out the probability of certain outcomes. The measurement result will not yield an eigenvalue, which corresponds to a physical property of the system, but weak values, and the way one should interpret these is not clear-cut.

To make sense of this in a quantum sense, we need an intuitive mental image, even a limited one. This is why quantum Cheshire cats are a powerful metaphor, but they are also more than that, guiding researchers into new directions. Indeed, since the initial discovery, Aharonov, Popescu and colleagues have stumbled upon more surprises.

In 2021 they generalized the quantum Cheshire cat effect to a dynamical picture in which the "disembodied" property can propagate in space (*Nature Comms* **12** 4770). For example, there could be a flow of angular momentum without anything carrying it (*Phys. Rev. A* **110** L030201). In another generalization, Aharonov imagined a massive particle with a mass that could be measured in one place with no momentum, while its momentum could be measured in another place without its mass (*Quantum* **8** 1536). A gedankenexperiment to test this effect would involve a pair of nested Mach–Zehnder interferometers with moving mirrors and beam splitters.

Physicists were too busy applying quantum mechanics to various problems to be bothered with foundational questions

Provocative interpretations

If you find these ideas bewildering, you're in good company. "They're brain teasers," explains Jonte Hance, a researcher in quantum foundations at Newcastle University, UK. In fact, Hance thinks that quantum Cheshire cats are a great way to get people interested in the foundations of quantum mechanics.

Sure, the early years of quantum physics saw famous debates between Niels Bohr and Albert Einstein, culminating in the criticism in the Einstein–Podolski–Rosen (EPR) paradox (*Phys. Rev.* **47** 777) in 1935. But after that, physicists were too busy applying quantum mechanics to various problems to be bothered with foundational questions.

This lack of interest in quantum fundamentals is perfectly illustrated by two anecdotes, the first involving Aharonov himself. When he was studying physics at Technion in Israel in the 1950s, he asked Nathan Rosen (the R of the EPR) about working on the foundations of quantum mechanics. The topic was deemed so unfashionable that Rosen advised him to focus on applications. Luckily, Aharonov ignored the advice and went on to work with American quantum theorist David Bohm.

The other story concerns Alain Aspect, who in 1975 visited CERN physicist John Bell to ask for advice on his plans to do an experimental test of Bell's inequalities to settle the EPR paradox. Bell's very first question was not about the details of the experiment – but whether Aspect had a permanent position (*Nature Phys.* **3** 674). Luckily, Aspect did, so he carried out the test, which went on to earn him a share of the 2022 Nobel Prize for Physics.

As quantum computing and quantum information began to emerge, there was a brief renaissance in quantum foundations culminating in the early 2010s. But over the past decade, with many of aspects of quantum physics reaching commercial fruition, research interest has shifted firmly once again towards applications.

Despite popular science's constant reminder of how "weird" quantum mechanics is, physicists often take the pragmatic "shut up and calculate" approach. Hance says that researchers "tend to forget how weird quantum mechanics is, and to me you need that intuition of it being weird". Indeed, paradoxes like Schrödinger's cat and EPR have attracted and inspired generations of physicists and have been instrumental in the development of quantum technologies.

The point of the quantum Cheshire cat, and related paradoxes, is to challenge our intuition and provoke us to think outside the box. That's important even if applications may not be immediately in sight. "Most people agree that although we know the basic laws of quantum mechanics, we don't really understand what quantum mechanics is all about," says Popescu.

Aharonov and colleagues' programme is to develop a correct intuition that can guide us further. "We strongly believe that one can find an intuitive way of thinking about quantum mechanics," adds Popescu. That may, or may not, involve felines. ■

How to ensure that quantum technologies continue thriving

Quantum physicist **Mauro Paternostro** talks to Tushna Commissariat about the most exciting quantum breakthroughs, its intersection with AI, and his vision of the quantum future

As of 2025, the quantum technology landscape is a swiftly evolving place. From developments in error correction and progress in hybrid classical-quantum architectures all the way to the commercialization of quantum sensors, there is much to celebrate.

An expert in quantum information processing and quantum technology, physicist Mauro Paternostro is based at the University of Palermo and Queen's University Belfast. He is also editor-in-chief of the IOP Publishing journal *Quantum Science and Technology*, which celebrates its 10th anniversary this year. Paternostro shares his views on the most exciting recent developments in the filed, his call for a Quantum Erasmus programme and his plans for the future of the journal.

Queen's University Belfast

What's been the most interesting development in quantum technologies over the last year or so?

I have a straightforward answer as well as a more controversial one. First, the simpler point: the advances in quantum error correction for large-scale quantum registers are genuinely exciting. I'm specifically referring to the work conducted by Mikhail Lukin, Dolev Bluvstein and colleagues at Harvard University, and at the Massachusetts Institute of Technology and QuEra Computing, who built a quantum processor with 48 logical qubits that can execute algorithms while correcting errors in real time. In my opinion, this marks a significant step forward in developing computational platforms with embedded robustness. Error correction plays a vital role in the development of practical quantum computers, and Lukin and colleagues won *Physics World*'s 2024 Breakthrough of the Year award for their work.

Now, for the more complex perspective. Aside from ongoing debate about whether Microsoft's much-discussed eight-qubit topological quantum processor – Majorana 1 – is genuinely using topological qubits, I believe the device will help to catalyze progress in integrated quantum chips. While it may not qualify as a genuine breakthrough in the long run, this moment could be the pivotal turning-point in the evolution of quantum computational platforms. All the major players will likely feel compelled to accelerate their efforts toward the unequivocal demonstration of "quantum chip" capabilities, and such a competitive drive is just want both industry and government need right now.

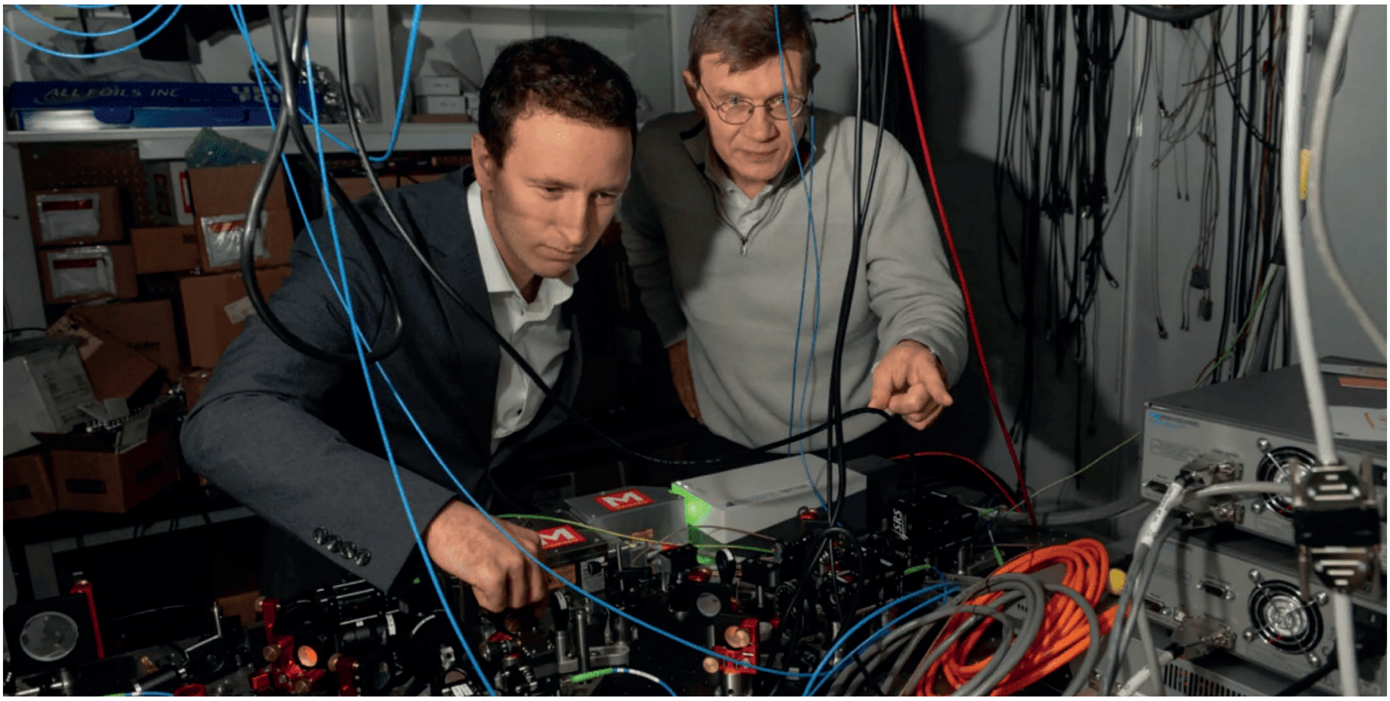
How do you think quantum technologies will scale up as they emerge from the lab and into real-world applications?

I am optimistic in this regard. In fact, progress is already underway, with quantum-sensing devices and atomic quantum clocks are achieving the levels of technological readiness necessary for practical, real-world applications. In the future, hybrid quantum-high-performance computing (HPC) architectures will play crucial roles in bridging classical data-analysis with whatever the field evolves into, once quantum computers can offer genuine "quantum advantage" over classical machines.

Regarding communication, the substantial push toward networked, large-scale communication structures is noteworthy. The availability of the first operating system for programmable quantum networks opens "highways" toward constructing a large-scale "quantum internet". This development promises to transform the landscape of communication, enabling new possibilities that we are just beginning to explore.

What needs to be done to ensure that the quantum sector can deliver on its promises in Europe and the rest of the world?

We must prioritize continuity and stability to maintain momen-


Jon Chase/Harvard University

Logical minds Dolev Bluvstein (left) and Mikhail Lukin with their quantum processor.

tum. The national and supranational funding programmes that have supported developments and achievements over the past few years should not only continue, but be enhanced. I am concerned, however, that the current geopolitical climate, which is undoubtedly challenging, may divert attention and funding away from quantum technologies. Additionally, I worry that some researchers might feel compelled to shift their focus toward areas that align more closely with present priorities, such as military applications. While such shifts are understandable, they may not help us keep pace with the remarkable progress the field has made since governments in Europe and beyond began to invest substantially.

On a related note, we must take education seriously. It would be fantastic to establish a Quantum Erasmus programme that allows bachelor's, master's and PhD students in quantum technology to move freely across Europe so that they can acquire knowledge and expertise. We need coordinated national and supranational initiatives to build a pipeline of specialists in this field. Such efforts would provide the significant boost that quantum technology needs to continue thriving.

How can the overlap between quantum technology and artificial intelligence (AI) help each other develop?

The intersection and overlap between AI, high-performance computing, and quantum technologies are significant, and their interplay is, in my opinion, one of the most promising areas of exploration. While we are still in the early stages, we have only just started to tap into the potential of AI-based tools for tackling quantum tasks. We are already witnessing the emergence of the first quantum experiments supported by this hybrid approach to information processing.

The convergence of AI, HPC, and quantum computing would revolutionize how we conceive data processing, analysis, forecasting and many other such tasks. As we continue to explore and refine these technologies, the possibilities for innovation and advancement are vast, paving the way for transformations in various fields.

> The IYQ presents an opportunity to raise awareness worldwide about what a quantum paradigm for technological development can mean for humankind

What do you hope the International Year of Quantum Science and Technology (IYQ) will have achieved, going forward?

The IYQ represents a global acknowledgement, at the highest levels, of the immense potential within this field. It presents a genuine opportunity to raise awareness worldwide about what a quantum paradigm for technological development can mean for humankind. It serves as a keyhole into the future, and IYQ could enable an unprecedented number of individuals – governments, leaders and policymakers alike – to peek though it and glimpse at this potential.

All stakeholders in the field should contribute to making this a memorable year. With IYQ, 2025 might even be considered as "year zero" of the quantum technology era.

As we mark its 10th anniversary, how have you enjoyed your time over the last year as editor-in-chief of the journal *Quantum Science and Technology* (QST)?

Time flies when you have fun, and this is a good time for me to reflect on the past year. Firstly, I want to express my heartfelt gratitude to Rob Thew, the founding editor-in-chief of QST, for his remarkable leadership during the journal's early years. With unwavering dedication, he and the rest of the entire editorial board, has established QST as an authoritative and selective reference point for the community engaged in the broad field of quantum science and technology. The journal is now firmly recognized as a leading platform for timely and significant research outcomes. A 94% increase in submissions since our fifth anniversary has led to an impressive 747 submissions from 62 countries in 2024 alone, revealing the growing recognition and popularity of QST among scholars. Our acceptance rate of 27% further demonstrates our commitment to publishing only the highest calibre research.

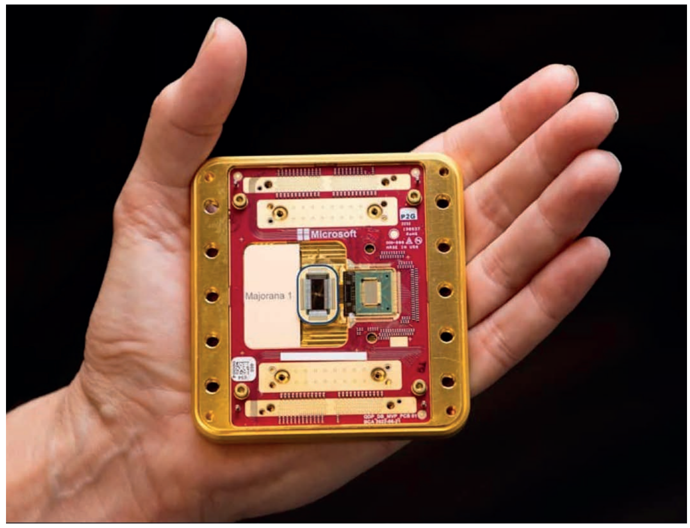
QST has, over the last 10 years, sought to feature research covering the breadth of the field within our curated focus issues covering topics such as: *Quantum Optomechanics; Quantum Photonics: Chips and Dots; Quantum Software; Perspectives on Societal Aspects and Impacts of Quantum Technologies* and *Cold Atoms in Space*.

As we celebrate IYQ, QST will lead the way with several exciting editorial initiatives aimed at disseminating the latest achievements in addressing the essential "pillars" of quantum technologies – computing, communication, sensing and simulation – while also providing authoritative perspectives and visions for the future. Our focus collections seek research within *Quantum Technologies for Quantum Gravity* and *Focus on Perspectives on the Future of Variational Quantum Computing*.

What are your goals with QST, looking ahead?

As quantum technologies advance into an inter- and multi-disciplinary realm, merging fundamental quantum-science with technological applications, QST is evolving as well. We have an increasing number of submissions addressing the burgeoning area of machine learning-enhanced quantum information processing, alongside pioneering studies exploring the application of quantum computing in fields such as chemistry, materials science and quantitative finance. All of this illustrates how QST is proactive in seizing opportunities to advance knowledge from our community of scholars and authors.

This dynamic growth is a fantastic way to celebrate the journal's 10th anniversary, especially with the added significant milestone of IYQ. Finally, I want to highlight a matter that is very close to my heart, reflecting a much-needed "duty of care" for our readership. As editor-in-chief, I am honoured to support a journal that is part of the "Purpose-Led Publishing" initiative. I view this as a significant commitment to integrity, ethics, high standards and transparency, which should be the foundation of any scientific endeavour.

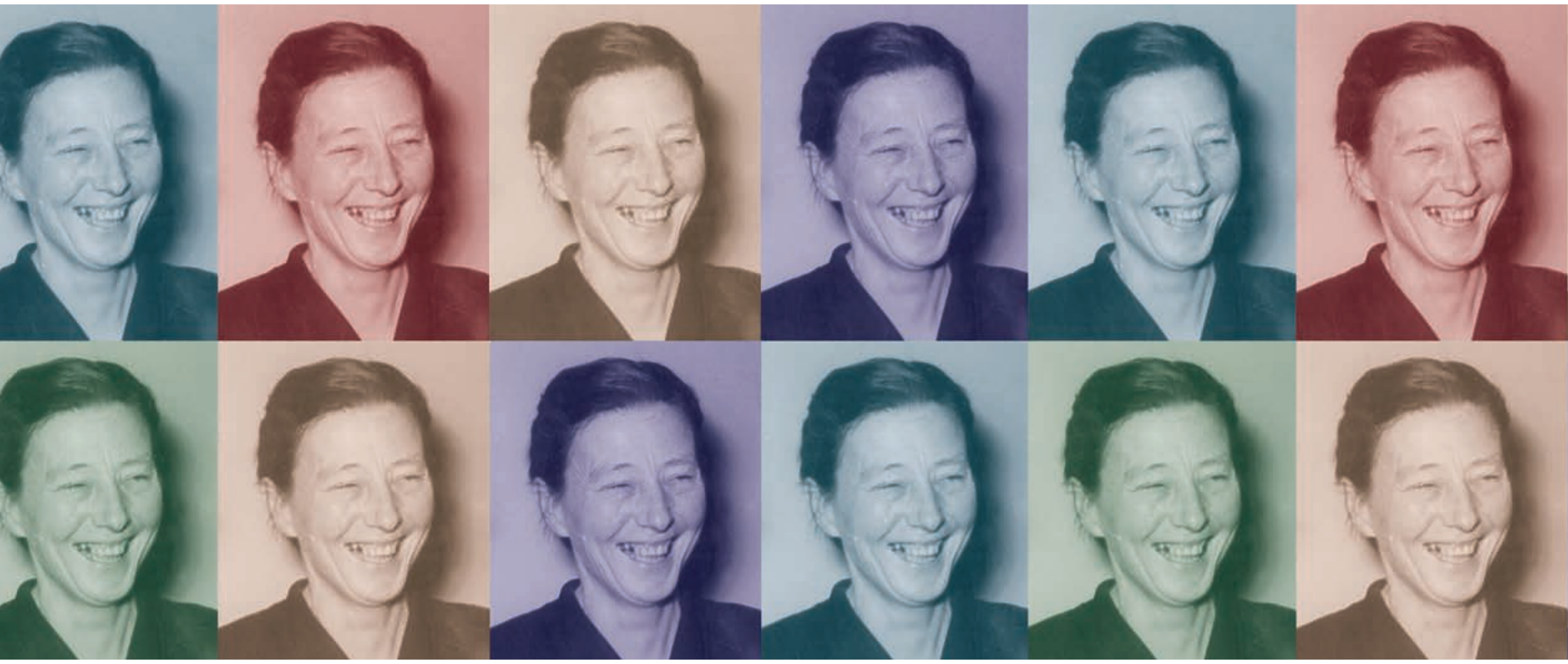


John Brecher/Microsoft

Technical turning-point? Microsoft has unveiled a quantum processor – Majorana 1 –that boasts a "topological core".

Tushna Commissariat is a features editor of *Physics World*

Grete Hermann: the quantum



Sidney Perkowitz uncovers the pioneering work of the German physicist and philosopher Grete Hermann, who sparred with the likes of Werner Heisenberg and John von Neumann – but whose contributions to quantum science have only recently come to light

INTERNATIONAL YEAR OF Quantum Science and Technology

In the early days of quantum mechanics, physicists found its radical nature difficult to accept – even though the theory had successes. In particular Werner Heisenberg developed the first comprehensive formulation of quantum mechanics in 1925, while the following year Erwin Schrödinger was able to predict the spectrum of light emitted by hydrogen using his eponymous equation. Satisfying though these achievements were, there was trouble in store.

Long accustomed to Isaac Newton's mechanical view of the universe, physicists had assumed that identical systems always evolve with time in exactly the same way, that is to say "deterministically". But Heisenberg's uncertainty principle and the probabilistic nature of Schrödinger's wave function suggested worrying flaws in this notion. Those doubts were famously expressed by Albert Einstein, Boris Podolsky and Nathan Rosen in their "EPR" paper of 1935 (*Phys. Rev.* **47** 777) and in debates between Einstein and Niels Bohr.

But the issues at stake went deeper than just a disagreement among physicists. They also touched on long-standing philosophical questions about whether we inhabit a deterministic universe, the related question of human free will, and the centrality of cause and effect. One person who rigorously addressed the questions raised by quantum theory was the German mathematician and philosopher Grete Hermann (1901–1984).

Hermann stands out in an era when it was rare for women to contribute to physics or philosophy, let alone to both. Writing in *The Oxford Handbook of the History of Quantum Interpretations*, published in 2022, the City University of New York philosopher of science Elise Crull has called Hermann's work "one of the first, and finest, philosophical treatments of quantum mechanics".

What's more, Hermann upended the famous "proof", developed by the Hungarian-American mathematician and physicist John von Neumann, that "hidden variables" are impossible in quantum mechanics. But why have Hermann's successes in studying the roots and meanings of quantum physics been so often overlooked? With 2025 being the International Year of Quantum Science and Technology, it's time to find out.

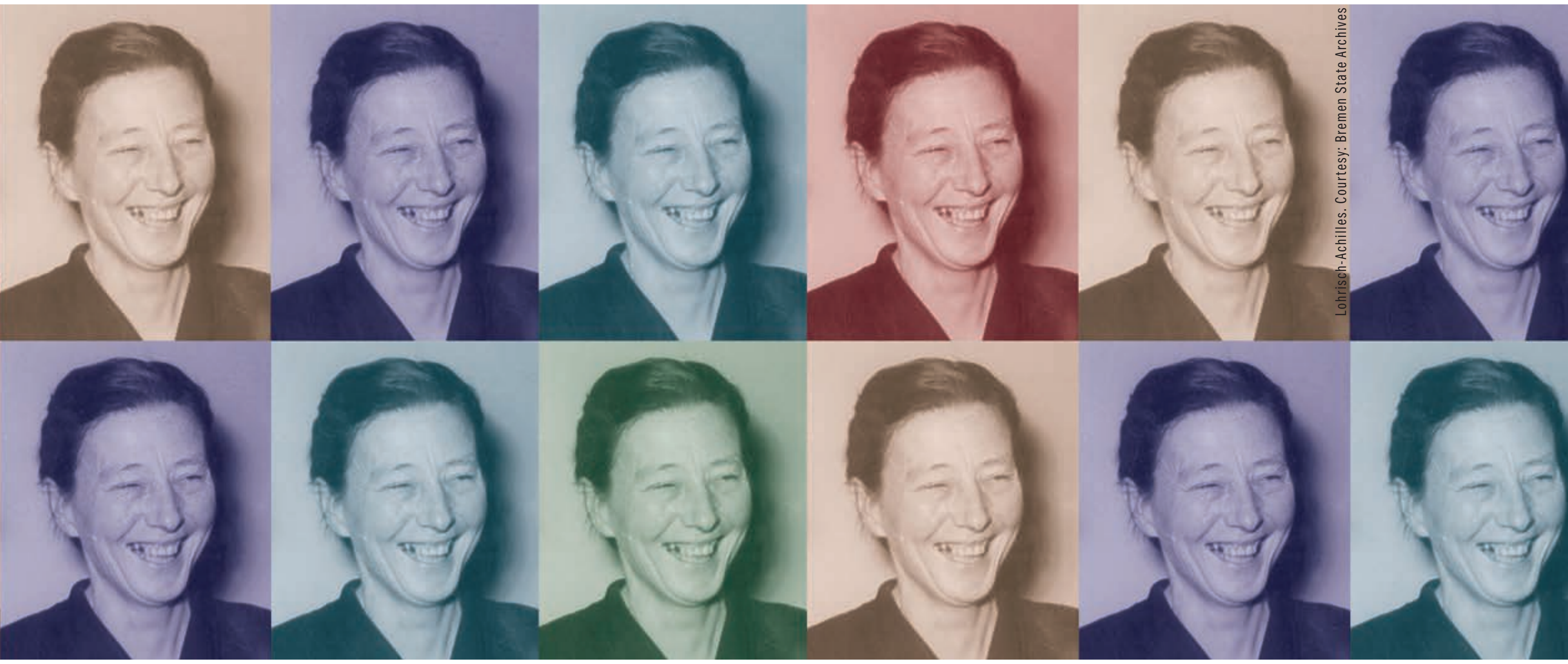
Free thinker

Hermann was born on 2 March 1901 in the north German port city of Bremen. One of seven children, her mother was deeply religious, while her father was a merchant, a sailor and later an itinerant preacher. According to the 2016 book *Grete Hermann: Between Physics and Philosophy* by Crull and Guido Bacciagaluppi, she was raised according to her father's maxim: "I train my children in freedom!" Essentially, he enabled Hermann to develop a wide range of interests and benefit from the best that the educational system could offer a woman at the time.

She was eventually admitted as one of a handful of girls at the Neue Gymnasium – a grammar school in Bremen

Sidney Perkowitz is the Charles Howard Candler Professor of Physics Emeritus at Emory University in the US, and the recipient of the 2023 American Institute of Physics Andrew Gemant Award for writing about physics. His latest book is *A Degree in a Book: Physics* (in press)

physicist who was overlooked



Lohrisch-Achilles. Courtesy: Bremen State Archives

– where she took a rigorous and broad programme of subjects. In 1921 Hermann earned a certificate to teach high-school pupils – an interest in education that reappeared in her later life – and began studying mathematics, physics and philosophy at the University of Göttingen.

In just four years, Hermann earned a PhD under the exceptional Göttingen mathematician Emmy Noether (1882–1935), famous for her groundbreaking theorem linking symmetry to physical conservation laws. Hermann's final oral exam in 1925 featured not just mathematics, which was the subject of her PhD, but physics and philosophy too. She had specifically requested to be examined in the latter by the Göttingen philosopher Leonard Nelson, whose "logical sharpness" in lectures had impressed her.

By this time, Hermann's interest in philosophy was starting to dominate her commitment to mathematics. Although Noether had found a mathematics position for her at the University of Freiburg, Hermann instead decided to become Nelson's assistant, editing his books on philosophy. "She studies mathematics for four years," Noether declared, "and suddenly she discovers her philosophical heart!"

Hermann found Nelson to be demanding and sometimes overbearing but benefitted from the challenges he set. "I gradually learnt to eke out, step by step," she later declared, "the courage for truth that is necessary if one is to utterly place one's trust, also within one's own thinking, in a method of thought recognized as cogent." Hermann, it appeared, was searching for a path to the internal discovery of truth, rather like Einstein's *Gedankenexperimente*.

After Nelson died in 1927 aged just 45, Hermann stayed in Göttingen, where she continued editing and expanding his philosophical work and related political ideas. Espousing a form of socialism based on ethical reasoning to produce a just society, Nelson had co-founded a political action group and set up the associated Philosophical-Political Academy (PPA) to teach his ideas. Hermann contributed to both and also wrote for the PPA's anti-Nazi newspaper.

Amid these disruptions, Grete Hermann continued to bring her dual philosophical and mathematical perspectives to physics, and especially to quantum mechanics

Hermann's involvement in the organizations Nelson had founded later saw her move to other locations in Germany, including Berlin. But after Hitler came to power in 1933, the Nazis banned the PPA, and Hermann and her socialist associates drew up plans to leave Germany. Initially, she lived at a PPA "school-in-exile" in neighbouring Denmark. As the Nazis began to arrest socialists, Hermann feared that Germany might occupy Denmark (as it indeed later did) and so moved again, first to Paris and then London.

Arriving in Britain in early 1938, Hermann became acquainted with Edward Henry, another socialist, whom she later married. It was, however, merely a marriage of convenience that gave Hermann British citizenship and – when the Second World War started in 1939 – stopped iStock/agsandrew

Mutual interconnections Grete Hermann was one of the first scientists to consider the philosophical implications of quantum mechanics.

her from being interned as an enemy alien. (The couple divorced after the war.) Amid all these disruptions, Hermann continued to bring her dual philosophical and mathematical perspectives to physics, and especially to quantum mechanics.

Mixing philosophy and physics

A major stimulus for Hermann's work came from discussions she had in 1934 with Heisenberg and Carl Friedrich von Weizsäcker, who was then his research assistant at the Institute for Theoretical Physics in Leipzig. The previous year Hermann had written an essay entitled "Determinism and quantum mechanics", which analysed whether the indeterminate nature of quantum mechanics – central to the "Copenhagen interpretation" of quantum behaviour – challenged the concept of causality.

Hermann used her mathematical training to point out a flaw in von Neumann's famous 1932 proof, which said that no hidden-variable theory can ever reproduce the features of quantum mechanics

Much cherished by physicists, causality says that every event has a cause, and that a given cause always produces a single specific event. Causality was also a tenet of the 18th-century German philosopher Immanuel Kant, best known for his famous 1781 treatise *Critique of Pure Reason*. He believed that causality is fundamental for how humans organize their experiences and make sense of the world.

Hermann, like Nelson, was a "neo-Kantian" who believed that Kant's ideas should be treated with scientific rigour. In her 1933 essay, Hermann examined how the Copenhagen interpretation undermines Kant's principle of causality. Although the article was not published at the time, she sent copies to Heisenberg, von Weizsäcker, Bohr and also Paul Dirac, who was then at the University of Cambridge in the UK.

In fact, we only know of the essay's existence because Crull and Bacciagaluppi discovered a copy in Dirac's archives at Churchill College, Cambridge. They also found a 1933 letter to Hermann from Gustav Heckmann, a physicist who said that Heisenberg, von Weizsäcker and Bohr had all read her essay and took it "absolutely and completely *seriously*". Heisenberg added that Hermann was a "fabulously clever woman".

Heckmann then advised Hermann to discuss her ideas more fully with Heisenberg, who he felt would be more open than Bohr to new ideas from an unexpected source. In 1934 Hermann visited Heisenberg and von Weizsäcker in Leipzig, with Heisenberg later describing their interaction in his 1971 memoir *Physics and Beyond: Encounters and Conversations*.

In that book, Heisenberg relates how rigorously Hermann wanted to treat philosophical questions. "[She] believed she could prove that the causal law – in the form Kant had given it – was unshakable," Heisenberg recalled. "Now the new quantum mechanics seemed to be challenging the Kantian conception, and she had accordingly decided to fight the matter out with us."

Their interaction was no fight, but a spirited discussion, with some sharp questioning from Hermann. When Heisenberg suggested, for instance, that a particular radium atom emitting an electron is an example of an unpredictable random event that has no cause, Hermann countered by saying that just because no cause has been found, it didn't mean no such cause exists.

Significantly, this was a reference to what we now call "hidden variables" – the idea that quantum mechanics is being steered by additional parameters that we possibly don't know anything about. Heisenberg then argued that even with such causes, knowing them would lead to complications in other experiments because of the wave nature of electrons.

Suppose, using a hidden variable, we could predict exactly which direction an electron would move. The electron wave wouldn't then be able to split and interfere with itself, resulting in an extinction of the electron. But such electron interference effects are experimentally observed, which Heisenberg took as evidence that no additional hidden variables are needed to make quantum mechanics complete. Once again, Hermann pointed out a discrepancy in Heisenberg's argument.

In the end, neither side fully convinced the other, but inroads were made, with Heisenberg concluding in his 1971 book that "we had all learned a good deal about the

Grete Hermann: 30 years ahead of John Bell

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According to Grete Hermann, John von Neumann's 1932 proof that quantum mechanics doesn't need hidden variables "stands or falls" on his assumption concerning "expectation values", which is the sum of all possible outcomes weighted by their respective probabilities. In the case of two quantities, say, r and s, von Neumann supposed that the expectation value of $(r + s)$ is the same as the expectation value of r plus the expectation value of s. In other words, $\langle (r + s)\rangle = \langle r\rangle + \langle s\rangle$.

This is clearly true in classical physics, Hermann writes, but the truth is more complicated in quantum mechanics. Suppose r and s are the conjugate variables in an uncertainty relationship, such as momentum q and position p given by $\Delta q \Delta p \geq h$. By definition, measuring q eliminates making a precise measurement of p, so it is impossible to simultaneously measure them and satisfy the relation $\langle q + p\rangle = \langle q\rangle + \langle p\rangle$.

Further analysis, which Hermann supplied and Bell presented more fully, shows exactly why this invalidates or at least strongly limits the applicability of von Neumann's proof; but Hermann caught the essence of the error first. Bell did not recognize or cite Hermann's work, most probably because it was hardly known to the physics community until years after his 1966 paper.

relationship between Kant's philosophy and modern science". Hermann herself paid tribute to Heisenberg in a 1935 paper "Natural-philosophical foundations of quantum mechanics", which appeared in a relatively obscure philosophy journal called *Abhandlungen der Fries'schen Schule* (**6** 69). In it, she thanked Heisenberg "above all for his willingness to discuss the foundations of quantum mechanics, which was crucial in helping the present investigations".

Quantum indeterminacy versus causality

In her 1933 paper, Hermann aimed to understand if the indeterminacy of quantum mechanics threatens causality. Her overall finding was that wherever indeterminacy is invoked in quantum mechanics, it is not logically essential to the theory. So without claiming that quantum theory actually supports causality, she left the possibility open that it might.

To illustrate her point, Hermann considered Heisenberg's uncertainty principle, which says that there's a limit to the accuracy with which complementary variables, such as position, q, and momentum, p, can be measured, namely $\Delta q \Delta p \geq h$ where h is Planck's constant. Does this principle, she wondered, truly indicate quantum indeterminism?

Hermann asserted that this relation can mean only one of two possible things. One is that measuring one variable leaves the value of the other undetermined. Alternatively, the result of measuring the other variable can't be precisely predicted. Hermann dismissed the first option because its very statement implies that exact values exist, and so it cannot be logically used to argue against determinism. The second choice could be valid, but that does not exclude the possibility of finding new properties – hidden variables – that give an exact prediction.

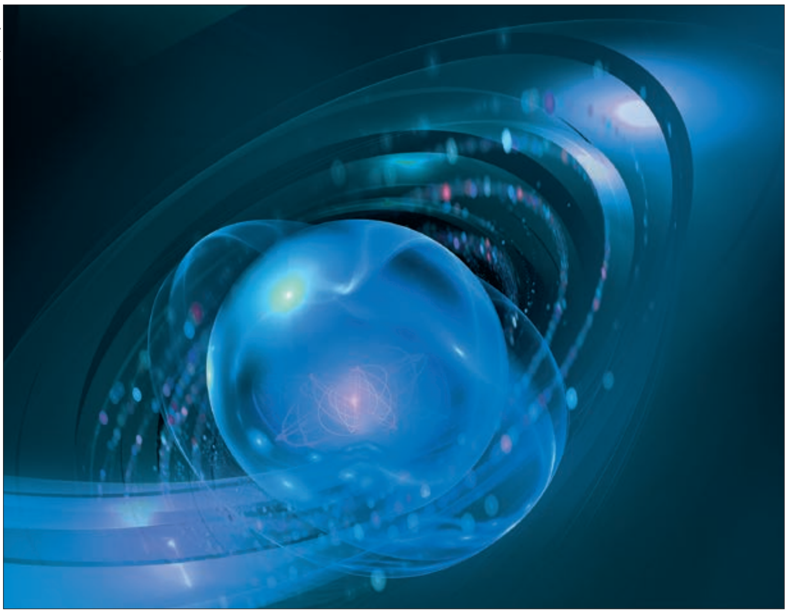
In making her argument about hidden variables, Hermann used her mathematical training to point out a flaw in von Neumann's famous 1932 proof, which said that no hidden-variable theory can ever reproduce the features of quantum mechanics. Quantum mechanics, according to von Neumann, is complete and no extra deterministic features need to be added.

For decades, his result was cited as "proof" that any deterministic addition to quantum mechanics must be wrong. Indeed, von Neumann had such a well-deserved reputation as a brilliant mathematician that few people had ever bothered to scrutinize his analysis. But in 1964 the Northern Irish theorist John Bell famously showed that a valid hidden-variable theory could indeed exist, though only if it's "non-local" (*Physics Physique Fizika* **1** 195).

Non-locality says that things can happen at different parts of the universe simultaneously without needing faster-than-light communication. Despite being a notion that Einstein never liked, non-locality has been widely confirmed experimentally. In fact, non-locality is a defining feature of quantum physics and one that's eminently useful in quantum technology.

Then, in 1966 Bell examined von Neumann's reasoning and found an error that decisively refuted the proof (*Rev. Mod, Phys.* **38** 447). Bell, in other words, showed that quantum mechanics could permit hidden variables after all – a finding that opened the door to alternative interpretations of quantum mechanics. However, Hermann had reported the very same error in her 1933 paper, and again in her 1935 essay, with an especially lucid exposition that almost exactly foresees Bell's objection.

She had got there first, more than three decades earlier (see box "Grete Hermann: 30 years ahead of John Bell").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Forward thinker Grete Hermann was one of the first people to study the notion that quantum mechanics might be steered by mysterious additional parameters – now dubbed "hidden variables" – that we know nothing about.

A new view of causality

After rebutting von Neumann's proof in her 1935 essay, Hermann didn't actually turn to hidden variables. Instead, Hermann went in a different and surprising direction, probably as a result of her discussions with Heisenberg. She accepted that quantum mechanics is a complete theory that makes only statistical predictions, but proposed an alternative view of causality within this interpretation.

We cannot foresee precise causal links in a quantum mechanics that is statistical, she wrote. But once a measurement has been made with a known result, we can work backwards to get a cause that led to that result. In fact, Hermann showed exactly how to do this with various examples. In this way, she maintains, quantum mechanics does not refute the general Kantian category of causality.

Not all philosophers have been satisfied by the idea of retroactive causality. But writing in *The Oxford Handbook of the History of Quantum Interpretations*, Crull says that Hermann "provides the contours of a neo-Kantian interpretation of quantum mechanics". "With one foot squarely on Kant's turf and the other squarely on Bohr's and Heisenberg's," Crull concludes, "[Hermann's] interpretation truly stands on unique ground."

But Hermann's 1935 paper did more than just upset von Neumann's proof. In the article, she shows a deep and subtle grasp of elements of the Copenhagen interpretation such as its correspondence principle, which says that – in the limit of large quantum numbers – answers derived from quantum physics must approach those from classical physics.

The paper also shows that Hermann was fully aware – and indeed extended the meaning – of the implications of Heisenberg's thought experiment that he used to illustrate the uncertainty principle. Heisenberg envisaged a photon colliding with an electron, but after that contact, she writes, the wave function of the physical system is a linear combination of terms, each being "the product of one wave function describing the electron and one describing the light quantum".

As she went on to say, "The light quantum and the electron are thus not described each by itself, but only in their relation to each other. Each state of the one is associated with one of the other." Remarkably, this amounts to an early perception of quantum entanglement, which Schrödinger described and named later in 1935. There is no evidence, however, that Schrödinger knew of Hermann's insights.

> Had Grete Hermann's 1935 paper been more widely known, it could have altered the early development of quantum mechanics

Hermann's legacy

On the centenary of the birth of a full theory of quantum mechanics, how should we remember Hermann? According to Crull, the early founders of quantum mechanics were "asking philosophical questions about the implications of their theory [but] none of these men were *trained* in both physics and philosophy". Hermann, however, was an expert in the two. "[She] composed a brilliant philosophical analysis of quantum mechanics, as only one with her training and insight could have done," Crull says.

Sadly for Hermann, few physicists at the time were aware of her 1935 paper even though she had sent copies to some of them. Had it been more widely known, her paper could have altered the early development of quantum mechanics. Reading it today shows how Hermann's style of incisive logical examination can bring new understanding.

Hermann leaves other legacies too. As the Second World War drew to a close, she started writing about the ethics of science, especially the way in which it was carried out under the Nazis. After the war, she returned to Germany, where she devoted herself to pedagogy and teacher training. She disseminated Nelson's views as well as her own through the reconstituted PPA, and took on governmental positions where she worked to rebuild the German educational system, apparently to good effect according to contemporary testimony.

Hermann also became active in politics as an adviser to the Social Democratic Party. She continued to have an interest in quantum mechanics, but it is not clear how seriously she pursued it in later life, which saw her move back to Bremen to care for an ill comrade from her early socialist days.

Hermann's achievements first came to light in 1974 when the physicist and historian Max Jammer revealed her 1935 critique of von Neumann's proof in his book *The Philosophy of Quantum Mechanics*. Following Hermann's death in Bremen on 15 April 1984, interest slowly grew, culminating in Crull and Bacciagaluppi's 2016 landmark study *Grete Hermann: Between Physics and Philosophy*.

The life of this deep thinker, who also worked to educate others and to achieve worthy societal goals, remains an inspiration for any scientist or philosopher today. ■

Reviews

Celebrating Emmy Noether

Isabel Rabey reviews *Einstein's Tutor: the Story of Emmy Noether and the Invention of Modern Physics* by Lee Philips

Einstein's Tutor: the Story of Emmy Noether and the Invention of Modern Physics
Lee Philips
2024 Hachette UK
£25hb 368pp

In his debut book, *Einstein's Tutor: the Story of Emmy Noether and the Invention of Modern Physics*, Lee Phillips champions the life and work of German mathematician Emmy Noether (1882–1935). Despite living a life filled with obstacles, injustices and discrimination as a Jewish mathematician, Noether revolutionized the field and discovered "the single most profound result in all of physics". Phillips' book weaves the story of her extraordinary life around the central subject of "Noether's theorem", which itself sits at the heart of a fascinating era in the development of modern theoretical physics.

Noether grew up at a time when women had few rights. Unable to officially register as a student, she was instead able to audit courses at the University of Erlangen in Bavaria, with the support of her father who was a mathematics professor there. At the time, young Noether was one of only two female auditors in the university of 986 students. Just two years previously, the university faculty had declared that mixed-sex education would "overthrow academic order". Despite going against this formidable status quo, she was able to graduate in 1903.

Noether continued her pursuit of advanced mathematics, travelling to the "[world's] centre of mathematics" – the University of Göttingen. Here, she was able to sit in the lectures of some of the brightest mathematical minds of the time – Karl Schwarzschild, Hermann Minkowski, Otto Blumenthal, Felix Klein and David Hilbert. While there, the law finally changed: women were, at last, allowed to enrol as students at university. In 1904 Noether returned to the University of Erlangen to complete her postgraduate dissertation under the supervision of Paul Gordan. At the time, she was the only woman to matriculate alongside 46 men.


Public domain. Photographer unknown
Mathematical genius Emmy Noether, around 1900.

Infiltrating the boys' club

Despite being more than qualified, Noether was unable to secure a university position after graduating from her PhD in 1907. Instead, she worked unpaid for almost a decade – teaching her father's courses and supervising his PhD students. As of 1915, Noether was the only woman in the whole of Europe with a PhD in mathematics. She had worked hard to be recognized as an expert on symmetry and invariant theory, and eventually accepted an invitation from Klein and Hilbert to work alongside them in Göttingen. Here, the three of them would meet Albert Einstein to discuss his latest project – a general theory of relativity.

In *Einstein's Tutor*, Phillips paints an especially vivid picture of Noether's life at Göttingen, among colleagues including Klein, Hilbert and Einstein, who loom large and bring a richness to the story. Indeed, much of the first three chapters are dedicated to these men, setting the scene for Noether's arrival in Göttingen. Phillips makes it easy to imagine these exceptionally talented and somewhat eccentric individuals working at the forefront of mathematics and theoretical physics together. And it was here, when supporting Einstein with the devel-

View this e-magazine online to watch our video about who Emmy Noether was.

opment of general relativity (GR), that Noether discovered a profound result: for every symmetry in the universe, there is a corresponding conservation law.

Throughout the book, Phillips makes the case that, without Noether, Einstein would never have been able to get to the heart of GR. Einstein himself "expressed wonderment at what happened to his equations in her hands, how he never imagined that things could be expressed with such elegance and generality". Phillips argues that Einstein should not be credited as the sole architect of GR. Indeed, the contributions of Grossman, Klein, Besso, Hilbert, and crucially, Noether, remain largely unacknowledged – a wrong that Phillips is trying to right with this book.

A key theme running through *Einstein's Tutor* is the importance of the support and allyship that Noether received from her male contemporaries. While at Göttingen, there was a battle to allow Noether to receive her *habilitation* (eligibility for tenure). Many argued in her favour but considered her an exception, and believed that in general, women were not suited as university professors. Hilbert, in contrast, saw her sex as irrelevant (famously declaring "this is not a bath house") and pointed out that science requires the best people, of which she was one. Einstein also fought for her on the basis of equal rights for women.

Eventually, in 1919 Noether was allowed to habilitate (as an exception to the rule) and was promoted to professor in 1922. However, she was still not paid for her work. In fact, her promotion came with the specific condition that she remained unpaid, making it clear that Noether "would not be granted any form of authority over any male employee". Hilbert however, managed to secure a contract with a small salary for her from the university administration.

Her allies rose to the cause again in 1933, when Noether was one of the first Jewish academics to be dismissed under the Nazi regime. After her expulsion, German mathematician Helmut Hasse convinced 14 other colleagues to write letters advocating for her importance, asking that she be allowed to continue as a teacher to a small group of advanced students – the government denied this request.

Noether's legacy

When the time came to leave Germany, many colleagues wrote testimonials in her support for immigration, with one writing "She is one of the 10 or 12 leading mathematicians of the present generation in the entire world." Rather than being placed at a prestigious university or research institute (Hermann Weyl and Einstein were both placed at "the men's university", the Institute for Advanced Study in Princeton), it was recommended she join Bryn Mawr, a women's college in Pennsylvania, US. Her position there would "compete with no-one… the most distinguished feminine mathematician connected with the most distinguished feminine university". Phillips makes clear his distaste for the phrasing of this recommendation. However, all accounts show that she was happy at Bryn Mawr and stayed there until her unexpected death in 1935 at the age of 53.

With a PhD in theoretical physics, Phillips has worked for many years in both academia and industry. His background shows itself clearly in some unusual writing choices. While his writing style is relaxed and conversational, it includes the occasional academic turn of phrase (e.g. "In this chapter I will explain…"), which feels out of place in a popular-science book. He also has a habit of piling repetitive and overly sincere praise onto Noether. I personally prefer stories that adopt the "show, don't tell" approach – her abilities speak for themselves, so it should be easy to let the reader come to their own conclusions.

Phillips has made the ambitious choice to write a popular-science book about complex mathematical concepts such as symmetries and conservation laws that are challenging to explain, especially to general readers. He does his best to describe the mathematics and physics behind some of the key concepts around Noether's theorem. However, in places, you do need to have some familiarity with university-level physics and maths to properly follow his explanations. The book also includes a 40-page appendix filled with additional physics content, which I found unnecessary.

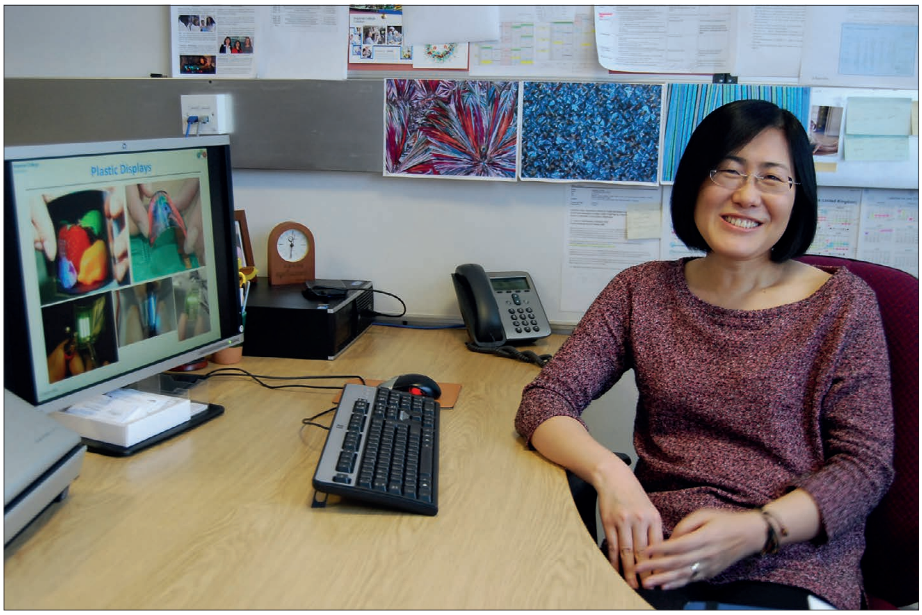
Einstein's Tutor does achieve its primary goal of familiarizing the reader with Emmy Noether and the tremendous significance of her work. The final chapter on her legacy breezes quickly through developments in particle physics, astrophysics, quantum computers, economics and *XKCD Comics* to highlight the range and impact this single theorem has had. Phillips' goal was to take Noether into the mainstream, and this book is a small step in the right direction. As cosmologist and author Katie Mack summarizes perfectly: "Noether's theorem is to theoretical physics what natural selection is to biology."

Isabel Rabey is a teaching fellow in the Department of Physics, Imperial College, London, UK

Careers

Organic magic: Ji-Seon Kim

Ji-Seon Kim, who won the 2023 Nevill Mott Medal and Prize from the Institute of Physics, talks to Laura Hiscott about the transformative potential of carbon-based semiconductors, the need for strong international research collaboration, and the irreplaceable excitement of tangible experiences in the lab



Imperial College London

Semiconductor superstar Ji-Seon Kim is moving to the University of Oxford after almost two decades at Imperial College London.

In a sunny office, Ji-Seon Kim holds up a sheet of stripy plastic. In the middle of dark blue and transparent bands, a small red glow catches the eye, clearly visible even against the bright daylight. There are no sockets or chargers, but that little light is no magic trick.

"It's a printed solar cell from my industrial collaborator," Kim explains. "This blue material is the organic semiconductor printed in the plastic. It absorbs indoor light and generates electricity to power the LED."

Kim is a professor in the Department of Physics at Imperial College London, and was director of the university's EPSRC Plastic Electronics Centre for Doctoral Training, which closed in 2023. She researches carbon-based semiconductors, sometimes called organic, molecular or plastic semiconductors. In 2023 the Institute of Physics (IOP) awarded her the Nevill Mott Medal and Prize in recognition of her "outstanding contributions to the materials physics" of this area.

Yet she came to the field almost by accident. After completing her master's degree in theoretical physics in Seoul in 1994, Kim was about to embark on a theory-focused PhD studying nonlinear optics at Imperial, when her master's supervisor told her about some exciting work happening at the University of Cambridge.

A team there had just created the first organic light-emitting diodes (OLEDs) based on conjugated polymers, successfully stimulating carbon-based molecules to glow under an applied voltage. Intrigued by the nascent field, Kim contacted Richard Friend, who led the research and, following an interview, he offered her a PhD position. Friend himself won the IOP's Isaac Newton Medal and Prize in 2024.

"I spent almost six months learning how to use certain equipment in the lab," Kim recalls of the tricky transition from theory to experimental work. "For example, there's a big glove box you have to put your hands in to make the devices inside it, and I wasn't sure whether I was even able to open the chamber."

But as she found her feet, she became increasingly passionate about the work. "I was really lucky to be in the right place at the right time, just after this new discovery."

Seeing the light

You could hardly find a clearer example of fundamental research moving into consumer applications in recent years than OLEDs – now a familiar term in the world of TVs and smartphones. But when Kim joined the field, the first OLEDs were inefficient and degraded quickly due to high electric fields, heat and oxygen exposure. So, during her PhD, Kim focused on making the devices more efficient and last for longer.

She also helped to develop a better understanding of the physics underlying the phenomenon. At the time, researchers disagreed about the fundamental limit of device efficiency determined by excited state (singlet vs triplet) formation under charge injection. Drawing on her theoretical background, Kim developed innovative simulation work on display device outcoupling, which provided a new way of determining the orientation of emitting molecules and the device efficiency, which is now commonly used in the OLED community.

Kim completed her PhD in 2000 and continued studying organic semiconductors, moving to Imperial in 2007. Besides display screens, she is interested in numerous other potential applications of the materials, including sustainable energy. After all, just as the molecules can emit light in response to injected charges, so too can they absorb photons and generate electricity.

Organic semiconductors have several advantages over traditional silicon-based photovoltaic materials. As well as being lightweight, carbon molecules can be tuned to absorb different wavelengths. Whereas silicon solar cells only work with sunlight, and must be installed as heavy panels on roofs or in fields, organic semiconductors offer more options. They could be inconspicuously integrated into buildings, capturing indoor office light that is normally wasted and using it to power appliances. They could even be made into a transparent film and incorporated into windows to convert sunlight into electricity.

Plastic fabrication methods offer a further benefit. Unlike silicon, carbon-based semiconductors can be dissolved in common organic solvents to create a kind of ink, opening the door to low-cost, flexible printing techniques.

And it doesn't stop there. "A future direction I am particularly interested in is using organic semiconductors for neuromorphic applications," says Kim. "You can make synaptic transistors – which mimic biological neurons – using molecular semiconductors."

With all the promise of these materials, the field has flourished. Kim's group is currently tackling the challenge of the high binding energy between the electron–hole pair in organic semiconductors, which resists separation into free charges, increasing the intrinsic energy cost of using them. Kim and her team are exploring new small molecules, which create an energy level offset by simply changing their packing and orientations, providing an extra driving force to separate the charges.

Building bridges

Alongside her work at Imperial, Kim was also a visiting professor at KAIST in Korea, and is actively involved in strengthening UK–Korea research ties. In 2016 she co-established the GIST-ICL Research and Development Centre for Plastic Electronics, a collaboration between the Gwangju Institute for Science and Technology and Imperial.

"International interactions are critical not only for scientific development but also for future technology," Kim says. "The UK is really strong in fundamental science, but we don't have many manufacturing sites compared to Asian countries like Korea. For a fundamental discovery to be applied in a commercial device, there's a transition from the lab to the manufacturing scale. For that we need a partner, and those partners are overseas."

Kim is also seeking to build bridges across disciplines. She will soon be moving to the University of Oxford to work on physical chemistry as part of a research initiative focused on sustainable materials and chemistry. She will draw on her expertise in spectroscopic techniques to study and engineer molecules for sustainable applications.

"These days physics is multidisciplinary," she notes. "For future technology and science, you have to be able to integrate different disciplines. I hope I can contribute as a physicist to bridge different disciplines in molecular semiconductors."

But one constant is how Kim mentors undergraduate students. Her advice is to engage them with innovations from the lab, which is why she likes to get out the plastic sheet powering the LED. The emphasis on tangible experience is inspired by the excitement and motivation she remembers feeling when she saw organic semiconductors glowing at the start of her PhD. "Even though the efficiency was so poor that we had to turn the overhead light off and use a really high voltage to see the faint light, that exposure to the real physics was really important," she says. "That was for me a Eureka moment."

Laura Hiscott is a freelance science journalist

Ask me anything: Hannah Earley

Hannah Earley is the chief technical officer and co-founder of Vaire Computing

Vaire Computing is a start-up seeking to commercialize computer chips based on the principles of reversible computing – a topic Earley studied during her PhD in applied mathematics and theoretical physics at the University of Cambridge, UK. The central idea behind reversible computing is that reversible operations use much less energy, and thus generate much less waste heat, than those in conventional computers.


Intel Ignite

What skills do you use every day in your job?

In an early-stage start-up environment, you have to wear lots of different hats. Right now, I'm planning for the next few years, but I'm also very deep into the engineering side of Vaire, which spans a lot of different areas.

The skill I use most is my ability to jump into a new field and get up to speed with it as quickly as possible, because I cannot claim to be an expert in all the different areas we work in. I cannot be an expert in integrated circuit design as well as developing electronic design automation tooling as well as building better resonators. But what I can do is try to learn about all these things at as deep a level as I can, very quickly, and then guide the people around me with higher-level decisions while also having a bit of fun and actually doing some engineering work.

What do you like best and least about your job?

We have so many great people at Vaire, and being able to talk with them and discuss all the most interesting aspects of their specialities is probably the part I like best. But I'm also enjoying the fact that in a few years, all this work will culminate in an actual product based on things I worked on when I was in academia. I love theory, and I love thinking about what could be possible in hundreds of years' time, but seeing an idea get closer and closer to reality is great.

The part I have more of a love-hate relationship with is just how intense this job is. I'm probably intrinsically a workaholic. I don't think I've ever had a good balance in terms of how much time I spend on work, whether now or when I was doing my PhD or even before. But when you are responsible for making your company succeed, that degree of intensity becomes unavoidable. It feels difficult to take breaks or to feel comfortable taking breaks, but I hope that as our company grows and gets more structured, that part will improve.

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

There are so many specifics of what it means to build a computer chip that I wish I'd known. I may even have suffered a little bit from the Dunning–Kruger effect [in which people with limited experience of a particular topic overestimate their knowledge] at the beginning, thinking, "I know what a transistor is like. How hard can it be to build a large-scale integrated circuit?"

It turns out it's very, very hard, and there's a lot of complexity around it. When I was a PhD student, it felt like there wasn't that big a gap between theory and implementation. But there is, and while to some extent it's not possible to know about something until you've done it, I wish I'd known a lot more about chip design a few years ago.

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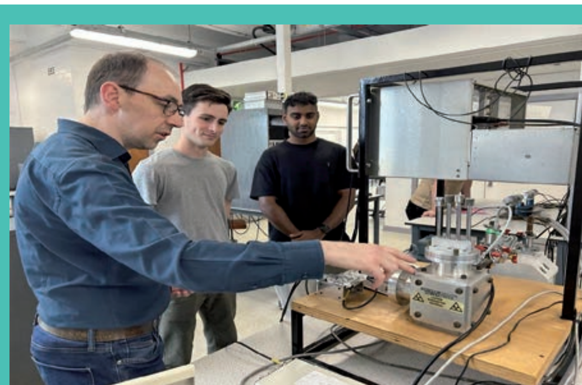

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Roses, ant gripper and swing-top bottles

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

The curves and curls of leaves and flower petals arise due to the interplay between their natural growth and geometry. Uneven growth in a flat sheet, in which the edges grow quicker than the interior, gives rise to strain and in plant leaves and petals, for example, this can result in a variety of shapes such as saddle and ripple shapes. Yet when it comes to rose petals, the sharply pointed cusps – a point where two curves meet – that form at the edge of the petals set it apart from soft, wavy patterns seen in many other plants. To investigate this intriguing difference, researchers from the Hebrew University of Jerusalem carried out theoretical modelling and conducted a series of experiments with synthetic disc "petals" (*Science* **388** 520). They found that the pointed cusps that form at the edge of rose petals are due to a type of geometric frustration called a Mainardi–Codazzi–Peterson (MCP) incompatibility. This type of mechanism results in stress concentrating in a specific area, which goes on to form cusps to avoid tearing or forming unnatural folding. When the researchers suppressed the formation of cusps, they found that the discs revert to being smooth and concave. The researchers say that the findings could be used for applications in soft robotics and even in the deployment of spacecraft components.

A rosy outlook Researchers have found that rose petal growth is all about geometric frustration.

The situation is changing drastically

Josef Aschbacher, director general of the European Space Agency, says it is "crystal clear" that in a more volatile geopolitical situation, Europe will need to boost investment in space to guarantee autonomy from other countries including the US. (Source: *Guardian*)

We cannot at this stage make the claim that, it is [certainly] due to life

Nikku Madhusudhan of the Institute of Astronomy at the University of Cambridge is sceptical about drawing too many conclusions from his team's discovery that planet K2-18b contains at least one gas that, on Earth, is uniquely produced by living organisms in nature. (Source: *Times*)

Get a grip

Scientists at the University of Edinburgh in the UK have built a prototype "hairy robotic gripper" that is inspired by the small hairs found on ant jaws. Ants are not only excellent nest builders but are also expert foragers thanks to their powerful jaws. Edinburgh researchers filmed ants and the sequence of movements they do when picking up seeds and other objects. They then used this to build a device that consists of two aluminium plates, each containing four rows of "hairs" made from thermoplastic polyurethane. The hairs are 20 mm long and 1 mm in diameter, protruding in a V-shape. This allows the hairs to surround circular objects, which can be particularly difficult to grasp and hold onto using parallel plates alone. In tests picking up 30 different household items, including a jam jar and a shampoo bottle, adding hairs to the gripper increased the prototype's grasp success rate from 64% to 90%. Barbara Webb, who led the research, says the work is "just the first step". "Now we can see how [ants'] antennae, front legs and jaws combine to sense, manipulate, grasp and move objects," she adds. "This will inform further development of our technology."

Swinging with the times

Physicist Max Koch from the University of Göttingen in Germany is a keen homebrewer, so investigating the physics of swing-top bottles was a no-brainer. Koch and colleagues examined transparent 0.33 litre bottles, which contained home-brewed ginger beer under 2–5 bars of pressure (*Physics of Fluids* **37** 036135). The team found that the sound emitted when opening the bottles – what can be described as an "ah" sound – was due to condensation in the bottleneck forming a standing wave. "The pop's frequency is much lower than the resonation if you blow on the full bottle like a whistle," notes Koch. "This is caused by the sudden expansion of the carbon dioxide and air mixture in the bottle, as well as a strong cooling effect to about –50 °C, which reduces sound speed." The team also investigated the sloshing of the beverage as it is opened. First, the dissolved carbon dioxide inside the beer triggers the level of the liquid to rise while the motion of the bottle as it opens also causes the liquid to slosh. Another effect during opening is the bottle top hitting the glass with its sharp edge. This triggers further "gushing" in the liquid due to the enhanced formation of bubbles. There are still some unanswered questions, however, which will require further work. "One thing we didn't resolve is that our numerical simulations showed an initial strong peak in the acoustic emission before the short 'ah' resonance, but this peak was absent in the experimentation," adds Koch.

Michael Banks is news editor of *Physics World*