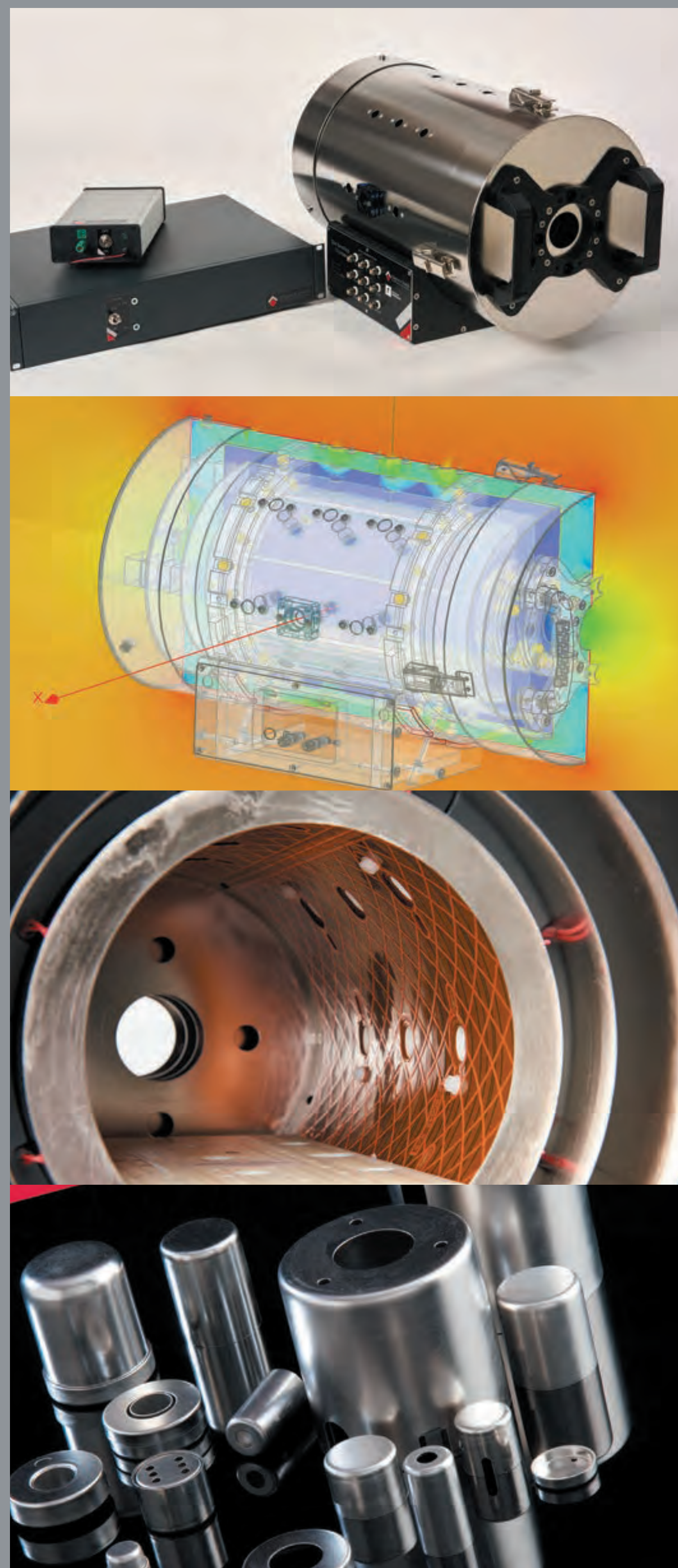
physicsworld
2025

Quantum Briefing

Curiouser and curiouser
The strangest and weirdest quantum effects

Heisenberg on Helgoland
How quantum mechanics emerged 100 years ago

Global success story
Celebrating the International Year of Quantum Science and Technology



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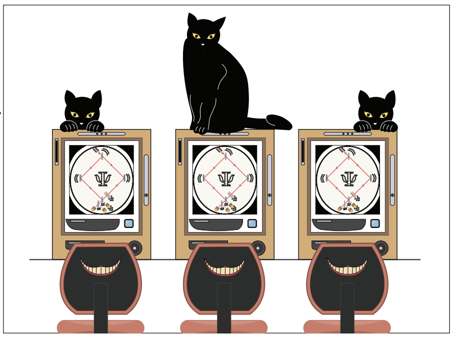
Mayank Shreshtha



Curiouser and curiouser Quantum Cheshire cats are a perplexing phenomenon where the property of a quantum particle can be completely separate from the particle itself. p33

This year marks the centenary of Werner Heisenberg's pioneering work on quantum mechanics p3

Peter Knight *Co-chair of the IYQ steering committee*

INTERNATIONAL YEAR OF Quantum Science and Technology

On the cover *Qubits, Duality*
Felicity Inkpen. Oil paint on board, 2025

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Quantum Briefing

Foreword

INTERNATIONAL YEAR OF
Quantum Science
and Technology

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Source of inspiration It was on the island of Helgoland in the North Sea that Werner Heisenberg pioneered quantum mechanics in June 1925. 12

It's not often you get an invitation a full three years in advance p16

Nathalie de Leon *Princeton University quantum physicist, who is one of an elite group of researchers attending a conference on Helgoland in June 2025, marking 100 years of quantum mechanics.*

Celebrating a century of quantum science and technology

Sit back and enjoy the 2025 *Physics World Quantum Briefing*, which brings a selection of amazing articles on the history, mystery and industry of quantum mechanics

I am delighted to welcome you to this year's *Physics World Quantum Briefing* celebrating the International Year of Quantum Science and Technology (IYQ).

Endorsed by the United Nations Educational, Scientific and Cultural Organization (UNESCO), the IYQ is a global initiative to raise awareness of the impact of quantum science and applications on all aspects of life.

This year was chosen for IYQ as it marks the centenary of Werner Heisenberg's pioneering work on quantum mechanics on the island of Helgoland, off the coast of Germany, in June 1925.

Heisenberg's work – and that of other great physicists such as Niels Bohr, Paul Dirac and Erwin Schrödinger – revolutionized our understanding of the world. But it also changed the face of modern life, leading to semiconductors, transistors and lasers as part of the "first quantum revolution".

These days we are in the midst of a "second quantum revolution" that promises to be even more exciting. It involves exploiting inherently quantum effects such as entanglement and superposition for quantum computing, cryptography, communication, sensing and more besides.

The work is not just fascinating from a physics point of view, but is also starting to have a tremendous real-word impact, with huge opportunities for business and industry alike.

It truly is a remarkable time for quantum science and technology and I hope you enjoy finding out more about its past, present and future in the 2025 *Physics World Quantum Briefing*.

National Physical Laboratory

Peter Knight
Co-chair of the International Year of Quantum Science and Technology steering committee and chair of the UK National Quantum Technology Programme strategic advisory board

Welcome

The transformative potential of quantum science

Felicity Inkpen

Qubits, Duality Artist Felicity Inkpen wanted to find a way to visually represent wave-particle duality, and show that quantum mechanics is present in the everyday. "As an artist, I am interested not only in colour, form and figurative representation, but also in exploiting different art materials and the varying molecular properties of pigments," explains Inkpen. "Using sugar, water, expired printer cartridges, powdered paint, a glass oven dish and a re-purposed seasonal affective disorder lamp, I captured hundreds of images and hours of footage of pigments swirling and diffusing, creating spontaneous moments of colour," she adds. Inkpen then recreated the swirling images of dyes in water – pictured above – in oil paint on board, for the cover.

Welcome to the 2025 *Physics World Quantum Briefing*, which commemorates the centenary of quantum mechanics and celebrates the International Year of Quantum Science and Technology (IYQ)

Right from its inception 100 years ago, quantum mechanics transformed our view of the universe. Physicists grappled with the seeming inconsistences of Newtonian mechanics, as they further investigated how particles behave at the atomic level. With determinism being summarily dismissed, the wave nature of light opened up a quantum of probabilities.

The inherently intertwined identities of quantum particles are at the heart of our reality, with concepts such as "entanglement" and "superposition" intriguing physicists and laypeople alike. Indeed, the cover of this briefing explores these concepts via a specially commissioned painting by the UK-based artist and scientist Felicity Inkpen, entitled *Qubits, Duality*.

Quantum science underpins how our cosmos works on a fundamental level, but quantum technologies are already a part of our everyday lives – from the laser in your lab, to the MRI machine in a hospital, and even the transistors and semiconductors in your phone. The ineffable abilities of quantum mechanics are no longer mere theoretical curiosities; instead they are the engines of innovation, as cutting-edge quantum technologies – from sensors to cryptographic networks, and crucially, quantum computers – emerge from the lab into the real world.

As the second quantum revolution flourishes, the 2025 *Physics World Quantum Briefing* looks back at some pivotal moments in the history of quantum mechanics. It examines some of the dizzying paradoxes that underpin its mystery, and shines a light on the ever-growing industry that is quantum tech today. Also, don't miss our fictionalized tale, spanning multiple realities, of the birth of matrix mechanics (p56).

A key aim of the IYQ 2025 is to emphasize the importance of equitable and ethical quantum development across the globe, with quantum education resources being available to everyone. As quantum technologies mature, so too must our efforts to ensure they benefit all of society, and help tackle global challenges such as health and climate change. Calls for initiatives like a "Quantum Erasmus" programme and responsible innovation frameworks (p51) underscore the need for inclusive growth in this transformative field.

Whether you are a physicist, student, policymaker, or curious reader, this issue invites you to delve into the quantum landscape. It is a celebration of how far we've come in 100 years – and the infinite impact of quantum technologies that lies ahead.

Join us in exploring the quantum frontier.

Tushna Commissariat
Features editor, *Physics World*

Quantum year launches in style

The International Year of Quantum Science and Technology got under way at an event at UNESCO headquarters in Paris at the start of the year, as **Matin Durrani** reports

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

Opening remarks came from Cephas Adjej Mensah, a research director in the Ghanaian government, which last year submitted the draft resolution to the United Nations for 2025 to be proclaimed as the IYQ. "Let us commit to making quantum science accessible to all," Mensah declared, reminding delegates that the IYQ is intended to be a global initiative, spreading the benefits of quantum equitably around the world. "We can unleash the power of quantum science and technology to make an equitable and prosperous future for all."

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

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

Matin Durrani

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

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

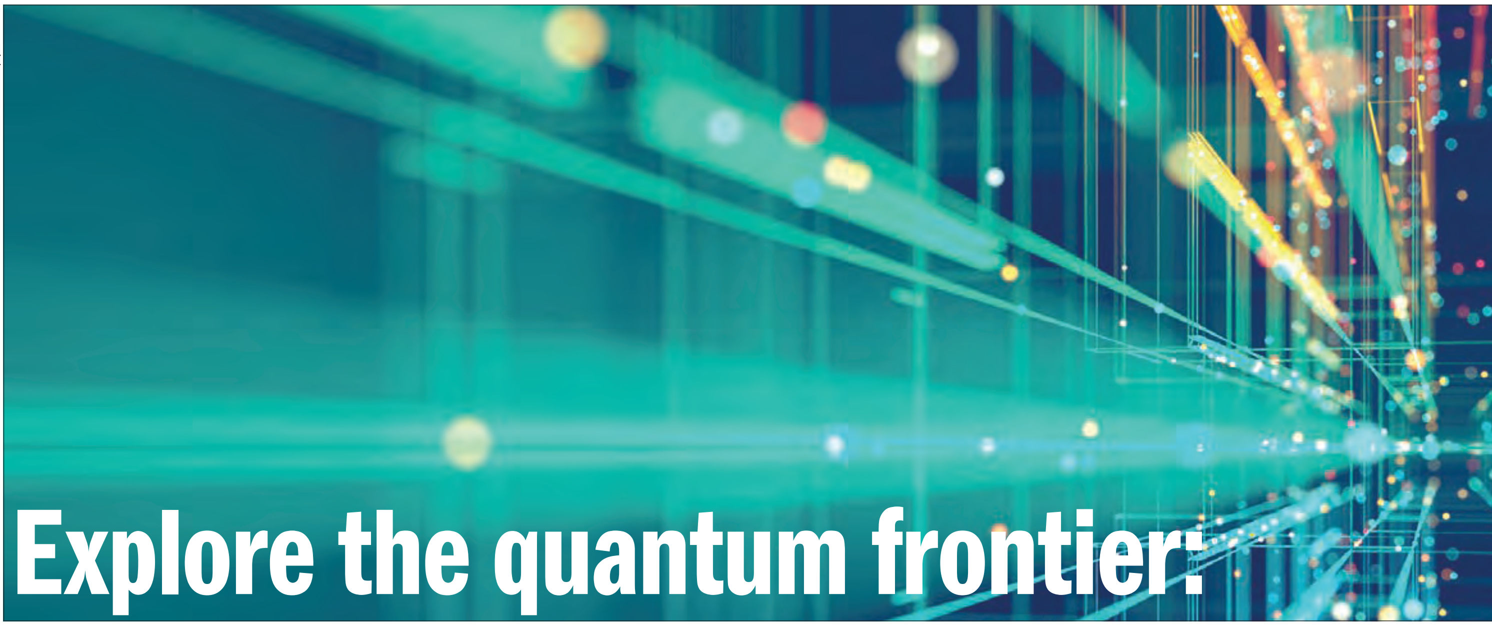
Leaders of the burgeoning quantum tech sector were in Paris too. Addressing the challenges and opportunities of scaling quantum technologies to practical use was a panel made up of Quantinuum chief executive Rajeeb Hazra, QuEra president Takuya Kitawawa, IBM's quantum-algorithms vice president Katie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

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

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

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

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



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Explore the quantum frontier: all about the 2025 International Year of Quantum Science and Technology

From public talks and hackathons to festivals and careers events, **Tushna Commissariat** gives you a whistle-stop tour of key activities in the IYQ calendar across the UK

In June 1925, a relatively unknown physics postdoc by the name of Werner Heisenberg developed the basic mathematical framework that would be the basis for the first quantum revolution. Heisenberg, who would later win the Nobel Prize for Physics, famously came up with quantum mechanics on a two-week vacation on the tiny island of Helgoland off the coast of Germany, where he had gone to cure a bad bout of hay fever (see "Return to Helgoland" pp12–17).

Now, a century later, we are on the cusp of a second quantum revolution, with quantum science and technologies growing rapidly across the globe. According to the *State of Quantum 2024* report, a total of 33 countries around the world currently have government initiatives in quantum technology, of which more than 20 have national strategies with large-scale funding.

It's a fitting tribute, then, that the United Nations (UN) has chosen 2025 to be the International Year of Quantum Science and Technology (IYQ). The hope is that the year will raise global awareness of quantum physics and its applications. The UN also aims to highlight the myriad potential future applications of quantum technologies and how they could help tackle universal issues – from climate and clean energy to health and infrastructure – while also addressing the UN's sustainable development goals.

The Institute of Physics (IOP), which publishes *Physics World*, is one of the IYQ's six "founding partners" alongside the German and American physical societies, SPIE, Optica and the Chinese Optical Society. "The UNESCO International Year of Quantum is a wonderful opportunity to spread the word about quantum research and technology and the transformational opportunities it is opening up" says Tom Grinyer, chief executive of the IOP. "The Institute of Physics is co-ordinating the UK and Irish elements of the year, which mark the 100th anniversary of the first formulation of quantum mechanics, and we are keen to celebrate the milestone, making sure that as many people as possible get the opportunity to find out more about this fascinating area of science and technology," he adds.

Tim Smith, head of portfolio development at IOP Publishing, echoes those thoughts. "Quantum science and technology represents one of the most exciting and rapidly developing areas of science today" he says, "encompassing the global physical-sciences community in a way that connects scientific wonder with fundamental research, technological innovation, industry, and funding programmes worldwide."

Taking shape

The official opening ceremony for IYQ took place on 4–5 February at the UNESCO headquarters in Paris, France, although several countries, including Germany and India, held their own launches in advance of the main event . Working together, the IOP and IOP Publishing have developed a wide array of quantum resources, talks, conferences, festivals and public-themed events planned as a part of the UK's celebrations for IYQ.

In February, the Royal Society – the world's oldest continuously active learned society – hosted a two-day "Quantum information" conference that served as the UK and Ireland launch of IYQ, with opening talks from Grinyer and quantum physicist Peter Knight, co-chair of the IYQ steering committee. The conference brought together scientists, industry leaders and public-sector officials to discuss the challenges of quantum computing, networks and sensing systems.

The *Economist*'s fourth annual *Commercialising Quantum Global* conference on 13–14 May focused on the theme of "From qubits to profits: achieving near-term quantum advantage". The event also saw the announcement of the winner of the IOP's quantum Business Innovation and Growth (qBIG) Prize, which is awarded to small and

medium-sized companies working on taking quantum technology products or solutions to market in the UK and Ireland.

In Scotland, the Quantum Software Lab at the School of Informatics at the University of Edinburgh is hosting a "Quantum Fringe 2025" event through June and July. It will include a quantum machine-learning school on the Isle of Skye and well as the annual UK Quantum Hackathon, which brings together teams of aspiring coders with industry mentors to tackle practical challenges and develop solutions using quantum computing.

In June, the IOP will run a week-long parliamentary exhibition at the House of Commons, to make parliamentarians more aware of the quantum sector, as well as its impacts on the economy and society. June also sees the Institution of Engineering and Technology hosting a Quantum Engineering and Technologies conference, as part of its newly launched Quantum technologies and 6G and Future Networks events.

Further IYQ-themed events will take place at public engagement programmes for families and younger children throughout the summer, while QuAMP, the IOP's biennial international conference on quantum, atomic and molecular physics, will take place in September.

The year's activities culminate in a week of celebrations in November, to coincide with the UK National Quantum Technologies Showcase. Events include the National Physical Laboratory's "Quantum Metrology: From Foundations to the Future" on 3 November, which will bring global experts together to discuss the history and future impact of metrology on quantum science.

On 4 and 5 November, the IOP will run its "quantum community celebration" events, with the two days led by the IOP's history of physics and qBIG special interest groups. The week will also include a schools event at the Royal Institution, and a public celebration with a keynote speech from University of Surrey quantum physicist and broadcaster Jim Al-Khalili.

The IOP will use the focus this year gives us to continue to make the case for the investment in research and development, and support for physics skills, which will be crucial if we are to fully unlock the economic and social potential of the quantum sector

"The UK and Ireland already have a globally important position in many areas of quantum research, with the UK, for instance, having established one of the world's first National Quantum Technology Programmes," explains Grinyer. "We will also be using the focus this year gives us to continue to make the case for the investment in research and development, and support for physics skills, which will be crucial if we are to fully unlock the economic and social potential of what is both a fascinating area of research, and a fast growing physics-powered business sector," he adds.

Quantum careers

With the booming quantum marketplace, it's no surprise that employers are on the hunt for many skilled physicists to join the workforce. And indeed, there is a significant scarcity of skilled quantum professionals for the many roles across industry and academia. Also, with quantum research advancing everything from software and machine learning to materials science and drug discovery, physicists' skills will be transferable across the board.

If you plan to join the quantum workforce, then choosing the right PhD programme, having the right skills for a specific role and managing risk and reward in the emerging quantum industry are all crucial. There are a number of careers events on the IYQ calendar, to learn more about the many career prospects for physicists in the sector. In April, for example, the University of Bristol's Quantum Engineering Centre for Doctoral Training hosted a Careers in Quantum event that featured talks, panel discussions and exhibitors from a plethora of companies from across the quantum ecosystem.

To learn more about "How quantum tech is boosting quantum fundamentals", be sure to tune in to our live quantum panel discussion on 17 June, as part of our newly launched Physics World Live. This year's *Physics World Careers 2025* guide also has a special quantum focus. The *Physics World* quantum channel (physicsworld.com/quantum) will be regularly updated throughout the year so you don't miss a thing.

Read all about it

IOP Publishing's journals will include specially curated content – from a series of Perspectives articles – personal viewpoints from leading quantum scientists – in *Quantum Science and Technology* (see an interview with Mauro Paternostro, editor-in-chief of the journal, pp 51–53). The journal will also be publishing roadmaps in quantum computing, sensing and communication, as well as focus issues on topics such as quantum machine learning and technologies for quantum gravity and thermodynamics in quantum coherent platforms.

"Going right to the core of IOP Publishing's own historic coverage we're excited to be celebrating the IYQ through a year-long programme of articles in *Physics World* and across our journals, that will hopefully show a wide audience just why everyone should care about quantum science and the people behind it," says Smith.

Of course, we at *Physics World* have a Schrödinger's box full of fascinating quantum articles for the coming year – from historical features to the latest cutting-edge developments in quantum tech. So keep your eyes peeled.

Tushna Commissariat is a features editor of *Physics World*

Return to Helgoland: the centenary of quantum mechanics

One of the most significant events in the International Year of Quantum Science and Technology is a workshop being held in June 2025 in Helgoland – the island where Werner Heisenberg laid the foundations for quantum mechanics 100 years ago. **Robert P Crease** asks delegates what they'll be discussing and wonders whether Heisenberg's work was as definitive as we like to think

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

At 3 a.m. one morning in June 1925, an exhausted, allergy-ridden 23-year old climbed a rock at the edge of a small island off the coast of Germany in the North Sea. Werner Heisenberg, who was an unknown physics postdoc at the time, had just cobbled together, in crude and unfamiliar mathematics, a framework that would shortly become what we know as "matrix mechanics". If we insist on pegging the birth of quantum mechanics to a particular place and time, Helgoland in June 1925 it is.

Heisenberg's work a century ago is the reason why the United Nations has proclaimed 2025 to be the International Year of Quantum Science and Technology. It's a global initiative to raise the public's awareness of quantum science and its applications, with numerous activities in the works throughout the year. One of the most significant events for physicists will be a workshop running from 9–14 June on Helgoland, exactly 100 years on from the very place where quantum mechanics supposedly began.

Entitled "Helgoland 2025", the event is designed to honour Heisenberg's development of matrix mechanics, which organizers have dubbed "the first formulation of quantum theory". The workshop, they say, will explore "the increasingly fruitful intersection between the foundations of quantum mechanics and the application of these foundations in real-world settings".

But why was Heisenberg's work so vital to the development of quantum mechanics? Was it really as definitive as we like to think? And is the oft-repeated Helgoland story really true?

How it all began

The events leading up to Heisenberg's trip can be traced back to the work of Max Planck in 1900. Planck was trying to produce a formula for how certain kinds of materials absorb and emit light depending on energy. In what he later referred to as an "act of sheer desperation", Planck found himself having to use the idea of the "quantum", which implied that electromagnetic radiation is not continuous but can be absorbed and emitted only in discrete chunks.

Standing out as a smudge on the beautiful design of classical physics, the idea of quantization appeared of limited use. Some physicists called it "ugly", "grotesque" and "distasteful"; it was surely a theoretical sticking plaster that could soon be peeled off. But the quantum proved indispensable, cropping up in more and more branches of physics, including the structure of the hydrogen atom, thermodynamics and solid-state physics. It was like an obnoxious visitor whom you try to expel from your house but can't. Worse, its presence seemed to grow. The quantum, remarked one scientist at the time, was a "lusty infant".

> **"Quantum theory" was like having instructions for how to get from place A to place B. What you really wanted was a "quantum mechanics" – a map that showed you how to go from any place to any other**

Attempts to domesticate that infant in the first quarter of the 20th century were made not only by Planck but other physicists too, such as Wolfgang Pauli, Max Born, Niels Bohr and Ralph Kronig. They succeeded only in producing rules for calculating certain phenomena that started with classical theory and imposed conditions. "Quantum theory" was like having instructions for how to get from place A to place B. What you really wanted was a "quantum mechanics" – a map that, working with one set of rules, showed you how to go from any place to any other.

Heisenberg was a young crusader in this effort. Born on 5 December 1901 – the year after Planck's revolutionary discovery – Heisenberg had the character often associated with artists, with dashing looks, good musicianship and a physical frailty including a severe vulnerability to allergies. That summer in 1923, Heisenberg had just finished his PhD under Arnold Sommerfeld at the Ludwig Maximilian University in Munich and was starting a postdoc with Born at the University of Göttingen.

Like others, Heisenberg was stymied in his attempts to develop a mathematical framework for the frequencies, amplitudes, orbitals, positions and momenta of quantum phenomena. Maybe, he wondered, the trouble was trying to cast these phenomena in a Newtonian-like visualizable form. Instead of treating them as classical properties with specific values, he decided to look at them in purely mathematical terms as operators acting on functions. It was then that an "unfortunate personal setback" occurred.

Destination Helgoland

Referring to a bout of hay fever that had wiped him out, Heisenberg asked Born for a two-week leave of absence from Göttingen and took a boat to Helgoland. The island, which lies some 50 km off Germany's mainland, is barely 1 km^2 in size. However, its strategic military location had given it an outsized history that saw it swapped several times between different European powers. Part of Denmark from 1714, the island was occupied by Britain in 1807 before coming under Germany's control in 1890.

During the First World War, Germany turned the island into a military base and evacuated all its residents. By the time Heisenberg arrived, the soldiers had long gone and Helgoland was starting to recover its reputation as a centre for commercial fishing and a bracing tourist destination. Most importantly for Heisenberg, it had fresh winds and was remote from allergen producers.

Heisenberg arrived at Helgoland on Saturday 6 June 1925 coughing and sneezing, and with such a swollen face that his landlady decided he had been in a fight. She installed him in a quiet room on the second floor of her *Gasthaus* that overlooked the beach and the North Sea. But he didn't stop working. "What exactly happened on that barren, grassless island during the next ten days has been the subject of much speculation and no little romanticism," wrote historian David Cassidy in his definitive 1992 book *Uncertainty: The Life and Science of Werner Heisenberg*.

Into a new world
It was on the island of Helgoland off the coast of Germany in June 1925 that Werner Heisenberg created matrix mechanics.

iStock/Christian Horz

IanDagnall Computing/Alamy Stock Photo

Delicate figure Werner Heisenberg was said to be sensitive, good looking and talented at music but vulnerable to allergies.

Max-Planck-Institute, courtesy of AIP Emilio Segrè Visual Archives

That winning feeling Werner Heisenberg (right) won the 1932 Nobel Prize for Physics "for the creation of quantum mechanics". He was given the prize in December 1933, with that year's award shared by Paul Dirac and Erwin Schrödinger, shown here (left) with Crown Prince Gustav Adolf, later King of Sweden (middle) at the Nobel ceremony in Stockholm.

In Heisenberg's telling, decades later, he kept turning over all he knew and began to construct equations of observables – of frequencies and amplitudes – in what he called "quantum-mechanical series". He outlined a rough mathematical scheme, but one so awkward and clumsy that he wasn't even sure it obeyed the conservation of energy, as it surely must. One night Heisenberg turned to that issue.

"When the first terms seemed to accord with the energy principle, I became rather excited," he wrote much later in his 1971 book *Physics and Beyond*. But he was still so tired that he began to stumble over the maths. "As a result, it was almost three o'clock in the morning before the final result of my computations lay before me." The work still seemed finished yet incomplete – it succeeded in giving him a glimpse of a new world though not one worked out in detail – but his emotions were weighted with fear and longing.

"I was deeply alarmed," Heisenberg continued. "I had the feeling that, through the surface of atomic phenomena, I was looking at a strangely beautiful interior, and felt almost giddy at the thought that I now had to probe this wealth of mathematical structure nature had so generously spread out before me. I was far too excited to sleep and so, as a new day dawned, I made for the southern tip of the island, where I had been longing to climb a rock jutting out into the sea. I now did so without too much trouble, and waited for the sun to rise."

To modern ears, Heisenberg's comments may seem unremarkable. But his proposition certainly would have been nearly unthinkable to those steeped in Newtonian mechanics

What happened on Helgoland?

Historians are suspicious of Heisenberg's account. In their 2023 book *Constructing Quantum Mechanics Volume 2: The Arch 1923–1927*, Anthony Duncan and Michel Janssen suggest that Heisenberg made "somewhat less progress in his visit to Helgoland in June 1925 than later hagiographical accounts of this episode claim". They believe that Heisenberg, in *Physics and Beyond*, may "have misremembered exactly how much he accomplished in Helgoland four decades earlier".

What's more – as Cassidy wondered in *Uncertainty* – how could Heisenberg have been so sure that the result agreed with the conservation of energy without having carted all his reference books along to the island, which he surely had not. Could it really be, Cassidy speculated sceptically, that Heisenberg had memorized the relevant data?

Alexei Kojevnikov – another historian – even doubts that Heisenberg was entirely candid about the reasons behind his inspiration. In his 2020 book *The Copenhagen Network: The Birth of Quantum Mechanics from a Postdoctoral Perspective*, Kojevnikov notes that fleeing from strong-willed mentors such as Bohr, Born, Kronig, Pauli and Sommerfeld was key to Heisenberg's creativity. "In order to accomplish his most daring intellectual breakthrough," Kojevnikov writes, "Heisenberg had to escape from the authority of his academic supervisors into the temporary loneliness and freedom on a small island in the North Sea."

Whatever did occur on the island, one thing is clear. "Heisenberg had his breakthrough," decides Cassidy in his book. He left Helgoland 10 days after he arrived, returned to Göttingen, and dashed off a paper that was published in *Zeitschrift für Physik* in September 1925 (**33** 879). In the article, Heisenberg wrote that "it is not possible to assign a point in space that is a function of time to an electron by means of observable quantities." He then suggested that "it seems more advisable to give up completely on any hope of an observation of the hitherto-unobservable quantities (such as the position and orbital period of the electron)."

Helgoland 2025: have you packed your tent?

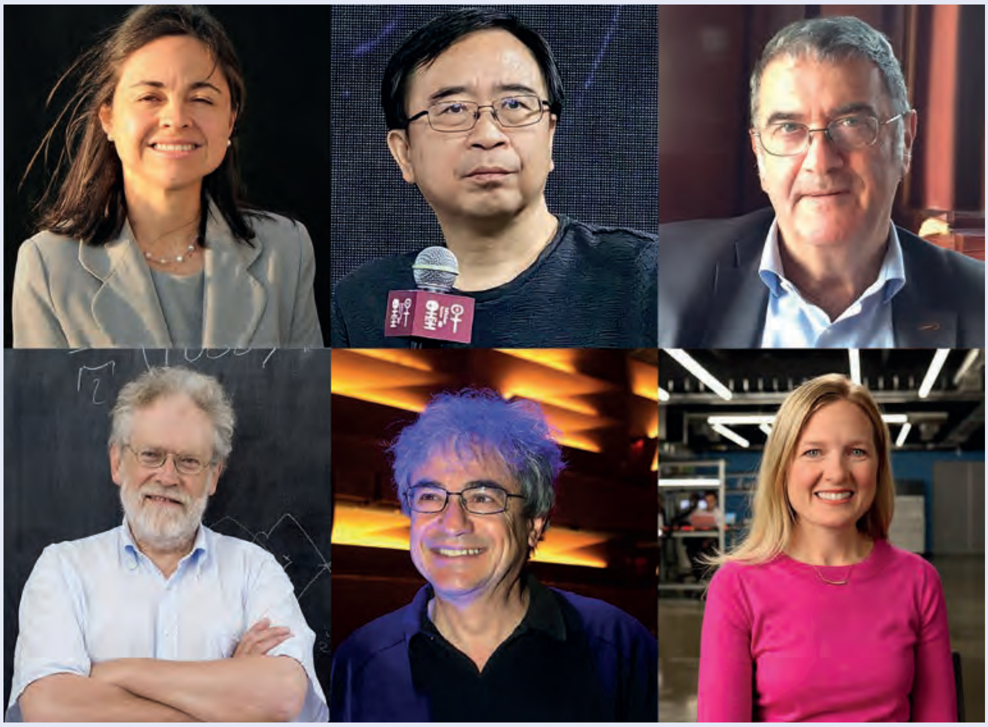
Running from 9–14 June 2025 on the island where Werner Heisenberg did his pioneering work on quantum mechanics, the Helgoland 2025 workshop is a who's who of quantum physics. Five Nobel laureates in the field of quantum foundations are coming. David Wineland and Serge Haroche, who won in 2012 for measuring and manipulating individual quantum systems, will be there. So too will Alain Aspect, John Clauser and Anton Zeilinger, who were honoured in 2022 for their work on quantum-information science.

There'll be Charles Bennett and Gilles Brassard, who pioneered quantum cryptography, quantum teleportation and other applications, as well quantum-sensing guru Carlton Caves. Researchers from industry are intending to be present, including Krysta Svore, who's vice-president of Microsoft Quantum.

Other attendees are from the intersection of foundations and applications. There will be researchers working on gravitation, mostly from quantum gravity phenomenology, where the aim is to seek experimental signatures of the effect. Others work on quantum clocks, quantum cryptography, and innovative ways of controlling light, such as using squeezed light at LIGO, to detect gravitational waves.

The programme starts in Hamburg on 9 June with a banquet and a few talks. Attendees will then take a ferry to Helgoland the following morning for a week of lectures, panel discussions and poster sessions. All talks are plenary, but in the evenings panels of a half-dozen or so people will address bigger questions familiar to every quantum physicist but rarely discussed in research papers. What is it about quantum mechanics, for instance, that makes it so compatible with so many interpretations?

If you're thinking of going, you're almost certainly out of luck. Registration closed in April 2024, while hotels, Airbnb and Booking.com venues are nearly exhausted. Participants are having to share double rooms or invited to camp on the beaches – with their own gear.



Entangled minds Helgoland 2025 boasts a who's who of quantum physics including (clockwise from top right) Serge Haroche, Krysta Svore, Carlo Rovelli, Anton Zeilinger, Ana Maria Rey and Jan-Wei Pan.

To modern ears, Heisenberg's comments may seem unremarkable. But his proposition certainly would have been nearly unthinkable to those steeped in Newtonian mechanics. Of course, the idea of completely abandoning the observability of those quantities wasn't quite true. Under certain conditions, it can make sense to speak of observing them. But they certainly captured the direction he was taking.

The only trouble was that his scheme, with its "quantum-mechanical relations", produced formulae that were "noncommutative" – a distressing asymmetry that was surely an incorrect feature in a physical theory. Heisenberg all but shoved this feature under the rug in his *Zeitschrift für Physik* article, where he relegated the point to a single sentence.

The more mathematically trained Born, on the other hand, sensed something familiar about the maths and soon recognized that Heisenberg's bizarre "quantum-mechanical relations" with their strange tables were what mathematicians called matrices. Heisenberg was unhappy with that particular name for his work, and considered returning to what he had called "quantum-mechanical series".

Fortunately, he didn't, for it would have made the rationale for the Helgoland 2025 conference clunkier to describe. Born was delighted with the connection to traditional mathematics. In particular he found that when the matrix p associated with momentum and the matrix q associated with position are multiplied in different orders, the difference between them is proportional to Planck's constant, h.

As Born wrote in his 1956 book *Physics in My Generation*: "I shall never forget the thrill I experienced when I succeeded in condensing Heisenberg's ideas on quantum conditions in the mysterious equation $pq - qp = h/2\pi i$, which is the centre of the new mechanics and was later found to imply the uncertainty relations". In February 1926, Born, Heisenberg and Jordan published a landmark paper that worked out the implications of this equation (*Zeit. Phys.* **35** 557). At last, physicists had a map of the quantum domain.

Almost four decades later in an interview with the historian Thomas Kuhn, Heisenberg recalled Pauli's "extremely enthusiastic" reaction to the developments. "[Pauli] said something like '*Morgenröte einer Neuzeit*'," Heisenberg told Kuhn. "The dawn of a new era." But it wasn't entirely smooth sailing after that dawn. Some physicists were unenthusiastic about Heisenberg's new mechanics, while others were outright sceptical.

Yet successful applications kept coming. Pauli applied the equation to light emitted by the hydrogen atom and derived the Balmer formula, a rule that had been known empirically since the mid-

Nathalie de Leon: heading for Helgoland

Princeton University/Sameer A Khan

Precision thinker Nathalie de Leon from Princeton University is one of the researchers invited to the Helgoland meeting in June 2025.

In June 2022, Nathalie de Leon, a physicist at Princeton University working on quantum computing and quantum metrology, was startled to receive an invitation to the Helgoland conference. "It's not often you get [one] a full three years in advance," says de Leon, who also found it unusual that participants had to attend for the entire six days. But she was not surprised at the composition of the conference with its mix of theorists, experimentalists and people applying what she calls the "weirder" aspects of quantum theory.

"When I was a graduate student [in the late 2000s], it was still the case that quantum theorists and researchers who built things like quantum computers were well aware of each other but they didn't talk to each other much," she recalls. "In their grant proposals, the physicists had to show they knew what the computer scientists were doing, and the computer scientists had to justify their work with appeals to physics. But they didn't often collaborate." De Leon points out that over the last five or 10 years, however, more and more opportunities for these groups to collaborate have emerged. "Companies like IBM, Google, QuEra and Quantinuum now have theorists and academics trying to develop the hardware to make quantum tech a practical reality," she says.

Some quantum applications have even cropped up in highly sophisticated technical devices, such as the huge Laser Interferometer Gravitational Wave Observatory (LIGO). "A crazy amount of classical engineering was used to build this giant interferometer," says de Leon, "which got all the way down to a minuscule sensitivity. Then as a last step the scientists injected something called squeezed light, which is a direct consequence of quantum mechanics and quantum measurement." According to de Leon, that squeezing let us see something like eight times more of the universe. "It's one of the few places where we get a real tangible advantage out of the strangeness of quantum mechanics," she adds.

Other, more practical benefits are also bound to emerge from quantum information theory and quantum measurement. "We don't yet have quantum technologies on the open consumer market in the same way we have lasers you can buy on Amazon for $15," de Leon says. But groups gathering in Helgoland will give us a better sense of where everything is heading. "Things," she adds, "are moving so fast."

A century on from Heisenberg's visit to Helgoland, quantum mechanics still has physicists scratching their heads

1880s. Then, in one of the most startling coincidences in the history of science, the Austrian physicist Erwin Schrödinger produced a complete map of the quantum domain stemming from a much more familiar mathematical basis called "wave mechanics". Crucially, Heisenberg's matrix mechanics and Schrödinger's maps turned out to be identical.

Even more fundamental implications followed. In an article published in *Naturwissenschaften* (**14** 899) in September 1926, Heisenberg wrote that our "ordinary intuition" does not work in the subatomic realm. "Because the electron and the atom possess not any degree of physical reality as the objects of our daily experience," he said, "investigation of the type of physical reality which is proper to electrons and atoms is precisely the subject of quantum mechanics."

Quantum mechanics, alarmingly, was upending reality itself, for the uncertainty it introduced was not only mathematical but "ontological" – meaning it had to do with the fundamental features of the universe. Early the next year, Heisenberg, in correspondence with Pauli, derived the equation $\Delta p \, \Delta q \geq h/4\pi$, the "uncertainty principle", which became the touchstone of quantum mechanics. The birth complications, however, persisted. Some even got worse.

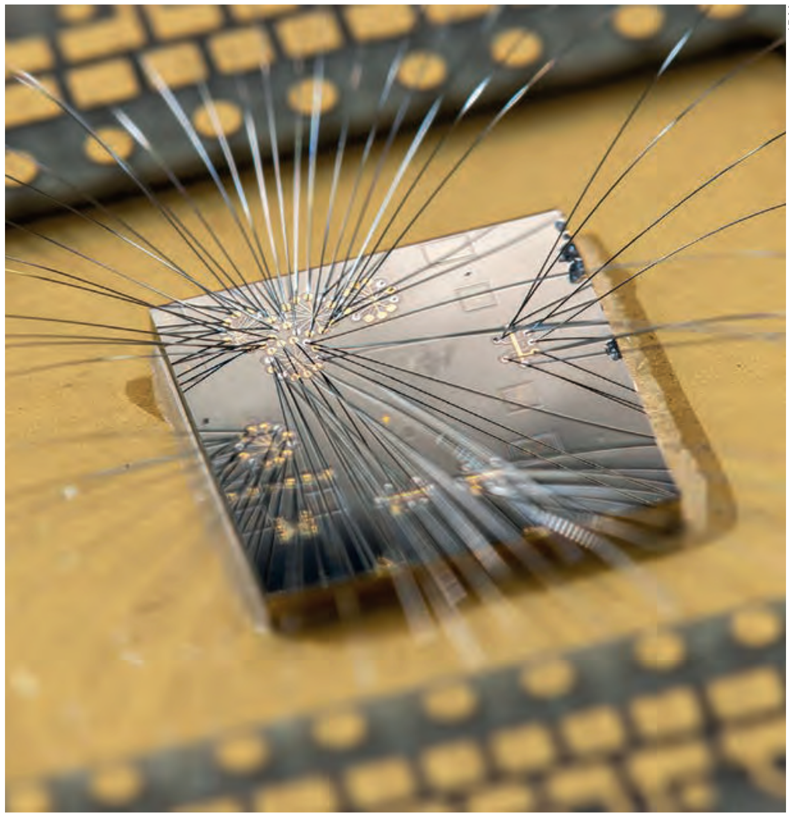
Catalytic conference

A century on from Heisenberg's visit to Helgoland, quantum mechanics still has physicists scratching their heads. "I think most people agree that we are still trying to make sense of even basic non-relativistic quantum mechanics," admits Jack Harris, a quantum physicist at Yale University who is co-organizing Helgoland 2025 with Časlav Brukner, Steven Girvin and Florian Marquardt.

"We really don't fully understand the quantum world yet," adds Igor Pikovsky from the Stevens Institute in New Jersey, who works in gravitational phenomena and quantum optics. "We apply it, we generalize it, we develop quantum field theories and so on, but still a lot of it is uncharted territory." Philosophers and quantum physicists with strong opinions have debated interpretations and foundational issues for a long time, he points out, but the results of those discussions have been unclear.

Helgoland 2025 hopes to change all that. Advances in experimental techniques let us ask new kinds of fundamental questions about quantum mechanics. "You have new opportunities for studying quantum physics at completely different scales," says Pikovsky. "You can make macroscopic, Schrödinger-cat-like systems, or very massive quantum systems to test. You don't need to debate philosophically about whether there's a measure-

Helgoland 2025 will focus on the two-way street between foundations and applications in what promises to be a unique event



IBM

ment problem or a classical-quantum barrier – you can start studying these questions experimentally."

One phenomenon fundamental to the puzzle of quantum mechanics is entanglement, which prevents the quantum state of a system from being described independently of the state of others. Thanks to the Einstein–Podolsky–Rosen (EPR) paper of 1935 (*Phys. Rev.* **47** 777), Chien-Shiung Wu and Irving Shaknov's experimental demonstration of entanglement in extended systems in 1949, and John Bell's theorem in 1964 (*Physics* **1** 195), physicists know that entanglement in extended systems is a large part of what's so weird about quantum mechanics.

Understanding all that entanglement entails, in turn, has led physicists to realize that information is a fundamental physical concept in quantum mechanics. "Even a basic physical quantum system behaves differently depending on how information about it is stored in other systems," Harris says. "That's a starting point both for deep insights into what quantum mechanics tells us about the world, and also for applying it."

Helgoland 2025 will therefore focus on the two-way street between foundations and applications in what promises to be a unique event. "The conference is intended to be a bit catalytic," Harris adds. "[There will be] people who didn't realize that others were working on similar issues in different fields, and a lot of people who will never have met each other". The disciplinary diversity will be augmented by the presence of students as well as poster sessions, which tend to bring in an even broader variety of research topics.

One of those looking forward to such encounters is Ana Maria Rey – a theoretical physicist at the University of Colorado, Boulder, and a JILA fellow who studies quantum phenomena in ways that have improved atomic clocks and quantum computing. "There will be people who work on black holes whose work is familiar to me but who I haven't met yet," she says. Finding people should be easy: Helgoland is tiny and only a hand-picked group of people have been invited to attend (see the box "Helgoland 2025: have you packed your tent?", p27).

What's also unusual about Helgoland is that it has as many practically-minded as theoretically-minded participants. But that doesn't faze Magdalena Zych, a physicist from Stockholm University in Sweden. "I'm biased because academically I grew up in Vienna, where Anton Zeilinger's group always had people working on theory and applications," she says.

Zych's group has, for example, recently discovered a way to use the uncertainty principle to get a better understanding of the semi-classical space–time trajectories of composite particles. She plans to talk about this research at Helgoland, finding it appropriate given that it relies on Heisenberg's principle, is a product of specific theoretical work and is valid more generally. "It relates to the arch of the conference, looking both backwards and forwards, and from theory to applications."

Sadly, participants will not be able to visit Heisenberg's Gasthaus, nor any other building where he might have been. During the Second World War, Germany again relocated Helgoland's inhabitants and turned the island into a military base. After the war, the Allies piled up unexploded ordinances on the island and set them off, in what is said to be one of the biggest conventional explosions in history. The razed homeland was then given back to its inhabitants.

Helgoland still has rocky outcroppings at its southern end, one of which may or may not be the site of Heisenberg's early morning climb and vision. But despite the powerful mythology of his story, participants at Helgoland 2025 are not being asked to herald another dawn. "We will not," says Harris, "be 300 Heisenbergs going for hikes. We certainly won't be trying to get away from each other."

The historian of science Mario Biagioli once wrote an article entitled "The scientific revolution is undead", underlining how arbitrary it is to pin key developments in science – no matter how influential or long-lasting – to specific beginnings and endings, for each new generation of scientists finds ever more to mine in the radical discoveries of predecessors. With so many people working on so many foundational issues set to be at Helgoland 2025, new light is bound to emerge. A century on, the quantum revolution is alive and well. ■

Strange world We might not fully understand quantum physics, but novel experimental techniques are helping us to make progress, while applications in areas such as quantum computing and cryptography are booming.

When Bohr got it wrong

Philip Ball peers into the quantum past, and uncovers a little-known paper published by Niels Bohr, Hendrik Kramers and John Slater in 1924, that proposed that the first law of thermodynamics may no longer hold firm. Their idea turned out to be wrong, but in interesting and provocative ways, and it demonstrates the intense turmoil in physics on the brink of quantum mechanics

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One hundred and one years ago, Danish physicist Niels Bohr proposed a radical theory together with two young colleagues – Hendrik Kramers and John Slater – in an attempt to resolve some of the most perplexing issues in fundamental physics at the time. Entitled "The Quantum Theory of Radiation", and published in the *Philosophical Magazine*, their hypothesis was quickly proved wrong, and has since become a mere footnote in the history of quantum mechanics.

Despite its swift demise, their theory perfectly illustrates the sense of crisis felt by physicists at that moment, and the radical ideas they were prepared to contemplate to resolve it. For in their 1924 paper Bohr and his colleagues argued that the discovery of the "quantum of action" might require the abandonment of nothing less than the first law of thermodynamics: the conservation of energy.

As we celebrate the centenary of Werner Heisenberg's 1925 quantum breakthrough with the International Year of Quantum Science and Technology (IYQ) 2025, Bohr's 1924 paper offers a lens through which to look at how the quantum revolution unfolded. Most physicists at that time felt that if anyone was going to rescue the field from the crisis, it would be Bohr. Indeed, this attempt clearly shows signs of the early rift between Bohr and Albert Einstein about the quantum realm, that would turn into a lifelong argument. Remarkably, the paper also drew on an idea that later featured in one of today's most prominent alternatives to Bohr's "Copenhagen" interpretation of quantum mechanics.

Genesis of a crisis

The quantum crisis began when German physicist Max Planck proposed the quantization of energy in 1900, as a mathematical trick for calculating the spectrum of radiation from a warm, perfectly absorbing "black body". Later, in 1905, Einstein suggested taking this idea literally to account for the photoelectric effect, arguing that light consisted of packets or quanta of electromagnetic energy, which we now call photons.

Bohr entered the story in 1912 when, working in the laboratory of Ernest Rutherford in Manchester, he devised a quantum theory of the atom. In Bohr's picture, the electrons encircling the atomic nucleus (that Rutherford had discovered in 1909) are constrained to specific orbits with quantized energies. The electrons can hop in "quantum jumps" by emitting or absorbing photons with the corresponding energy.

Bohr had no theoretical justification for this *ad hoc* assumption, but he showed that, by accepting it, he could predict (more or less) the spectrum of the hydrogen atom. For this work Bohr was awarded the 1922 Nobel Prize for Physics, the same year that Einstein collected the prize for his work on light quanta and the photoelectric effect (he had been awarded it in 1921 but was unable to attend the ceremony).

After establishing an institute of theoretical physics (now the Niels Bohr Institute) in Copenhagen in 1917, Bohr's mission was to find a true theory of the quantum: a mechanics to replace, at the atomic scale, the classical physics of Isaac Newton that worked at larger scales. It was clear that classical physics did not work at the scale of the atom, although Bohr's correspondence principle asserted that quantum theory should give the same results as classical physics at a large enough scale.

Quantum theory was at the forefront of physics at the time, and so was the most exciting topic for any aspiring young physicist. Three groups stood out as the most desirable places to work for anyone seeking a fundamental mathematical theory to replace the makeshift and sometimes contradictory "old" quantum theory that Bohr had cobbled together: that of Arnold Sommerfeld in Münich, of Max Born in Göttingen, and of Bohr in Copenhagen.

Dutch physicist Hendrik Kramers had hoped to work on his doctorate with Born – but in 1916 the First World War ruled that out, and so he opted instead for Copenhagen, in politically neutral Denmark. There he became Bohr's assistant for ten years: as was the case with several of Bohr's students, Kramers did the maths (it was never Bohr's forte) while Bohr supplied the ideas, philosophy and kudos. Kramers ended up working on an impressive range of problems, from chemical physics to pure mathematics.

Reckless and radical

One of the most vexing question for Bohr and his Copenhagen circle in the early 1920s was how to think about electron orbits in atoms. Try as they might, they

Perhaps, in quantum systems like atoms, we have to abandon any attempt to construct a physical picture at all

Sam Falconer, Debut Art/Science Photo Library


Paul Ehrenfest/Wikimedia Commons

Conflicting views Stalwart physicists Albert Einstein and Niels Bohr had opposing views on quantum fundamentals from early on, which turned into a lifelong scientific argument between the two.


Wikimedia Commons

Mathematical mind Dutch physicist Hendrik Kramers spent 10 years as Niels Bohr's assistant in Copenhagen.

couldn't find a way to make the orbits "fit" with experimental observations of atomic spectra. Bohr and others, including Heisenberg, began to voice a possibility that seemed almost reckless: perhaps, in quantum systems like atoms, we have to abandon any attempt to construct a physical picture at all. Maybe we just can't think of quantum particles as objects moving along trajectories in space and time.

This struck others, such as Einstein, as desperate, if not crazy. Surely the goal of science had always been to offer a picture of the world in terms of "things happening to objects in space". What else could there be than that? How could we just give it all up?

But it was worse than that. For one thing, Bohr's quantum jumps were supposed to happen instantaneously: an electron, say, jumping from one orbit to another in no time at all. In classical physics, everything happens continuously: a particle gets from here to there by moving smoothly across the intervening space, in some finite time. The discontinuities of quantum jumps seemed to some – like Austrian physicist Erwin Schrödinger in Vienna – bordering on the obscene.

In 1924 these virtually heretical ideas were only beginning to surface, but they were creating such a sense of crisis that it seemed anything was possible

Worse still was the fact that while the old quantum theory stipulated the energy of quantum jumps, there was nothing to dictate when they would happen – they simply did. In other words, there was no causal kick that instigated a quantum jump: the electron just seemed to make up its own mind about when to jump. As Heisenberg would later proclaim in his 1927 paper on the uncertainty principle (*Zeitschrift für Physik* **43** 172), quantum theory "establishes the final failure of causality".

Such notions were not the only source of friction between the Copenhagen team and Einstein. Bohr didn't like light quanta. While they seemed to explain the photoelectric effect, Bohr was convinced that light had to be fundamentally wave-like, so that photons (to use the anachronistic term) were only a way of speaking, not real entities.

To add to the turmoil in 1924, the French physicist Louis de Broglie had, in his doctoral thesis for the Sorbonne, turned the quantum idea on its head by proposing that particles such as electrons might show wave-like behaviour. Einstein had at first considered this too wild, but soon came round to the idea.

Go where the waves take you

In 1924 these virtually heretical ideas were only beginning to surface, but they were creating such a sense of crisis that it seemed anything was possible. In the 1960s, science historian Paul Forman suggested that the feverish atmosphere in physics was part of an even wider cultural current. By rejecting causality and materialism, the German quantum physicists, Forman said, were attempting to align their ideas with a rejection of mechanistic thinking while embracing the irrational – as was the fashion in the philosophical and intellectual circles of the beleaguered Weimar republic. The idea has been hotly debated by historians and philosophers of science – but it was surely in Copenhagen, not Munich or Göttingen, that the most radical attitudes to quantum theory were developing.

Then, just before Christmas in 1923, a new student arrived at Copenhagen. John Clark Slater, who had a PhD in physics from Harvard, turned up at Bohr's institute with a bold idea. "You know those difficulties about not knowing whether light is old-fashioned waves or Mr Einstein's light particles", he wrote to his family during a spell in Cambridge that November. "I had a really hopeful idea… I have both the waves and the particles, and the particles are sort of carried along by the waves, so that the particles go where the waves take them." The waves were manifested in a kind of "virtual field" of some kind that spread throughout the system, and they acted to "pilot" the particles.

Emilio Segrè Visual Archives General Collection/MIT News Office

Particle pilot In 1923, US physicist John Clark Slater moved to Copenhagen, and suggested the concept of a "virtual field" that spread throughout a quantum system.

IPP/© Archives of the Max Planck Society

Experimental arbitrators German physicists Walther Bothe and Hans Geiger (right) conducted an experiment to explore the BKS paper, that looked at X-ray scattering from electrons to determine the conservation of energy at microscopic scales.

Bohr was mostly not a fan of Slater's idea, not least because it retained the light particles that he wished to dispose of. But he liked Slater's notion of a virtual field that could put one part of a quantum system in touch with others. Together with Slater and Kramers, Bohr prepared a paper in a remarkably short time (especially for him) outlining what became known as the Bohr-Kramers-Slater (BKS) theory. They sent it off to the *Philosophical Magazine* (where Bohr had published his seminal papers on the quantum atom) at the end of January 1924, and it was published in May (**47**(281) 785). As was increasingly characteristic of Bohr's style, it was free of any mathematics (beyond Einstein's quantum relationship $E=h\nu$).

In the BKS picture, an excited atom about to emit light can "communicate continually" with the other atoms around it via the virtual field. The transition, with emission of a light quantum, is then not spontaneous but induced by the virtual field. This mechanism could solve the long-standing question of how an atom "knows" which frequency of light to emit in order to reach another energy level: the virtual field effectively puts the atom "in touch" with all the possible energy states of the system.

The problem was that this meant the emitting atom was in instant communication with its environment all around – which violated the law of causality. Well then, so much the worse for causality: BKS abandoned it. The trio's theory also violated the conservation of energy and momentum – so they had to go too.

Causality and conservation, abandoned

But wait: hadn't these conservation laws been proved? In 1923 the American physicist Arthur Compton in Cambridge had shown that when light is scattered by electrons, they exchange energy, and the frequency of the light decreases as it gives up energy to the electrons. The results of Compton's experiments agreed perfectly with predictions made on the assumptions that light is a stream of quanta (photons) and that their collisions with electrons conserve energy and momentum.

Ah, said BKS, but that's only true statistically. The quantities are conserved on average, but not in individual collisions. After all, such statistical outcomes were familiar to physicists: that was the basis of the second law of thermodynamics, which presented the inexorable increase in entropy as a statistical phenomenon that need not constrain processes involving single particles.

The radicalism of the BKS paper got a mixed reception. Einstein, perhaps predictably, was dismissive. "Abandonment of causality as a matter of principle should be permitted only in the most extreme emergency", he wrote. Wolfgang Pauli, who had worked in Copenhagen in 1922–23, confessed to being "completely negative" about the idea. Born and Schrödinger were more favourable.

But the ultimate arbiter is experiment. Was energy conservation really violated in single-particle interactions? The BKS paper motivated others to find out. In early 1925, German physicists Walther Bothe and Hans Geiger in Berlin looked more closely at Compton's X-ray scattering by electrons. Having read the BKS paper, Bothe felt that "it was immediately obvious that this question would have to be decided experimentally, before definite progress could be made."

Geiger agreed, and the duo devised a scheme for detecting both the scattered electron and the scattered photon in separate detectors. If causality and energy conservation were preserved, the detections should be simultaneous; while any delay between them could indicate a violation. As Bothe would later recall "The 'question to Nature' which the experiment was designed to answer could therefore be formulated as follows: is it exactly a scatter quantum and a recoil electron that are simultaneously emitted in the elementary process, or is there merely a statistical relationship between the two?" It was incredibly painstaking work to seek such coincident detections using the resources then available.

Shutterstock/Vink Fan

Radical approach Despite its swift defeat, the BKS proposal showed how classical concepts could not apply to a quantum reality.

But in April 1925 Geiger and Bothe reported simultaneity within a millisecond – close enough to make a strong case that Compton's treatment, which assumed energy conservation, was correct. Compton himself, working with Alfred Simon using a cloud chamber, confirmed that energy and momentum were conserved for individual events (*Phys. Rev.* **26** 289).

Revolutionary defeat... singularly important

Bothe was awarded the 1954 Nobel Prize for Physics for the work. He shared it with Born for his work on quantum theory, and Geiger would surely have been a third recipient, if he had not died in 1945. In his Nobel speech, Bothe definitively stated that "the strict validity of the law of the conservation of energy even in the elementary process had been demonstrated, and the ingenious way out of the wave-particle problem discussed by Bohr, Kramers, and Slater was shown to be a blind alley."

Bohr was gracious in his defeat, writing to a colleague in April 1925 that "It seems… there is nothing else to do than to give our revolutionary efforts as honourable a funeral as possible." Yet he was soon to have no need of that particular revolution, for just a few months later Heisenberg, who had returned to Göttingen after working with Bohr in Copenhagen for six months, came up the first proper theory of quantum mechanics, later called matrix mechanics.

"In spite of its short lifetime, the BKS theory was singularly important," says historian of science Helge Kragh, now emeritus professor at the Niels Bohr Institute. "Its radically new approach paved the way for a greater understanding, that methods and concepts of classical physics could not be carried over in a future quantum mechanics."

The BKS paper was thus in a sense merely a mistaken curtain-raiser for the main event. But the Bothe-Geiger experiment that it inspired was not just an important milestone in early particle physics. It was also a crucial factor in Heisenberg's argument that the probabilistic character of his matrix mechanics (and also of Schrödinger's 1926 version of quantum mechanics, called wave mechanics) couldn't be explained away as a statistical expression of our ignorance about the details, as it is in classical statistical mechanics.

The Bothe-Geiger experiment that [the paper] inspired was not just an important milestone in early particle physics. It was also a crucial factor in Heisenberg's argument [about] the probabilistic character of his matrix mechanics

Rather, the probabilities that emerged from Heisenberg's and Schrödinger's theories applied to individual events: they were, Heisenberg said, fundamental to the way single particles behave. Schrödinger was never happy with that idea, but today it seems inescapable.

Over the next few years, Bohr and Heisenberg argued that the new quantum mechanics indeed smashed causality and shattered the conventional picture of reality as an objective world of objects moving in space–time with fixed properties. Assisted by Born, Wolfgang Pauli and others, they articulated the "Copenhagen interpretation", which became the predominant vision of the quantum world for the rest of the century.

Failed connections

Slater wasn't at all pleased with what became of the idea he took to Copenhagen. Bohr and Kramers had pressured him into accepting their take on it, "without the little lump carried along on the waves", as he put it in mid-January. "I am willing to let them have their way", he wrote at the time, but in retrospect he felt very unhappy about his time in Denmark. After the BKS theory was disproved, Bohr wrote to Slater saying "I have a bad conscience in persuading you to our views".

Slater replied that there was no need for that. But in later life – after he had made a name for himself in solid-state physics – Slater admitted to a great deal of resentment. "I completely failed to make any connection with Bohr", he said in a 1963 interview with the historian of science Thomas Kuhn. "I fought with them [Bohr and Kramers] so seriously that I've never had any respect for those people since. I had a horrible time in Copenhagen." While most of Bohr's colleagues and students expressed adulation, Slater's was a rare dissenting voice.

But Slater might have reasonably felt more aggrieved at what became of his "pilot-wave" idea. Today, that interpretation of quantum theory is generally attributed to de Broglie – who intimated a similar notion in his 1924 thesis, before presenting the theory in more detail at the famous 1927 Solvay Conference – and to American physicist David Bohm, who revitalized the idea in the 1950s. Initially dismissed on both occasions, the de Broglie-Bohm theory has gained advocates in recent years, not least because it can be applied to a classical hydrodynamic analogue, in which oil droplets are steered by waves on an oil surface.

Whether or not it is the right way to think about quantum mechanics, the pilot-wave theory touches on the deep philosophical problems of the field. Can we rescue an objective reality of concrete particles with properties described by hidden variables, as Einstein had advocated, from the fuzzy veil that Bohr and Heisenberg seemed to draw over the quantum world? Perhaps Slater would at least be gratified to know that Bohr has not yet had the last word. ■

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

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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 longstanding 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".

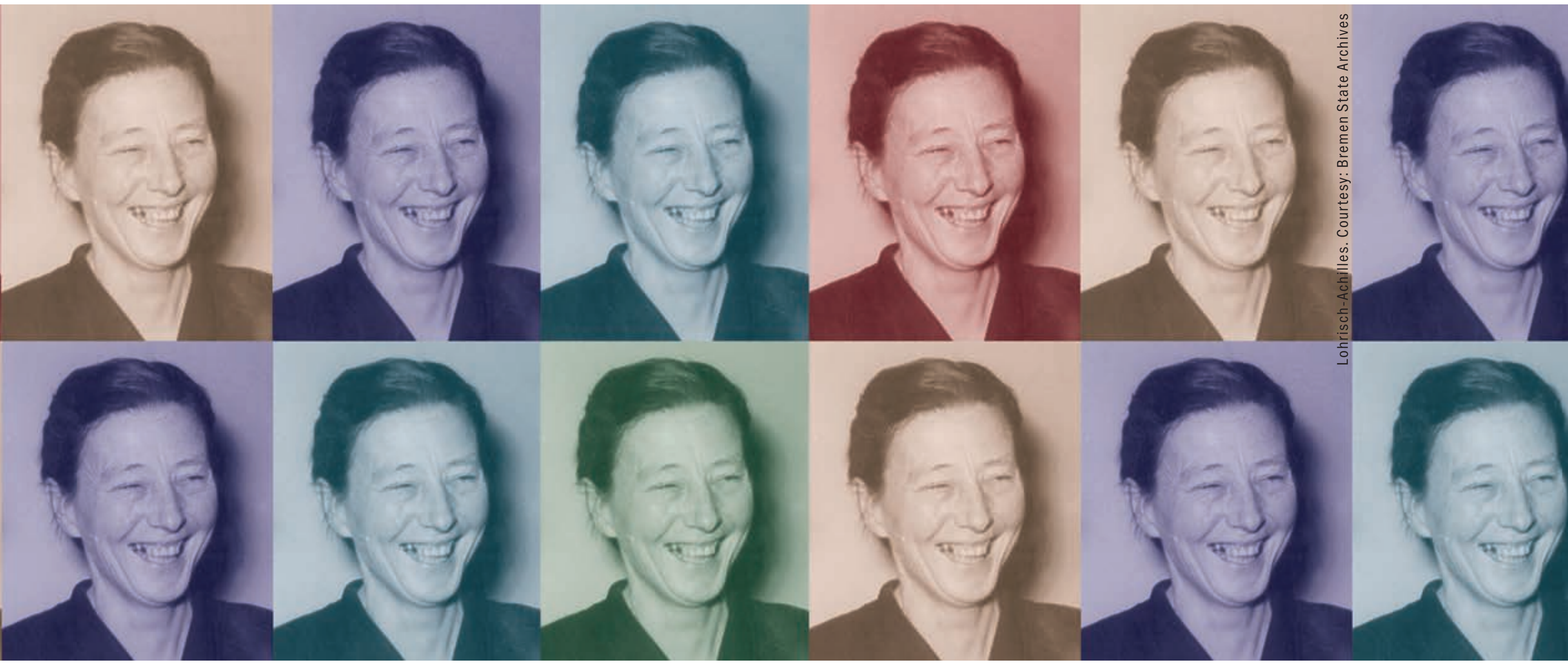
What's more, Hermann upended the famous "proof", developed by the Hungarian-American mathematician and physicist John von Neumann, that "hidden variables" are impossible in quantum mechanics. But why have Hermann's successes in studying the roots and meanings of quantum physics been so often overlooked? 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 – where she took a rigorous and broad programme of

physicist who was overlooked



Lohrisch-Achilles. Courtesy: Bremen State Archives

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

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.

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 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

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

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.

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 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

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 relationship between Kant's philosophy and modern science". Hermann herself paid tribute to Heisenberg in a

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.

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.

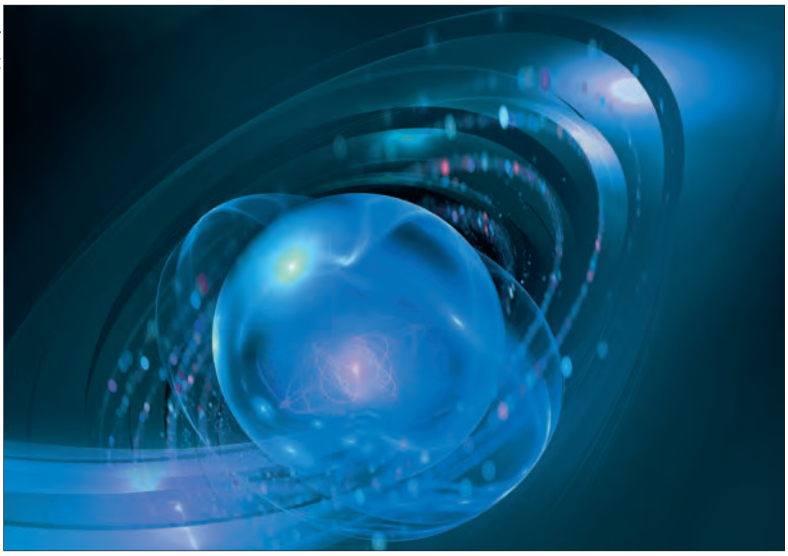
In making her argument about hidden variables, Hermann used her mathematical training to point out a flaw in von Neumann's famous 1932 proof, which said that no hidden-variable theory can ever reproduce the features of quantum mechanics. Quantum mechanics, according to von Neumann, is complete and no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

A frozen quantum arrow: the quantum Zeno effect

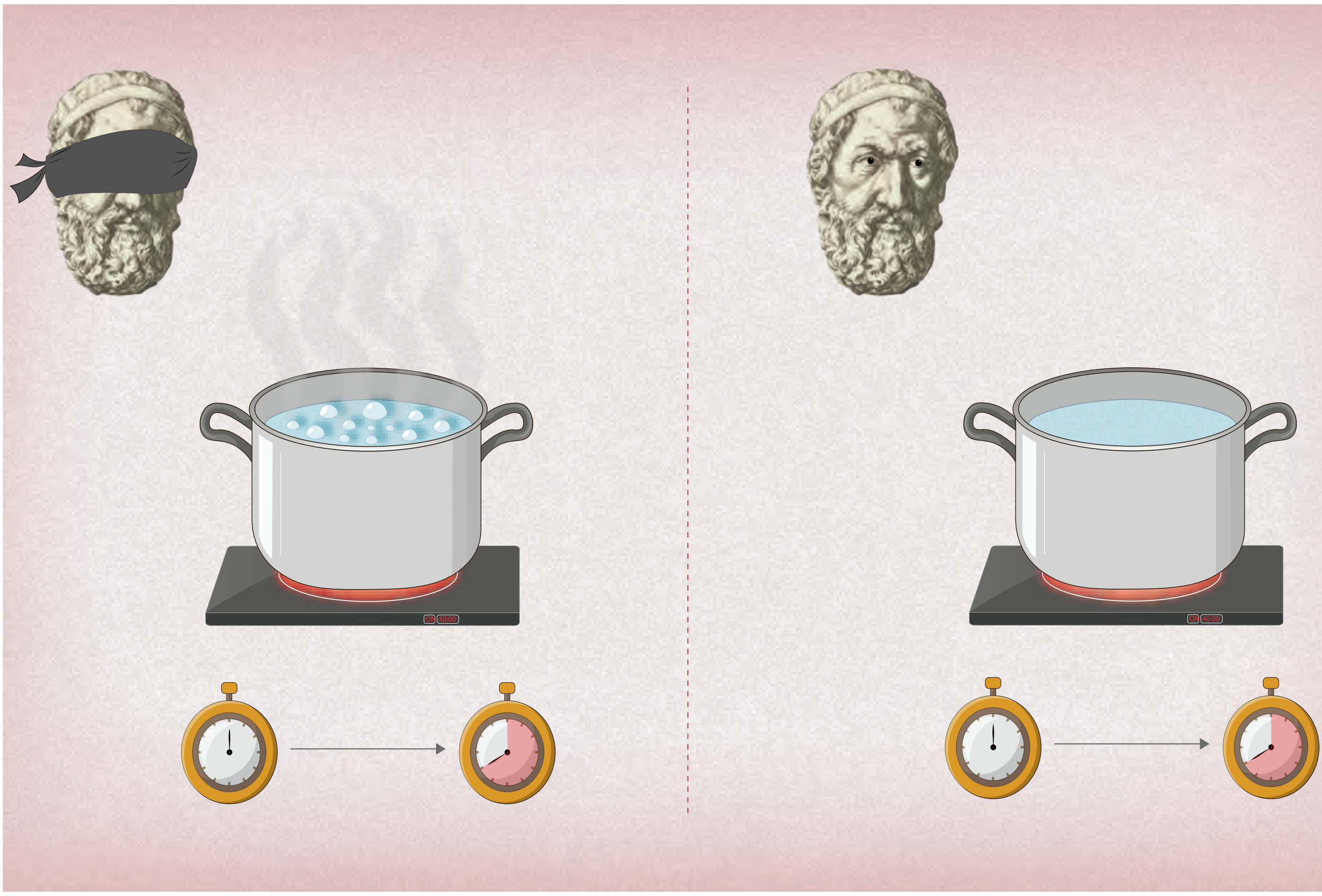


Illustration created by Mayank Shreshtha; Zeno image public domain; Zeno crop CC BY S Perquin

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 first of this series, Margaret Harris sets her sights on the quantum Zeno effect

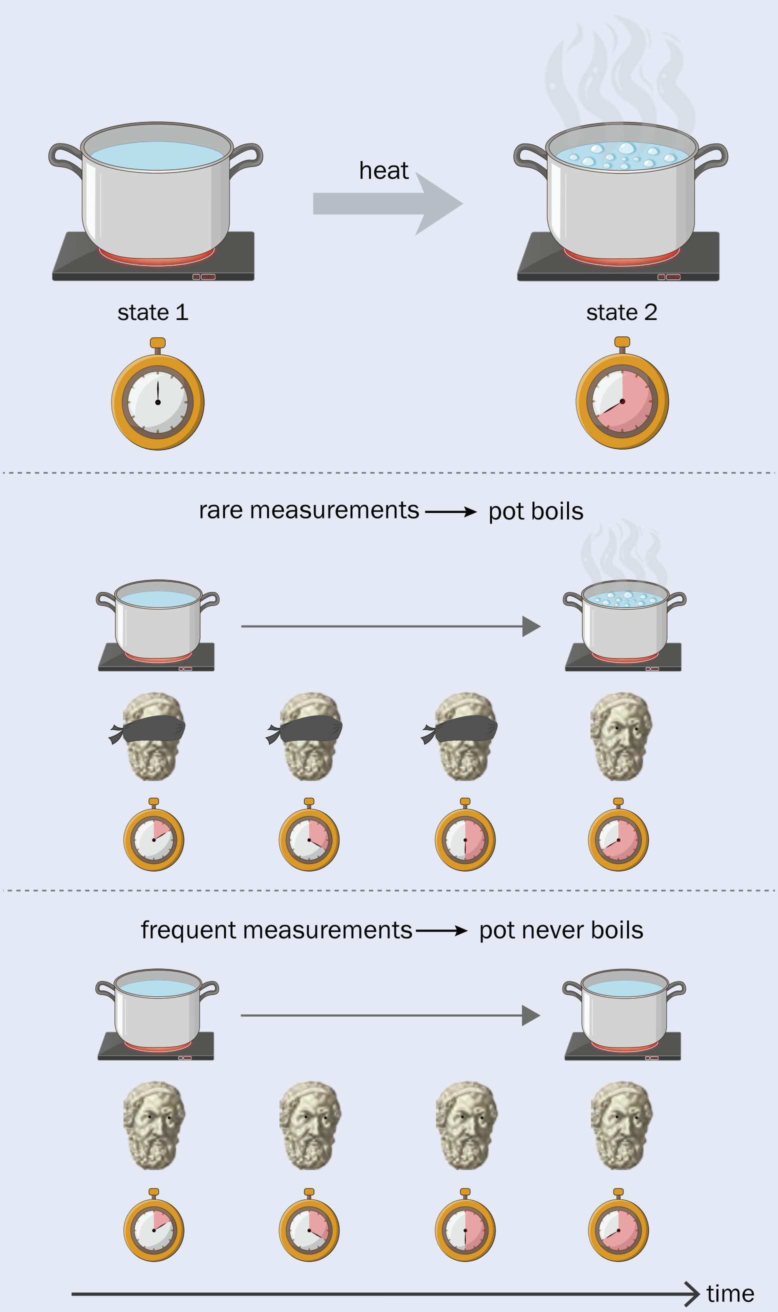
Imagine, if you will, that you are a quantum system. Specifically, you are an unstable quantum system – one that would, if left to its own devices, rapidly decay from one state (let's call it "awake") into another ("asleep"). But whenever you start to drift into the "asleep" state, something gets in the way. Maybe it's a message pinging on your phone. Maybe it's a curious child peppering you with questions. Whatever it is, it jolts you out of your awake–asleep superposition and projects you back into wakefulness. And because it keeps happening faster than you can fall asleep, you remain awake, diverted from slumber by a stream of interruptions – or, in quantum terms, measurements.

This phenomenon of repeated measurements "freezing" an unstable quantum system into a particular state is known as the quantum Zeno effect (figure 1). Named after a paradox from ancient Greek philosophy, it was hinted at in the 1950s by the scientific polymaths Alan Turing and John von Neumann but only fully articulated in 1977 by the physicists Baidyanath Misra and George Sudarshan (*J. Math. Phys.* **18** 756).

Since then, researchers have observed it in dozens of quantum systems, including trapped ions, superconducting flux qubits and atoms in optical cavities. But the apparent ubiquitousness of the quantum Zeno effect cannot hide the strangeness at its heart. How does the simple act of measuring a quantum system have such a profound effect on its behaviour?

Margaret Harris is an online editor at *Physics World*

1 A watched quantum pot



Applying heat to a normal, classical pot of water will cause it to evolve from state 1 (not boiling) to state 2 (boiling) at the same rate regardless of whether anyone is watching it (even if it doesn't seem like it). In the quantum world, however, a system that would normally evolve from one state to the other if left unobserved (blindfolded Zeno) can be "frozen" in place by repeated frequent measurements (eyes-open Zeno).

A watched quantum pot

"When you come across it for the first time, you think it's actually quite amazing because it really shows that the measurement in quantum mechanics influences the system," says Daniel Burgarth, a physicist at the Friedrich-Alexander-Universität in Erlangen-Nürnberg, Germany, who has done theoretical work on the quantum Zeno effect.

Giovanni Barontini, an experimentalist at the University of Birmingham, UK, who has studied the quantum Zeno effect in cold atoms, agrees. "It doesn't have a classical analogue," he says. "I can watch a classical system doing something forever and it will continue doing it. But a quantum system really cares if it's watched."

For the physicists who laid the foundations of quantum mechanics a century ago, any connection between measurement and outcome was a stumbling block. Several tried to find ways around it, for example by formalizing a role for observers in quantum wavefunction collapse (Niels Bohr and Werner Heisenberg); introducing new "hidden" variables (Louis de Broglie and David Bohm); and even hypothesizing the creation of new universes with each measurement (the "many worlds" theory of Hugh Everett).

But none of these solutions proved fully satisfactory. Indeed, the measurement problem seemed so intractable that most physicists in the next generation avoided it, preferring the approach sometimes described – not always pejoratively – as "shut up and calculate".

Today's quantum physicists are different. Rather than treating what Barontini calls "the apotheosis of the measurement effect" as a barrier to overcome or a triviality to ignore, they are doing something few of their forebears could have imagined. They are turning the quantum Zeno effect into something useful.

Noise management

To understand how freezing a quantum system by measuring it could be useful, consider a qubit in a quantum computer. Many quantum algorithms begin by initializing qubits into a desired state and keeping them there until they're required to perform computations. The problem is that quantum systems seldom stay where they're put. In fact, they're famously prone to losing their quantum nature (decohering) at the slightest disturbance (noise) from their environment. "Whenever we build quantum computers, we have to embed them in the real world, unfortunately, and that real world causes nothing but trouble," Burgarth says.

Quantum scientists have many strategies for dealing with environmental noise. Some of these strategies are passive, such as cooling superconducting qubits with dilution refrigerators and using electric and magnetic fields to suspend ionic and atomic qubits in a vacuum. Others, though, are active. They involve, in effect, tricking qubits into staying in the states they're meant to be in, and out of the states they're not.

The quantum Zeno effect is one such trick. "The way it works is that we apply a sequence of kicks to the system, and we are actually rotating the qubit with each kick," Burgarth explains. "You're rotating the system, and then effectively the environment wants to rotate it in the other direction." Over time, he adds, these opposing rotations average out, protecting the system from noise by freezing it in place.

Quantum state engineering

While noise mitigation is useful, it's not the quantum Zeno application that interests Burgarth and Barontini the most. The real prize, they agree, is something called quantum state engineering, which is much more complex than simply preventing a quantum system from decaying or rotating.

The source of this added complexity is that real quantum systems – much like real people – usually have more than two states available to them. For example, the set of permissible "awake" states for a person – the Hilbert space of wakefulness, let's call it – might include states such as cooking dinner, washing dishes and cleaning the bathroom. The goal of quantum state engineering is to restrict this state-space so the system can only occupy the state(s) required for a particular application.

As for how the quantum Zeno effect does this, Barontini explains it by referring to Zeno's original, classical paradox. In the fifth century BCE, the philosopher Zeno of Elea posed a conundrum based on an arrow flying through the air. If you look at this arrow at any possible moment during its flight, you will find that in that instant, it is motionless. Yet somehow, the arrow still moves. How?

In the quantum version, Barontini explains, looking at the arrow freezes it in place. But that isn't the only thing that happens. "The funniest thing is that if I look somewhere, then the arrow cannot go where I'm looking," he says. "It will have to go around it. It will have to modify its trajectory to go outside my field of view."

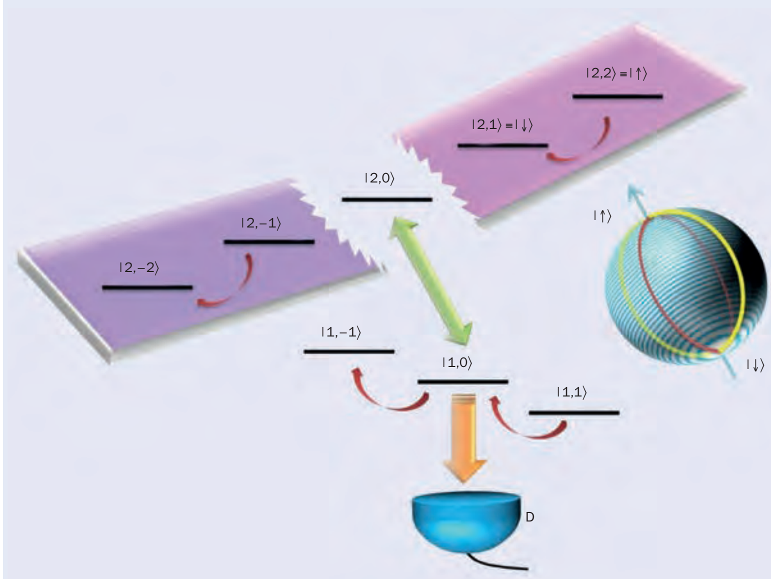
By shaping this field of view, Barontini continues, physicists can shape the system's behaviour. As an example, he cites work by Serge Haroche, who shared the 2012 Nobel Prize for Physics with another notable quantum Zeno experimentalist, David Wineland.

In 2014 Haroche and colleagues at the École Normale Supérieure (ENS) in Paris, France, sought to control the dynamics of an electron within a so-called Rydberg atom. In this type of atom, the outermost electron is very weakly bound to the nucleus and can occupy any of several highly excited states.

The researchers used a microwave field to divide 51 of these highly excited Rydberg states into two groups, before applying radio-frequency pulses to the system. Normally, these pulses would cause the electron to hop between states. However, the continual "measurement" supplied by the microwave field meant that although the electron could move within either group of states, it could not jump from one group to the other. It was stuck – or, more precisely, it was in a special type of quantum superposition known as a Schrödinger cat state.

Restricting the behaviour of an electron might not sound very exciting in itself. But in this and other experiments, Haroche and colleagues showed that imposing such restrictions brings forth a slew of unusual quantum states. It's as if telling the system what it can't do forces it to do a bunch of other things instead, like a procrastinator who cooks dinner and washes dishes to avoid cleaning the bathroom. "It really enriches your quantum toolbox," explains Barontini. "You can generate an entangled state that is more entangled or methodologically more useful than other states you could generate with traditional means."

2 Experimental realization of quantum Zeno dynamics



Nature Commun. **5** 3194

The energy level structure of a population of ultracold ^{87}Rb atoms , evolving in a five-level Hilbert space given by the five spin orientations of the F=2 hyperfine ground state. An applied RF field (red arrows) couples neighbouring quantum states together and allows atoms to "hop" between states. Normally, atoms initially placed in the $|F, m_F\rangle = |2,2\rangle$ state would cycle between this state and the other four F=2 states in a process known as Rabi oscillation. However, by introducing a "measurement" – shown here as a laser beam (green arrow) resonant with the transition between the $|1,0\rangle$ state and the $|2,0\rangle$ state – Smerzi and colleagues drastically changed the system's dynamics, forcing the atoms to oscillate between just the $|2,2\rangle$ and $|2,1\rangle$ states (represented by up and down arrows on the so-called Bloch sphere at right). An additional laser beam (orange arrow) and the detector D were used to monitor the system's evolution over time. (First published in *Nature Commun.* **5** 3194. Reproduced with permission from Springer Nature)

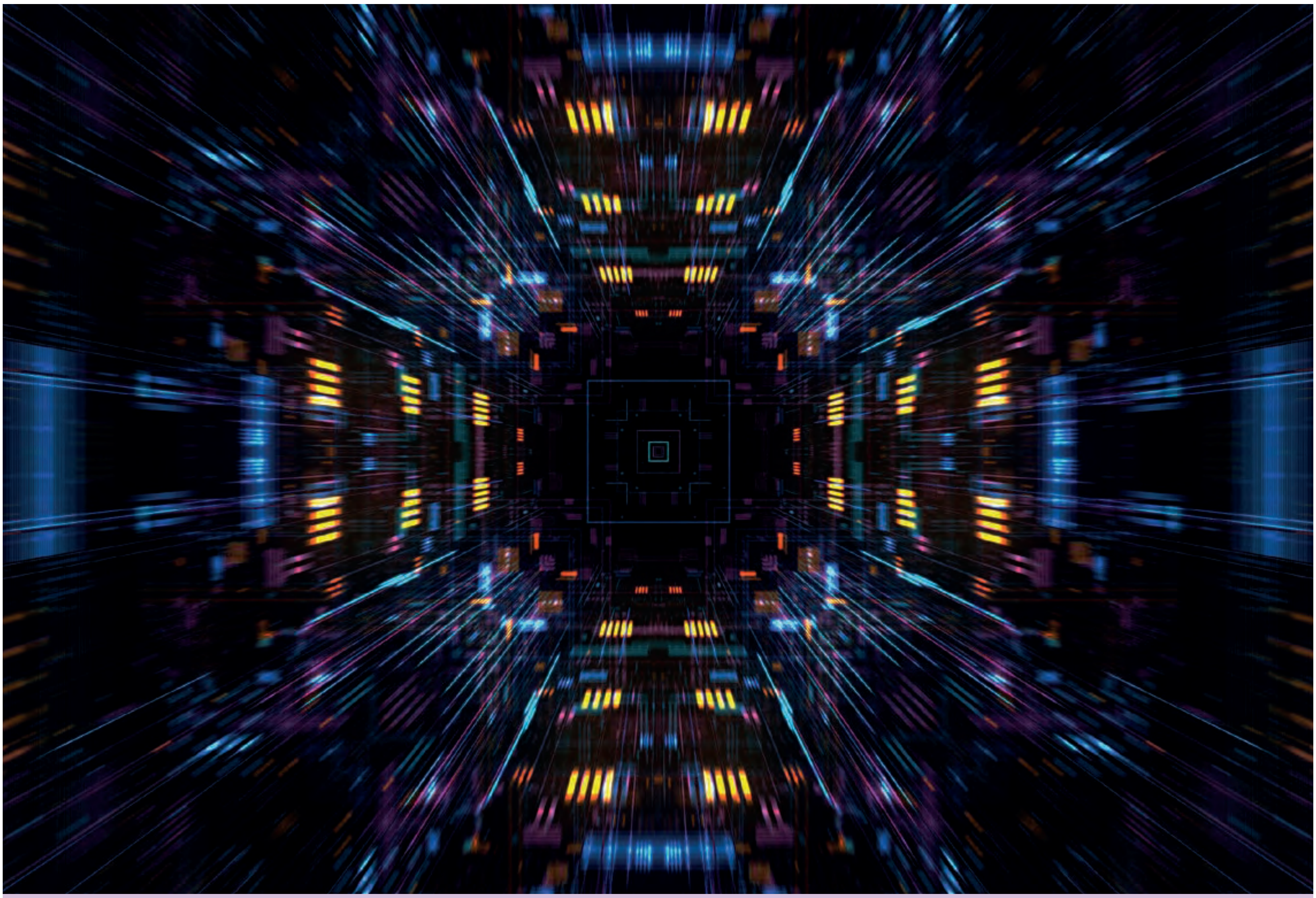
Just what is a measurement, anyway?

As well as generating interesting quantum states, the quantum Zeno effect is also shedding new light on the nature of quantum measurements. The question of what constitutes a "measurement" for quantum Zeno purposes turns out to be surprisingly broad. This was elegantly demonstrated in 2014, when physicists led by Augusto Smerzi at the Università di Firenze, Italy, showed that simply shining a resonant laser at their quantum system (figure 2) produced the same quantum Zeno dynamics as more elaborate "projective" measurements – which in this case involved applying pairs of laser pulses to the system at frequencies tailored to specific atomic transitions. "It's fair to say that almost anything causes a Zeno effect," says Burgarth. "It's a very universal and easy-to-trigger phenomenon."

Other research has broadened our understanding of what measurement can do. While the quantum Zeno effect uses repeated measurements to freeze a quantum system in place (or at least slow its evolution from one state to another), it is also possible to do the opposite and use measurements to accelerate quantum transitions. This phenomenon is known as the quantum anti-Zeno effect, and it has applications of its own. It could, for example, speed up reactions in quantum chemistry.

Over the past 25 years or so, much work has gone into understanding where the ordinary quantum Zeno effect leaves off and the quantum anti-Zeno effect begins. Some systems can display both Zeno and anti-Zeno dynamics, depending on the frequency of the measurements and various environmental conditions. Others seem to favour one over the other.

But regardless of which version turns out to be the most important, quantum Zeno research is anything but frozen in place. Some 2500 years after Zeno posed his paradox, his intellectual descendants are still puzzling over it. ■



The curious case of quantum Cheshire cats

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Continuing our spotlight on some especially "weird" quantum effects, **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 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, Aharo-

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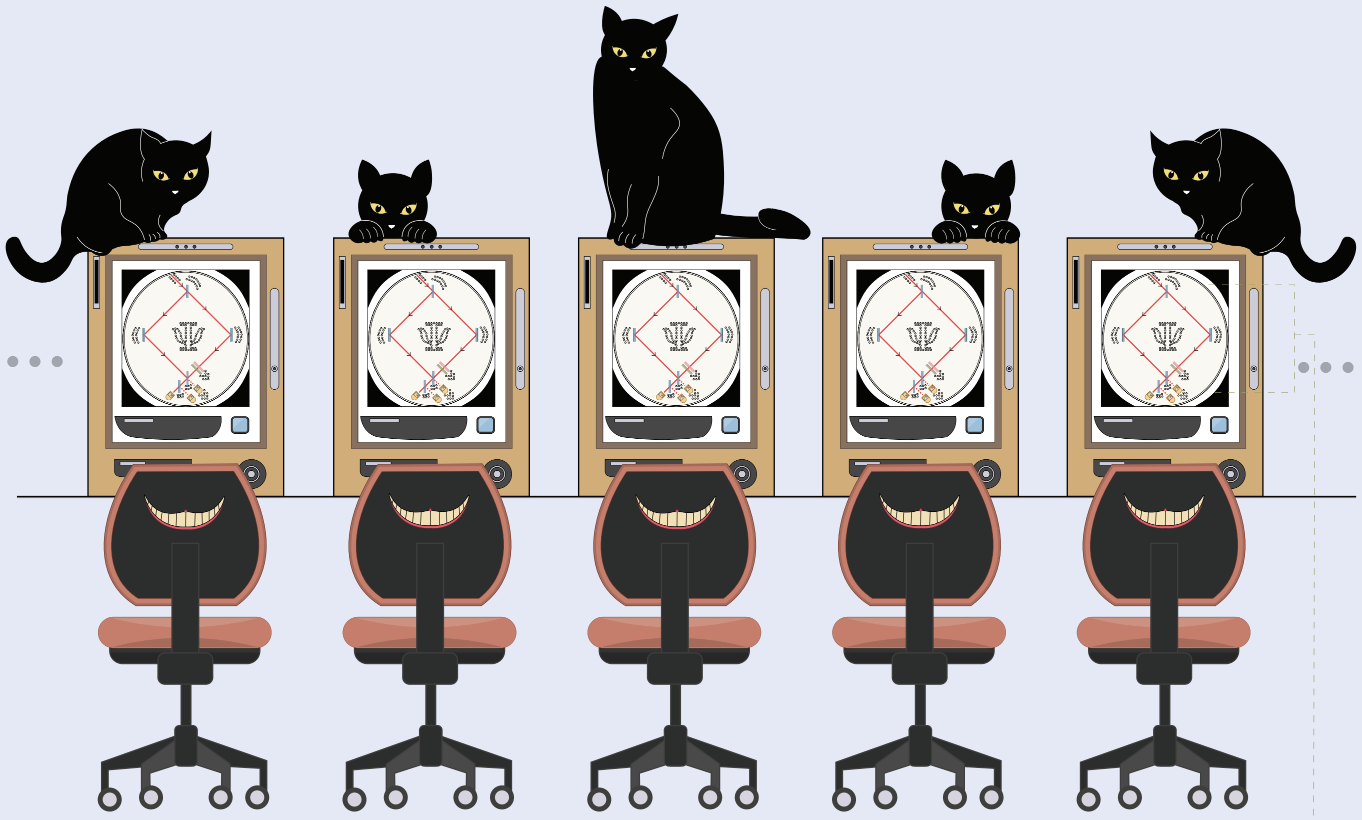
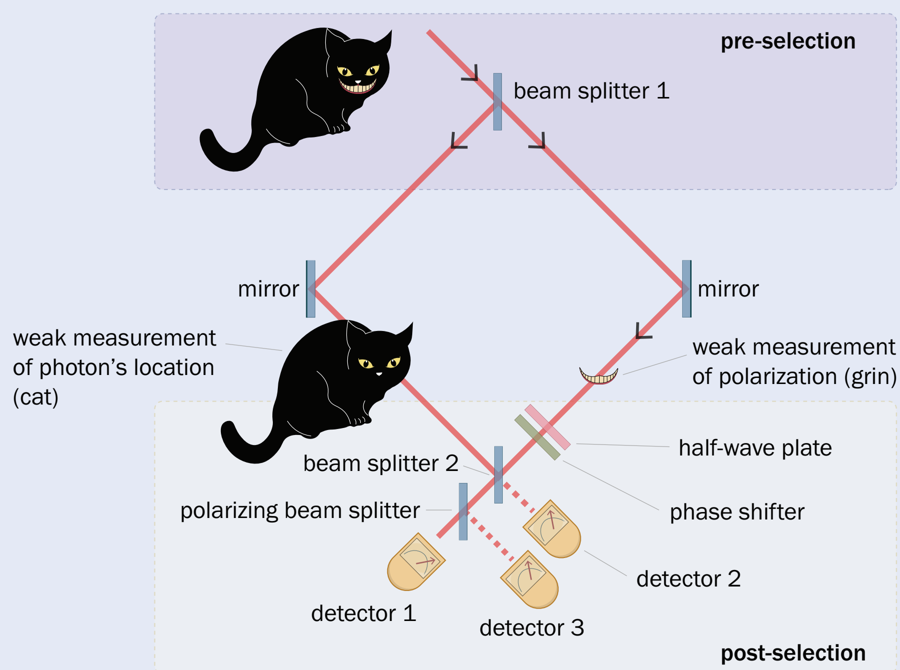
1 Split particle property



Mayank Shreshtha

Examples of disembodied properties:

photon	polarization
electron	charge
neutron	magnetic moment
atom	internal energy



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.

nov 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.

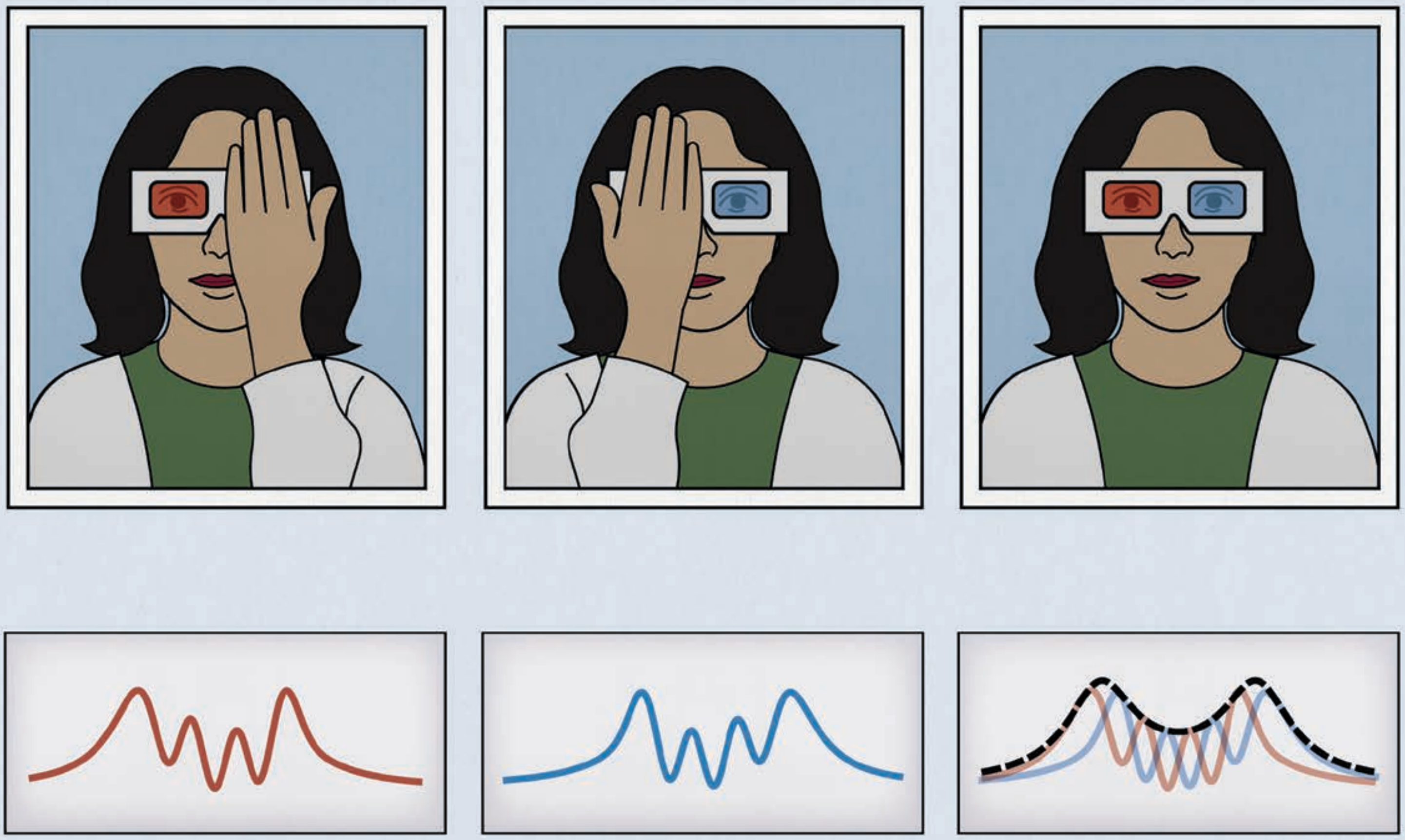
Despite popular science's constant reminder of how "weird" quantum mechanics is, physicists often take the pragmatic "shut up and calculate" approach. Hance says that researchers "tend to forget how weird quantum mechanics is, and to me you need that intuition of it being weird". Indeed, paradoxes like 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. ■

The quantum eraser doesn't rewrite the past – it rewrites observers

In the third of our series of truly weird quantum effects, **Maria Violaris** investigates the paradoxical delayed-choice quantum eraser



Mayank Shreshtha

"Welcome to this special issue of *Physics World*, marking the 200th anniversary of quantum mechanics. In this double-quantum edition, the letters in this text are stored using qubits. As you read, you project the letters into a fixed state, and that information gets copied into your mind as the article that you are reading. This text is actually in a superposition of many different articles, but only one of them gets copied into your memory. We hope you enjoy the one that you are reading."

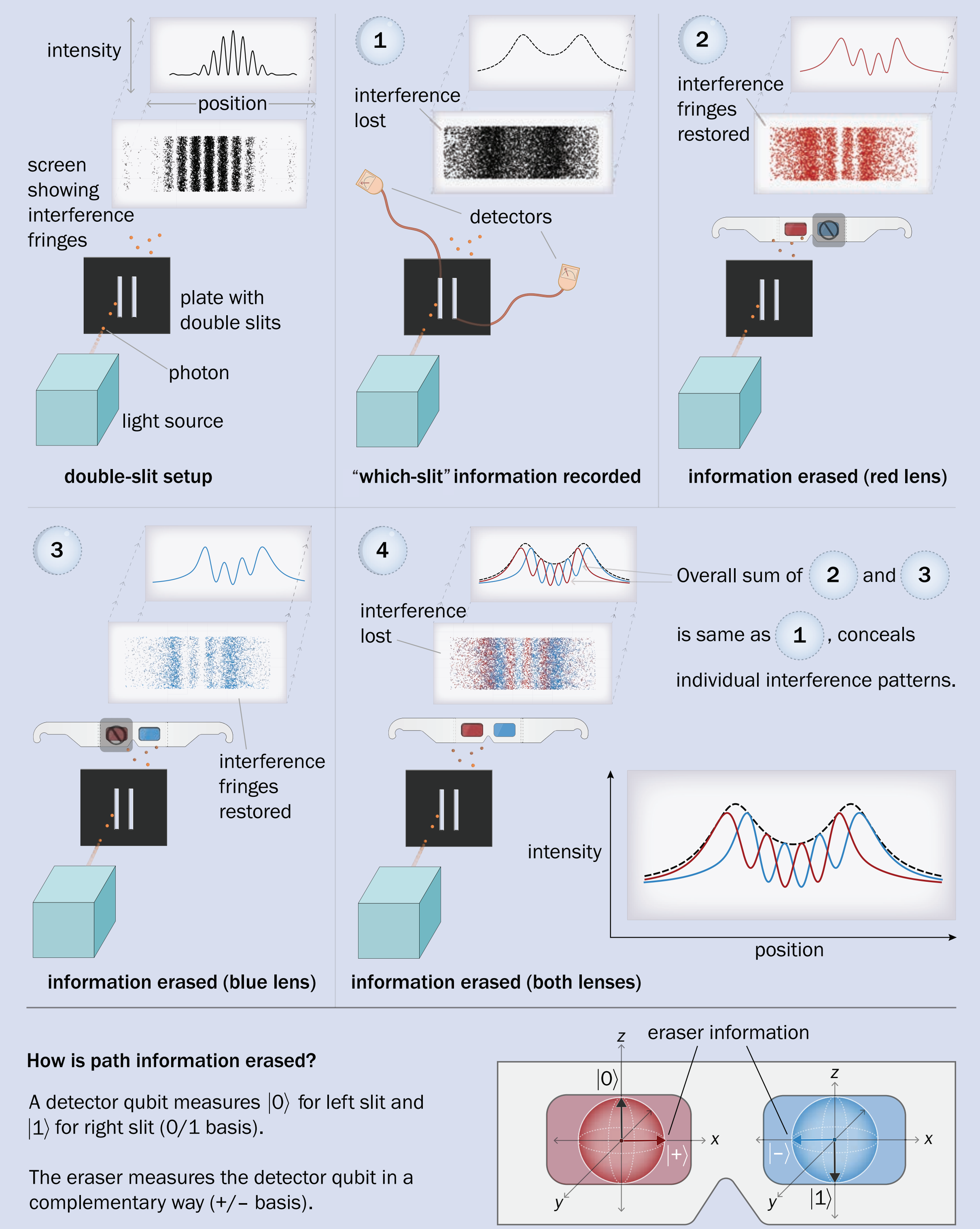
That's how I imagine the opening of the 2125 *Physics World* quantum special issue, when fully functional quantum computers are commonplace, and we have even figured out how to control individual qubits on display screens. If you are lucky enough to experience reading such a magazine, you might be disappointed as you can read only one of the articles the text gets projected into. The problem is that by reading the superposition of articles, you made them decohere, because you copied the information about each letter into your memory. Can you figure out a way to read the others too? After all, more *Physics World* articles is always better.

A possible solution may be if you could restore the coherence of the text just by erasing your memory of the particular article you read. Once you no longer have information identifying which article your magazine was projected into, there is then no fundamental reason for it to remain decohered into a single state. You could then reread it to enjoy a different article.

While this thought experiment may sound fantastical, the concept is closely connected to a mind-bending twist on the famous double-slit experiment, known as the delayed-choice quantum eraser. It is often claimed to exhibit a radical phenomenon: where measurements made in the present alter events that occurred in the past. But is such a paradoxical suggestion real, even in the notoriously strange quantum realm?

Maria Violaris is a quantum physicist, science communicator and content creator. She has a PhD from the University of Oxford in the foundations of quantum information science and was previously a PhD student contributor to *Physics World*

1 Delayed detections, path revelations and complementary measurements



Mayank Shreshtha

This illustration depicts how the quantum eraser restores the wave-like behaviour of photons in a double-slit experiment, using 3D-glasses as an analogy. The top left box shows the set-up for the standard double-slit experiment. As there are no detectors at the slits measuring which pathway a photon takes, an interference pattern emerges on the screen. In box 1, detectors are present at each slit, and measuring which slit the photon might have passed through, the interference patter is destroyed. Boxes 2 and 3 show that by erasing the "which-slit" information, the interference patterns are restored. This is done by separating out the photons using the eraser, represented here by a red filter and a blue filter of the 3D glasses. The final box 4 shows that the overall pattern with the eraser has no interference, identical to patten seen in box 1.

In boxes 2, 3 and 4, a detector qubit measures "which-slit" information, with states |0> for left and |1> for right. These are points on the z-axis of the "Bloch sphere", an abstract representation of the qubit. Then the eraser measures the detector qubit in a complementary way, along the x-axis of the Bloch sphere. This destroys the "which-slit information", but reveals the red and blue lens information used to filter the outcomes, as depicted in the image of the 3D glasses.

The results therefore reveal an intriguing aspect of quantum theory – the rich, counterintuitive structure of quantum correlations from entanglement – rather than past influences

for it to remain decohered into a single state. You could then reread it to enjoy a different article.

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A double twist on the double slit

In a standard double-slit experiment, photons are sent one by one through two slits to create an interference pattern on a screen, illustrating the wave-like behaviour of light. But if we add a detector that can spot which of the two slits the photon goes through, the interference disappears and we see only two distinct clumps on the screen, signifying particle-like behaviour. Crucially, gaining information about which path the photon took changes the photon's quantum state, from the wave-like interference pattern to the particle-like clumps.

The first twist on this thought experiment is attributed to proposals from physicist John Wheeler in 1978, and a later collaboration with Wojciech Zurek in 1983. Wheeler's idea was to delay the measurement of which slit the photon goes through. Instead of measuring the photon as it passes through the double-slit, the measurement could be delayed until just before the photon hits the screen. Interestingly, the delayed detection of which slit the photon goes through still determines whether or not it displays the wave-like or particle-like behaviour. In other words, even a detection done long after the photon has gone through the slit determines whether or not that photon is measured to have interfered with itself.

If that's not strange enough, the delayed-choice quantum eraser is a further modification of this idea. First proposed by American physicists Marlan Scully and Kai Drühl in 1982 (*Phys. Rev. A* **25** 2208), it was later experimentally implemented by Yoon-Ho Kim and collaborators using photons in 2000 (*Phys. Rev. Lett.* **84** 1). This variation adds a second twist: if recording which slit the photon passes through causes it to decohere, then what happens if we were to erase that information? Imagine shrinking the detector to a single qubit that becomes entangled with the photon: "left" slit might correlate to the qubit being 0, "right" slit to 1. Instead of measuring whether the qubit is a 0 or 1 (revealing the path), we could measure it in a complementary way, randomising the 0s and 1s (erasing the path information).

Strikingly, while the screen still shows particle-like clumps overall, these complementary measurements of the single-qubit detector can actually be used to extract a wave-like interference pattern. This works through a sorting process: the two possible outcomes of the complementary measurements are used to separate out the photon detections on the screen. The separated patterns then each individually show bright and dark fringes.

I like to visualize this using a pair of 3D glasses, with one blue and one red lens. Each colour lens reveals a different individual image, like the two separate interference patterns. Without the 3D glasses, you see only the overall sum of the images. In the quantum eraser experiment, this sum of the images is a fully decohered pattern, with no trace of interference. Having access to the complementary measurements of the detector is like getting access to the 3D glasses: you now get an extra tool to filter out the two separate interference patterns (see figure 1).

Rewriting the past – or not?

If erasing the information at the detector lets us extract wave-like patterns, it may seem like we've restored wave-like behaviour to an already particle-like photon. That seems truly head-scratching. However, Jonte Hance, a quantum physicist at Newcastle University in the UK, highlights a different conclusion, focused on how the individual interference patterns add up to show the usual decohered pattern. "They all feel like they shouldn't be able to fit together," Hance explains. "It's really showing that the correlations you get through entanglement have to be able to fit every possible way you could measure a system." The results therefore reveal an intriguing aspect of quantum theory – the rich, counterintuitive structure of quantum correlations from entanglement – rather than past influences.

Even Wheeler himself did not believe that his thought experiment actually allows for a backward-in-time influence, as explained by Lorenzo Catani, a researcher at the International Iberian Nanotechnology Laboratory (INL) in Portugal. Commenting on the history of the thought experiment, Catani notes that "Wheeler concluded that one must abandon a certain type of realism – namely, the idea that the past exists independently of its recording in the present. As far as I know, only a minority of researchers have interpreted the experiment as evidence for retrocausality."

Eraser vs Bell: a battle of the bizarre

One physicist who is attempting to unpack this problem is Johannes Fankhauser at the University of Innsbruck, Austria. "I'd heard about the quantum eraser, and it had puzzled me a lot because of all these bizarre claims of backwards-in-time influence", he explains. "I see something that sounds counterintuitive and puzzling and bizarre and then I want to understand it, and by understanding it, it gets a bit demystified."

Fankhauser realized that the quantum eraser set-up can be translated into a very standard Bell experiment.

The quantum eraser emphasizes that even a single entanglement between qubits will cause decoherence, whether or not it is measured afterwards – meaning that no mysterious macroscopic observer is required

These experiments are based on entangling a pair of qubits, the idea being to rule out local "hidden-variable" models of quantum theory. This led him to see that there is no need to explain the eraser using backwards-in-time influence, since the related Bell experiments can be understood without it, as explained in his 2017 paper (*Quanta* **8** 44). Fankhauser then further analysed the thought experiment using the de Broglie–Bohm interpretation of quantum theory, which gives a physical model for the quantum wavefunction (as particles are guided by a "pilot" wave). Using this, he showed explicitly that the outcomes of the eraser experiment can be fully explained without requiring backwards-in-time influences.

So does that mean that the eraser doesn't tell us anything else beyond what Bell experiments already tell us? Not quite. "It turns different knobs than the Bell experiment," explains Fankhauser. "I would say it asks the question 'what do measurements signify?', and 'when can I talk about the system having a property?'. That's an interesting question and I would say we don't have a full answer to this."

In particular, the eraser demonstrates the importance that the very act of observation has on outcomes, with the detector playing the role of an observer. "You measure some of its properties, you change another property," says Fankhauser. "So the next time you measure it, the new property was created through the observation. And I'm trying to formalize this now more concretely. I'm trying to come up with a new approach and framework to study these questions."

Meanwhile, Catani found an intriguing contrast between Bell experiments and the eraser in his research. "The implications of Bell's theorem are far more profound," says Catani. In the 2023 paper (*Quantum* **7** 1119) he co-authored, Catani considers a model for classical physics, with an extra condition: there is a restriction on what you can know about the underlying physical states. Applying this model to the quantum eraser, he finds that its results can be reproduced by such a classical theory. By contrast, the classical model cannot reproduce the statistical violations of a Bell experiment. This shows that having incomplete knowledge of the physical state is not, by itself, enough to explain the strange results of the Bell experiment. It is therefore demonstrating a more powerful deviation from classical physics than the eraser. Catani also contrasts the mathematical rigour of the two cases. While Bell experiments are based on explicitly formulated assumptions, claims about backwards-in-time influence in the quantum eraser rely on a particular narrative – one that gives rise to the apparent paradox.

The eraser as a brainteaser

Physicists therefore broadly agree that the mathematics of the quantum eraser thought experiment fits well within standard quantum theory. Even so, Hance argues that formal results alone are not the entire story: "This is something we need to pick apart, not just in terms of mathematical assumptions, but also in terms of building intuitions for us to be able to actually play around with what quantumness is." Hance has been analysing the physical implications of different assumptions in the thought experiment, with some options discussed in his 2021 preprint (arXiv:2111.09347) with collaborators on the quantum eraser paradox.

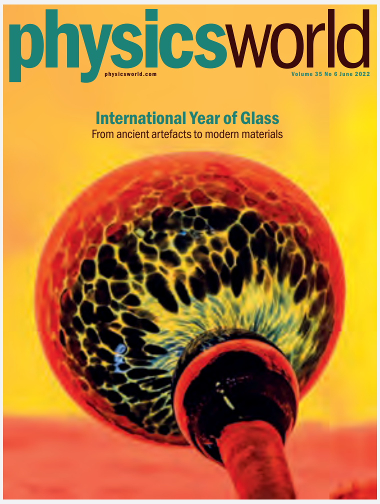
It therefore provides a tool for understanding how quantum correlations match up in a way that is not described by classical physics. "It's a great thinking aid – partly brainteaser, partly demonstration of the nature of this weirdness."

Information, observers and quantum computers

Every quantum physicist takes something different from the quantum eraser, whether it is a spotlight on the open problems surrounding the properties of measured systems; a lesson from history in mathematical rigour; or a counterintuitive puzzle to make sense of. For a minority that deviate from standard approaches to quantum theory, it may even be some form of backwards-in-time influence.

For myself, as explained in my related video on the Qiskit YouTube channel, and my 2023 paper (IEEE International Conference on Quantum Computing and Engineering 10.1109/QCE57702.2023.20325) on quantum thought experiments, the most dramatic implication of the quantum eraser is explaining the role of observers in the double-slit experiment. The quantum eraser emphasizes that even a single entanglement between qubits will cause decoherence, whether or not it is measured afterwards – meaning that no mysterious macroscopic observer is required. This also explains why building a quantum computer is so challenging, as unwanted entanglement with even one particle can cause the whole computation to collapse into a random state.

Where does this leave the futuristic readers of our 200-year double-quantum special issue of *Physics World*? Simply erasing their memories is not enough to restore the quantum behaviour of the article. It is too late to change which article was selected. Though, following an eraser-type protocol, our futurists can do one better than those sneaky magazine writers: they can use the outcomes of complementary measurements on their memory, to sort the article into two individual smaller articles, each displaying their own quantum entanglement structure that was otherwise hidden. So even if you can't use the quantum eraser to rewrite the past, perhaps it can rewrite what you read in the future. ■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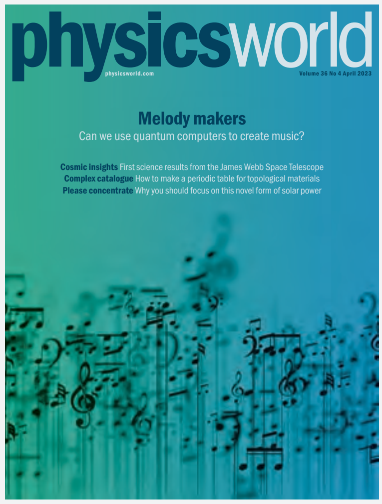
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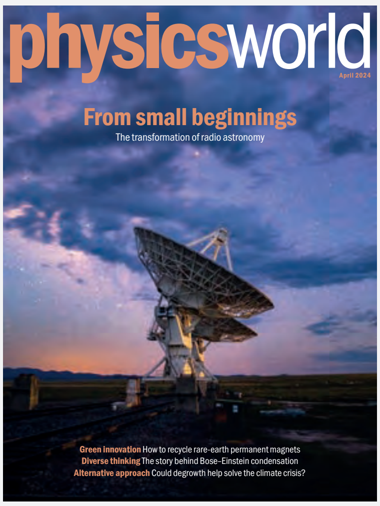
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On the path towards a quantum economy

Feasibility studies are enabling industry experts to collaborate with quantum specialists to discover the potential benefits of quantum computing for their businesses and their customers

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The high-street bank HSBC has worked with the NQCC, hardware provider Rigetti and the Quantum Software Lab to investigate the advantages that quantum computing could offer for detecting the signs of fraud in transactional data.

Rapid technical innovation in quantum computing is expected to yield an array of hardware platforms that can run increasingly sophisticated algorithms. In the real world, however, such technical advances will remain little more than a curiosity if they are not adopted by businesses and the public sector to drive positive change. As a result, one key priority for the UK's National Quantum Computing Centre (NQCC) has been to help companies and other organizations to gain an early understanding of the value that quantum computing can offer for improving performance and enhancing outcomes.

To meet that objective the NQCC has supported several feasibility studies that enable commercial organizations in the UK to work alongside quantum specialists to investigate specific use cases where quantum computing could have a significant impact within their industry. One prime example is a project involving the high-street bank HSBC, which has been exploring the potential of quantum technologies for spotting the signs of fraud in financial transactions. Such fraudulent activity, which affects millions of people every year, now accounts for about 40% of all criminal offences in the UK and in 2023 generated total losses of more than £2.3 bn across all sectors of the economy.

Banks like HSBC currently exploit classical machine learning to detect fraudulent transactions, but these techniques require a large computational overhead to train the models and deliver accurate results. Quantum specialists at the bank have therefore been working with the NQCC, along with hardware provider Rigetti and the Quantum Software Lab at the University of Edinburgh, to investigate the capabilities of quantum machine learning (QML) for identifying the tell-tale indicators of fraud.

"HSBC's involvement in this project has brought transactional fraud detection into the realm of cutting-edge technology, demonstrating our commitment to pushing the boundaries of quantum-inspired solutions for near-term benefit," comments Philip Intallura, Group Head of Quantum Technologies at HSBC. "Our philosophy is to innovate today while preparing for the quantum advantage of tomorrow."

Another study focused on a key problem in the aviation industry that has a direct impact on fuel consumption and the amount of carbon emissions produced during a flight. In this logistical challenge, the aim was to find the optimal way to load cargo containers onto a commercial aircraft. One motivation was to maximize the amount of cargo that can be carried, the other was to balance the weight of the cargo to reduce drag and improve fuel efficiency.

"Even a small shift in the centre of gravity can have a big effect," explains Salvatore Sinno of technology solutions company Unisys, who worked on the project along with applications engineers at the NQCC and mathematicians at the University of Newcastle. "On a Boeing 747 a displacement of just 75 cm can increase the carbon emissions on a flight of 10,000 miles by four tonnes, and also increases the fuel costs for the airline company."

With such a large number of possible loading combinations, classical computers cannot produce an exact solution for the optimal arrangement of cargo containers. In their project the team improved the precision of the solution by combining quantum annealing with high-performance computing, a hybrid approach that Unisys believes can offer immediate value for complex optimization problems. "We have reached the limit of what we can achieve with classical computing, and with this work we have shown the benefit of incorporating an element of quantum processing into our solution," explains Sinno.

The HSBC project team also found that a hybrid quantum–classical solution could provide an immediate performance boost for detecting anomalous transactions. In this case, a quantum simulator running on a classical computer was used to run quantum algorithms for machine learning. "These simulators allow us to execute simple QML programmes, even though they can't be run to the same level of complexity as we could achieve with a physical quantum processor," explains Marco Paini, the project lead for Rigetti. "These simulations show the potential of these low-depth QML programmes for fraud detection in the near term."

The team also simulated more complex QML approaches using a similar but smaller-scale problem, demonstrating a further improvement in performance. This outcome suggests that running deeper QML algorithms on a physical quantum processor could deliver an advantage

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A hybrid quantum–classical solution has been used to optimize the configuration of air freight, which can improve fuel efficiency and lower carbon emissions.

Working with the applications engineers at the NQCC has helped us to understand what is possible with today's quantum hardware

for detecting anomalies in larger datasets, even though the hardware does not yet provide the performance needed to achieve reliable results. "This initiative not only showcases the near-term applicability of advanced fraud models, but it also equips us with the expertise to leverage QML methods as quantum computing scales," comments Intellura.

Indeed, the results obtained so far have enabled the project partners to develop a roadmap that will guide their ongoing development work as the hardware matures. One key insight, for example, is that even a fault-tolerant quantum computer would struggle to process the huge financial datasets produced by a bank like HSBC, since a finite amount of time is needed to run the quantum calculation for each data point. "From the simulations we found that the hybrid quantum–classical solution produces more false positives than classical methods," says Paini. "One approach we can explore would be to use the simulations to flag suspicious transactions and then run the deeper algorithms on a quantum processor to analyse the filtered results."

This particular project also highlighted the need for agreed protocols to navigate the strict rules on data security within the banking sector. For this project the HSBC team was able to run the QML simulations on its existing computing infrastructure, avoiding the need to share sensitive financial data with external partners. In the longer term, however, banks will need reassurance that their customer information can be protected when processed using a quantum computer. Anticipating this need, the NQCC has already started to work with regulators such as the Financial Conduct Authority, which is exploring some of the key considerations around privacy and data security, with that initial work feeding into international initiatives that are starting to consider the regulatory frameworks for using quantum computing within the financial sector.

For the cargo-loading project, meanwhile, Sinno says that an important learning point has been the need to formulate the problem in a way that can be tackled by the current generation of quantum computers. In practical terms that means defining constraints that reduce the complexity of the problem, but that still reflect the requirements of the real-world scenario. "Working with the applications engineers at the NQCC has helped us to understand what is possible with today's quantum hardware, and how to make the quantum algorithms more viable for our particular problem," he says. "Participating in these studies is a great way to learn and has allowed us to start using these emerging quantum technologies without taking a huge risk."

Indeed, one key feature of these feasibility studies is the opportunity they offer for different project partners to learn from each other. Each project includes an end-user organization with a deep knowledge of the problem, quantum specialists who understand the capabilities and limitations of present-day solutions, and academic experts who offer an insight into emerging theoretical approaches as well as methodologies for benchmarking the results. The domain knowledge provided by the end users is particularly important, says Paini, to guide ongoing development work within the quantum sector. "If we only focused on the hardware for the next few years, we might come up with a better technical solution but it might not address the right problem," he says. "We need to know where quantum computing will be useful, and to find that convergence we need to develop the applications alongside the algorithms and the hardware."

Another major outcome from these projects has been the ability to make new connections and identify opportunities for future collaborations. As a national facility NQCC has played an important role in providing networking opportunities that bring diverse stakeholders together, creating a community of end users and technology providers, and supporting project partners with an expert and independent view of emerging quantum technologies. The NQCC has also helped the project teams to share their results more widely, generating positive feedback from the wider community that has already sparked new ideas and interactions.

"We have been able to network with start-up companies and larger enterprise firms, and with the NQCC we are already working with them to develop some proof-of-concept projects," says Sinno. "Having access to that wider network will be really important as we continue to develop our expertise and capability in quantum computing."

UKRI National Quantum Computing Centre

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

Quantum physics comes down to earth

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

Katherine Skipper is an associate editor at *Nature News and Views*. She was a features editor at *Physics World* between 2024 and 2025

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

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

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

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

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

What lies beneath

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

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

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

Falling atoms

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

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

Finally, another laser pulse, identical to the first, is applied. If the acceleration due to gravity were constant everywhere in space, the two states would fall exactly the same distance and overlap at the end of the sequence.


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

In this case, the final pulse would effectively reverse the first, and the atom would end up back in the ground state. However, because in the real world the atom's acceleration changes as it falls through the gravity gradient, the two states don't quite find each other at the end. Since the atom is wavelike, this spatial separation is equivalent to a phase difference. Now, the outcome of the final laser pulse is less certain; sometimes it will return the atom to the ground state, but sometimes it will collapse the wavefunction to the excited state instead.

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

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

Bad vibrations

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

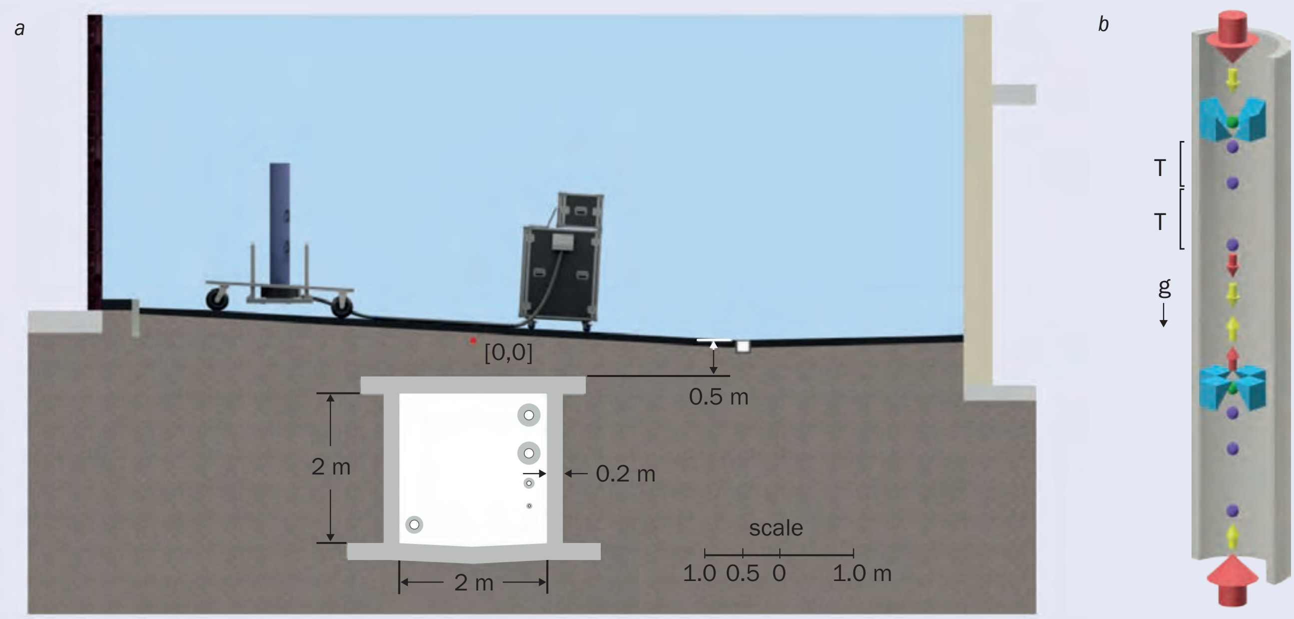
"It's always one thing to do the first demonstration of principle, and then it's a different thing to really get it to a performance level where it actually is useful and competitive," says Achim Peters, who started a PhD with Chu in 1992 and is now a researcher at the Humboldt University of Berlin.

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

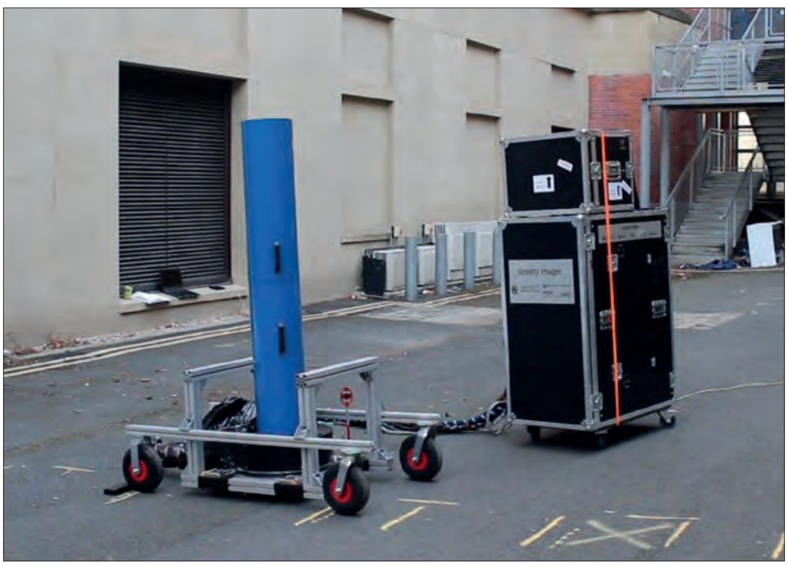
When Peters was at Stanford he built a sophisticated vibration isolation system where the extension of mechanical springs was controlled by electronic feedback. This brought the quantum device in line with other state-of-the-art measurement techniques, but such a complex apparatus would be difficult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

However, if a cold-atom gravity sensor could operate outside without being hampered by vibrations it would

1 Testing times



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



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

have an instant advantage over spring devices, where vibrations have to be averaged out by taking longer measurements. “If we want to measure several hectares, you’re talking about three weeks or plus [with spring gravimeters],” explains Metje. “That takes a lot of time and therefore also a lot of cost.”

Enter the gravity gradiometer

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

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

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

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

Ears to the ground

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

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

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

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

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

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


Courtesy: University of Birmingham © Crown Copyright

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

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

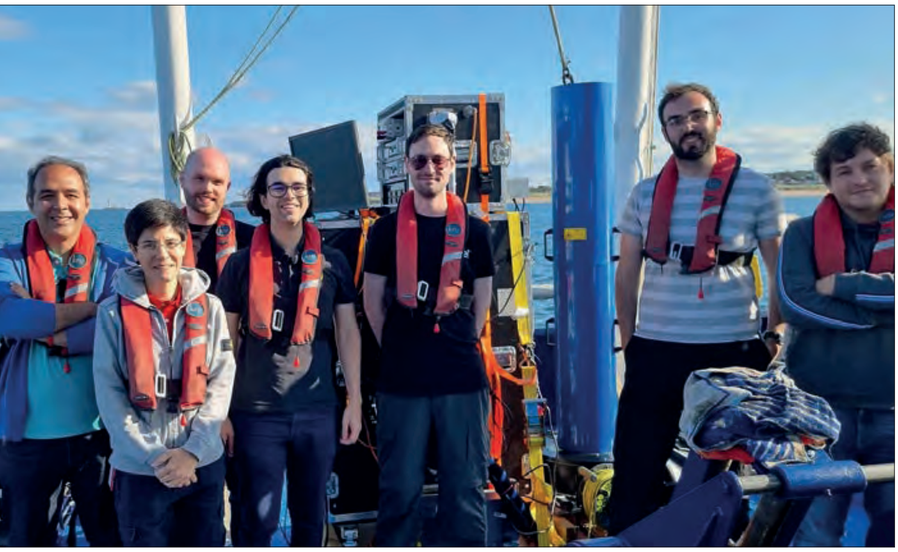
The researchers worked out that another gamble they had made, this time to reduce the cost of the magnetic shield, wasn't performing as well as hoped. External magnetic fields shift the atom's energy levels, but unlike the phase shift due to gravity, this source of error is the same whether the momentum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

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

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

Quantum tunnelling

"One of the things that changes about you when you work on gravity gradiometers is you start looking around for potential targets everywhere you go," says Holynski.



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

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

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

Elsewhere on campus, another team was busy analysing the data. The results, when they were done, were consistent with a hollow object, about two-by-two metres across, and about a metre below the surface. Millions of people will have walked over that road without thinking once about what's beneath it, but to the researchers, this was the culmination of a decade of work, and proof that cold-atom gradiometers can operate outside the lab (- -90).

The valley of death

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

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

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

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

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

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

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

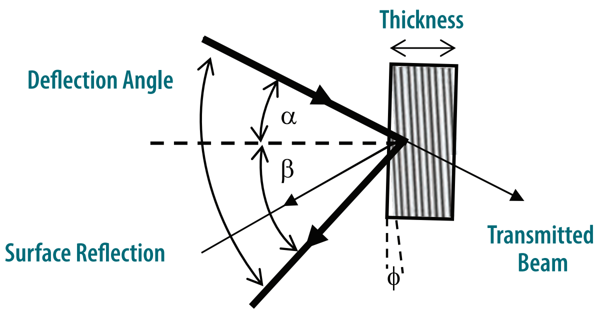
When Chu and Kasevich demonstrated it for the first time, the idea of atom interferometry was already three decades old, having been proposed by David Bohm and later Eugene Wigner (*Am. J. Phys.* **31** 6). Rather than lasers, this theoretical device was based on the Stern–Gerlach effect, in which an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

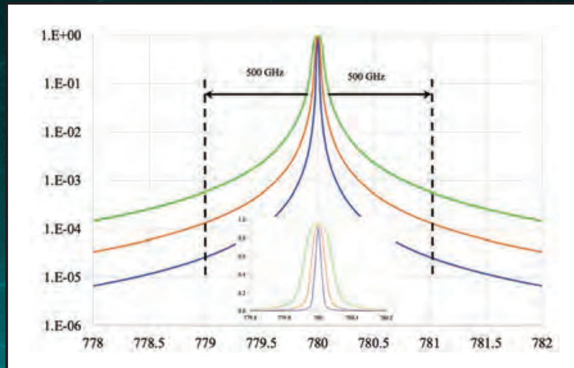
Decades in the making, the mobile cold-atom interferometer is a triumph of practical problem-solving and even if the commercial applications have yet to be realized, one thing is clear: when it comes to pushing the boundaries of quantum physics, sometimes it pays to think like an engineer. ■

Volume Bragg Gratings (VBGs) for
Quantum Optics

Available wavelength range: 600-2500 nm
Standard Wavelengths: 780; 795; 852; 894 nm
Standard Bandwidths: 10; 25; 50 GHz
Diffraction Efficiency: > 95%
Unmatched side-lobes suppression: > 50 dB

Parameters of 25-GHz Filter:
Spectral Bandwidth: <25 GHz;
Efficiency: >92%;
Attenuation: > 30 dB at >150 GHz shift



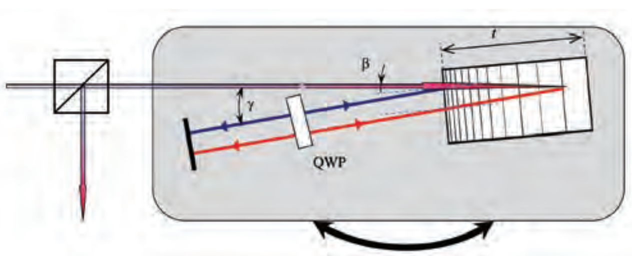


Spectral Shape of Reflecting VBG Filters with Bandwidth:
10 GHz; 25 GHz and 50 GHz

Chirped Bragg Gratings (CBGs) for
Qubit Control

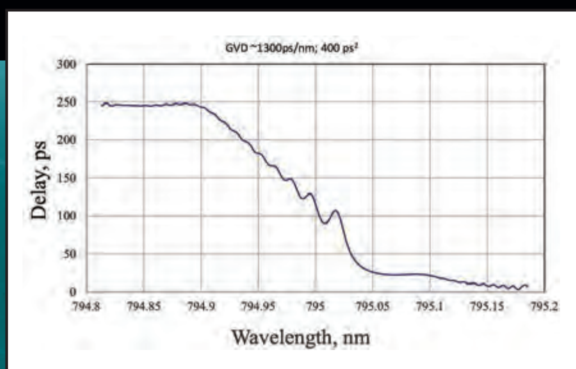
Extremely Large Dispersion 800 ps² enables effective and fast amplitude modulation

Spectral Range: 530-2500 nm; High Efficiency> 95%; Wavelength Tunable



Schematic Diagram of CBG deployment for Qubit Filtering and Control

Group delay dispersion of Chirped Bragg grating (CBG)



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

How to ensure that quantum technologies continue thriving

Quantum physicist **Mauro Paternostro** shares his views on the most exciting quantum breakthroughs, its intersection with AI, and his vision of the quantum future

Queen's University Belfast

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 talks to Tushna Commissariat about the most exciting recent developments in the filed, his call for a Quantum Erasmus programme and his plans for the future of the journal.

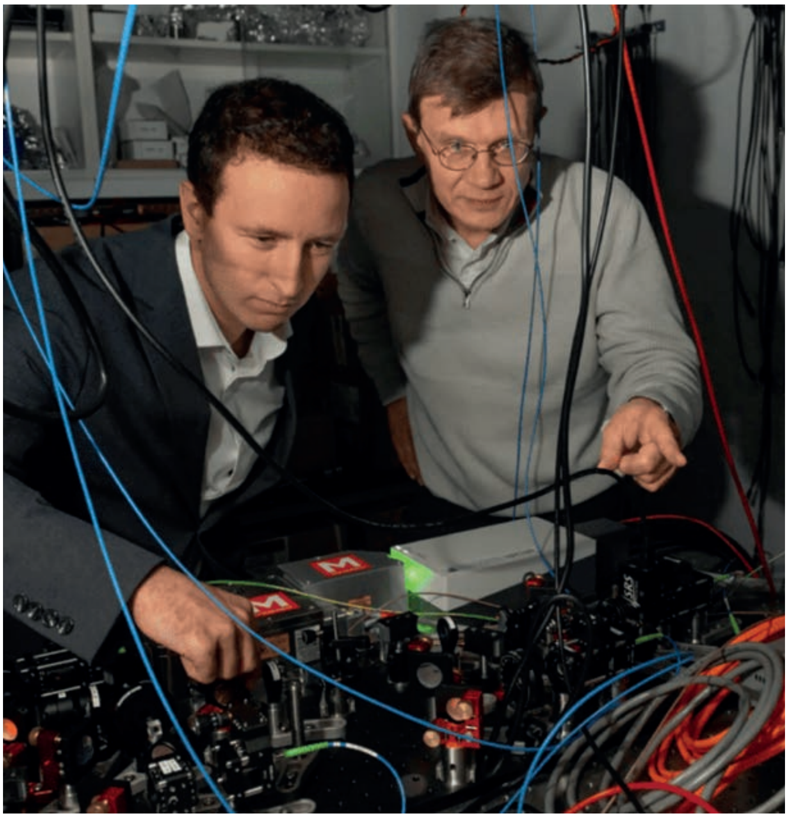
What's been the most interesting development in quantum technologies over the last year or so?

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



Jon Chase/Harvard University

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

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 momentum. 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.

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

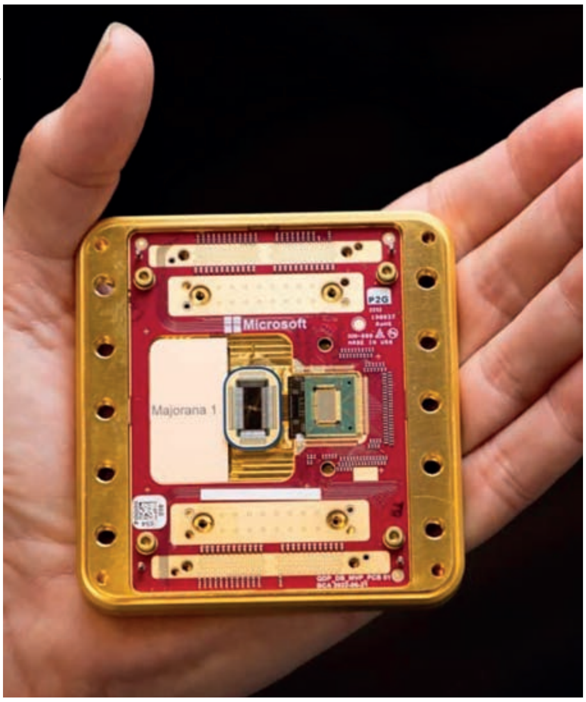
The IYQ represents a global acknowledgment, at the highest levels, of the immense potential within this field. It presents a genuine opportunity to raise awareness worldwide about what a quantum paradigm for technological development can mean for humankind. It serves as a keyhole into the future, and 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*



John Brecher/Microsoft

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

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. ■

Greetings to Ursula's cat

Robert P Crease pays tribute to the science-fiction writer Ursula K Le Guin, who first introduced Schrödinger's famous image into popular culture

Ursula K Le Guin Foundation

Feline inspiration Sketch by Ursula K Le Guin of her cat Lorenzo. A lifelong cat lover, in 1974 she published a short story called "Schrödinger's cat" in the science-fiction anthology *Universe 5*.

The world's most famous cat is everywhere. It appears on cartoons, T-shirts, board games, puzzle boxes and glow-in-the-dark coffee cups. There's even a gin named after the celebrity animal. Boasting "lovely aromas of fresh mint and lemon zest", with notes of basil, blueberries, cardamom and lemon-thyme – and "a strong backbone of juniper" – it's yours for just £42.95 for 500 ml.

You know whom I'm talking about. But despite its current ubiquity, the fictitious animal only really entered wider public consciousness after the US science-fiction and fantasy writer Ursula K Le Guin published a short story called "Schrödinger's cat" just over 50 years ago. Le Guin, who died in 2018 at the age of 88, was a widely admired writer, who produced more than 20 novels and over 100 short stories.

Schrödinger originally invented the cat image as a gag. If true believers in quantum mechanics are right that the microworld's uncertainties are dispelled only when we observe it, Schrödinger felt, this must also sometimes happen in the macroworld – and that's ridiculous. Writing in a paper published in 1935 in the German-language journal *Naturwissenschaften* (**23** 807), he presented his famous cat-in-a-box image to show why such a notion is foolish.

For a while, few paid attention. According to an "Ngram" search of Google Books carried out by Steven French, a philosopher of science at the University of Leeds in the UK, there were no citations of the phrase "Schrödinger's cat" in the literature for almost 20 years. As French describes in his 2023 book *A Phenomenological Approach to Quantum Mechanics*, the first reference appeared in a footnote to an essay by the philosopher Paul Feyerabend in the 1957 book *Observation and Interpretation in the Philosophy of Physics* edited by Stephan Körner.

The American philosopher and logician Hilary Putnam (1926–2016) first learned of Schrödinger's image around 1960. "I always assumed the physics community was familiar with the idea," Putnam later recalled, but he found few who were. In his 1965 paper "A philosopher looks at quantum mechanics" Putnam called it "absurd" to say that human observers determine what exists. But he was unable to refute the idea.

Invoking Schrödinger's image, Putnam found that we are indeed unable to say "that the cat is either alive or dead, or for that matter that the cat is even a cat, as long as no-one is looking". Putnam had another worry too. Quantum formalism required that if he looked at a quantum event, it would throw himself into superposition. Putnam concluded that "no satisfactory interpretation of quantum mechanics exists today".

> Le Guin was entranced by the implied uncertainties and appreciated the fantastic nature of Schrödinger's image

Enter Le Guin

It was to be another decade before the cat and its bizarre implications jumped into popular culture. In 1974 Le Guin published *The Dispossessed* (1974), an award-winning book about a physicist whose new, relativistic theory of time draws him into the politics of the pacifist-anarchist society in which he lived. According to Julie Phillips, who is writing a biography of Le Guin, she read up on relativity theory to make her character's "theory of simultaneity" sound plausible.

"My best guess," Phillips wrote in an e-mail to me, "is that she discovered Schrödinger's cat while doing research for the novel." Le Guin, it appears, seems to have read Putnam's article in about 1972. "The Cat & the apparatus exist, & will be in State 0 or State 1, IF somebody looks," Le Guin wrote in a note to herself. "But if he doesn't look, we can't say they're in State 0, or State 1, or in fact exist at all."

Unlike Putnam, Le Guin was entranced by the implied uncertainties and appreciated the fantastic nature of Schrödinger's image. "If we can say nothing about the definite values of micro-observables, when not measuring them, except that they exist, then their existence depends on our observation & measurement."

In "Schrödinger's cat", which Le Guin finished in September 1972 but didn't publish for another two years, an unnamed narrator senses that "things appear to be coming to some sort of climax". A yellow cat appears. The narrator grieves but doesn't know why.

A musical note makes her want to cry but she doesn't know for what, and thinks the cat knows but is unable to tell her. She then remembers Michelangelo's painting *The Last Judgment*, of a man dragged down to hell who clamps a hand over one eye in horror but keeps the other eye open and clear. The doorbell rings and in walks Rover, a dog.

Rover pulls a box out of his knapsack with a quantum-mechanical gadget that will either shoot or not shoot the cat once it gets inside and the lid is closed. Before we open the lid, Rover says, the cat is neither dead nor alive. "So it is beautifully demonstrated that if you desire certainty, any certainty, you must create it yourself."

The narrator is not sure. Don't we ourselves get "included in the system"; aren't we still inside a yet bigger box? She's reminded of the Greek legend of Pandora, who opens her box and lets out all its evil contents. She and Rover open the lid, but find the box empty.

The house roof flies off "just like the lid of a box" and "the unconscionable, inordinate light of the stars" shines down. The narrator finally identifies the note, whose tone is now much clearer once the stars are visible. The narrator wonders whether the cat knows what it was they lost.

Speculative genius Ursula K Le Guin in 1995.

Le Guin's story was soon followed by other fictional and non-fictional treatments of quantum mechanics in which Schrödinger's cat is a major figure. Examples include the *Schrödinger's Cat Trilogy* (Robert Anton Wilson, 1979); *Schrödinger's Baby: a Novel* (H R McGregor, 1999); *Schrödinger's Ball* (Adam Felber, 2006); *Blueprints of the Afterlife* (Ryan Budinot, 2012). There have also been a number of short stories including F Gwynplaine MacIntyre's "Schrödinger's cat-sitter" from 2001.

The critical point

Phillips called Le Guin's "Schrödinger's cat" a "slight, playful story with an undercurrent of sorrow", and warned me not to overthink it. "You could think of it as 'a fantasy writer looks at quantum mechanics'," she explained, adding that Le Guin wrote in her journal that fantasy as a genre and physics as a science are approaches to reality that reject common sense. "I think," Phillips concluded, "she may have been playing around with her sense, at that moment, that physics was another way of expressing the fantastic."

If so, Le Guin unerringly found the right image.

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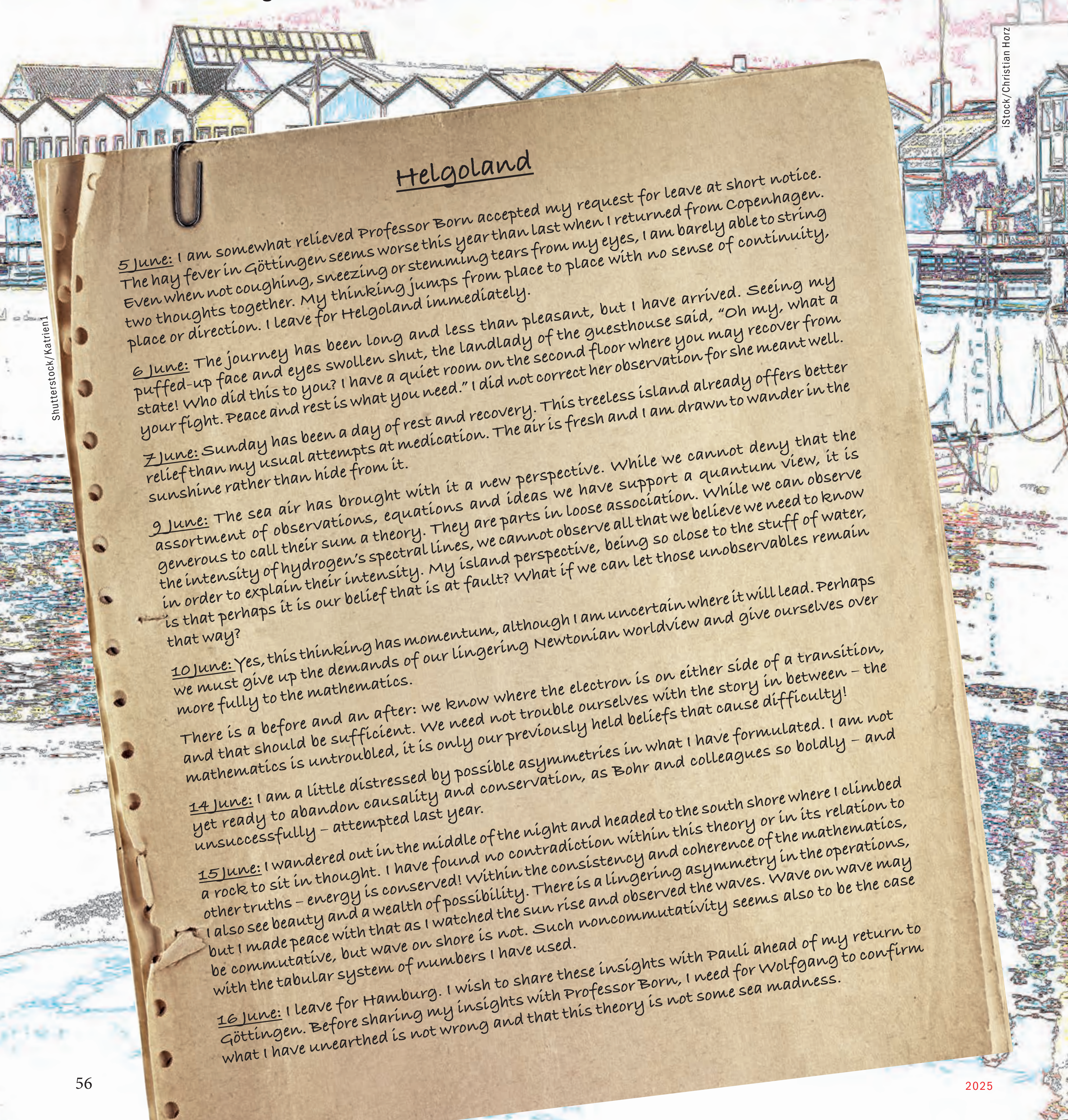
Heisenberg |not⟩ in Helgoland:

In a dark corner of a guest house in Helgoland, a diary by Werner Heisenberg has been discovered, describing how he developed quantum mechanics on the island 100 years ago. But in an even stranger twist of events, a second diary – perhaps from an alternate reality where he never made it to the island – has seemingly been unearthed in his lab at the University of Göttingen. **Kevlin Henney** presents edited extracts from the imagined notebooks.



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Helgoland

5 June: I am somewhat relieved Professor Born accepted my request for leave at short notice. The hay fever in Göttingen seems worse this year than last when I returned from Copenhagen. Even when not coughing, sneezing or stemming tears from my eyes, I am barely able to string two thoughts together. My thinking jumps from place to place with no sense of continuity, place or direction. I leave for Helgoland immediately.

6 June: The journey has been long and less than pleasant, but I have arrived. Seeing my puffed-up face and eyes swollen shut, the landlady of the guesthouse said, "Oh my, what a state! Who did this to you? I have a quiet room on the second floor where you may recover from your fight. Peace and rest is what you need." I did not correct her observation for she meant well.

7 June: Sunday has been a day of rest and recovery. This treeless island already offers better relief than my usual attempts at medication. The air is fresh and I am drawn to wander in the sunshine rather than hide from it.

9 June: The sea air has brought with it a new perspective. While we cannot deny that the assortment of observations, equations and ideas we have support a quantum view, it is generous to call their sum a theory. They are parts in loose association. While we can observe the intensity of hydrogen's spectral lines, we cannot observe all that we believe we need to know in order to explain their intensity. My island perspective, being so close to the stuff of water, is that perhaps it is our belief that is at fault? What if we can let those unobservables remain that way?

10 June: Yes, this thinking has momentum, although I am uncertain where it will lead. Perhaps we must give up the demands of our lingering Newtonian worldview and give ourselves over more fully to the mathematics.

There is a before and an after: we know where the electron is on either side of a transition, and that should be sufficient. We need not trouble ourselves with the story in between – the mathematics is untroubled, it is only our previously held beliefs that cause difficulty!

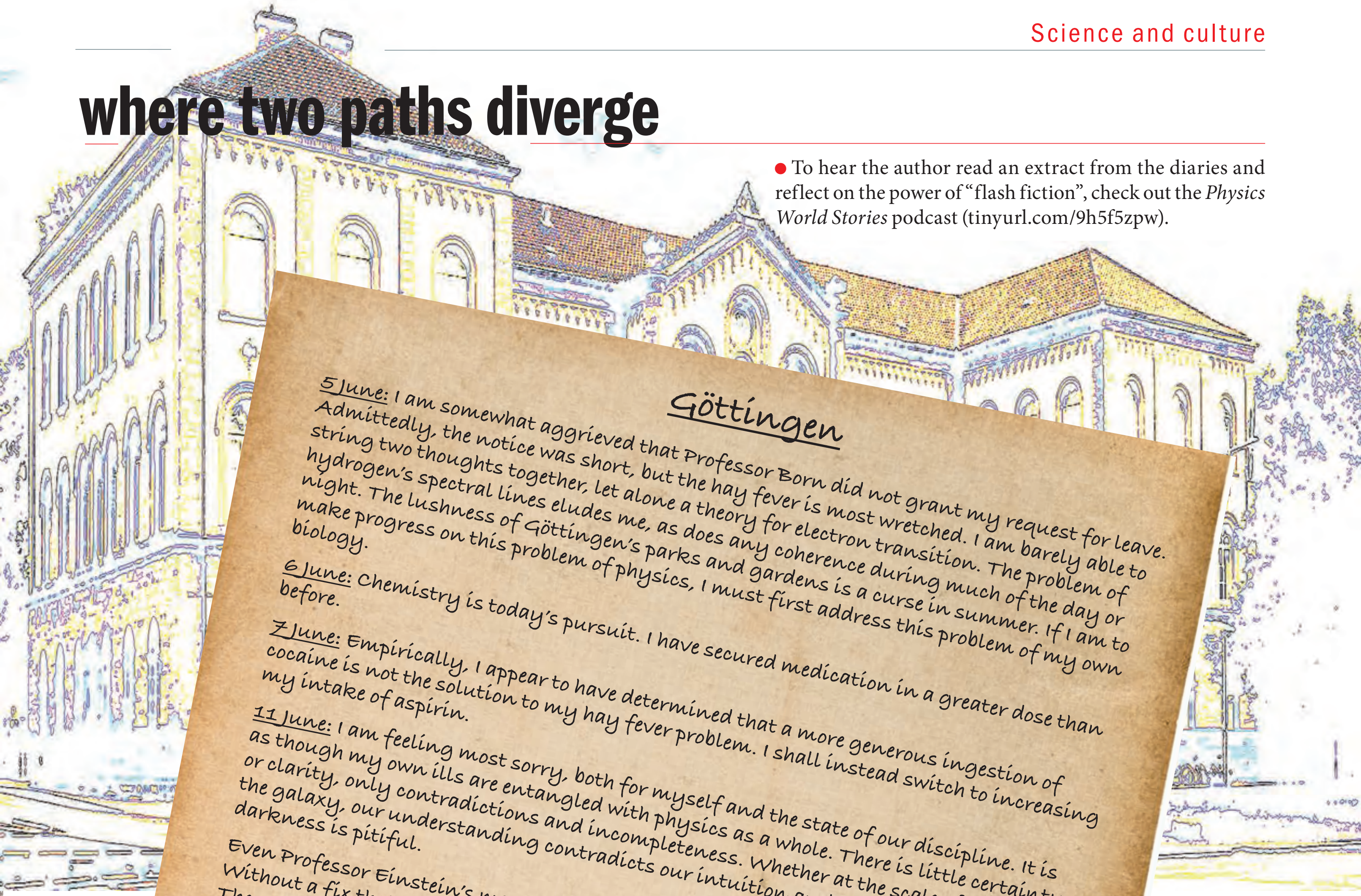
14 June: I am a little distressed by possible asymmetries in what I have formulated. I am not yet ready to abandon causality and conservation, as Bohr and colleagues so boldly – and unsuccessfully – attempted last year.

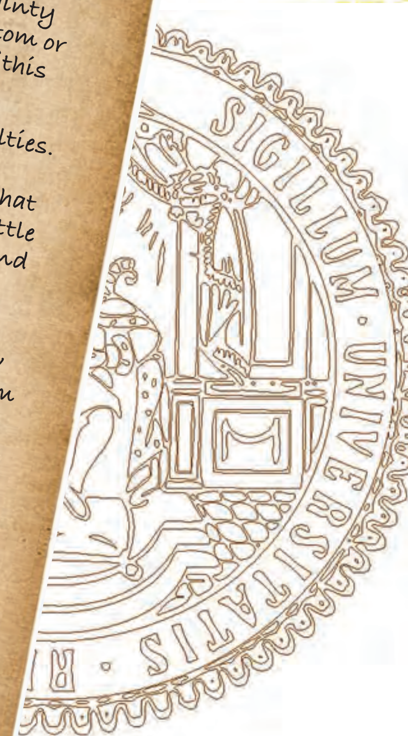
15 June: I wandered out in the middle of the night and headed to the south shore where I climbed a rock to sit in thought. I have found no contradiction within this theory or in its relation to other truths – energy is conserved! Within the consistency and coherence of the mathematics, I also see beauty and a wealth of possibility. There is a lingering asymmetry in the operations, but I made peace with that as I watched the sun rise and observed the waves. Wave on wave may be commutative, but wave on shore is not. Such noncommutativity seems also to be the case with the tabular system of numbers I have used.

16 June: I leave for Hamburg. I wish to share these insights with Pauli ahead of my return to Göttingen. Before sharing my insights with Professor Born, I need for Wolfgang to confirm what I have unearthed is not wrong and that this theory is not some sea madness.

where two paths diverge

● To hear the author read an extract from the diaries and reflect on the power of "flash fiction", check out the *Physics World Stories* podcast (tinyurl.com/9h5f5zpw).





Göttingen

5 June: I am somewhat aggrieved that Professor Born did not grant my request for leave. Admittedly, the notice was short, but the hay fever is most wretched. I am barely able to string two thoughts together, let alone a theory for electron transition. The problem of hydrogen's spectral lines eludes me, as does any coherence during much of the day or night. The lushness of Göttingen's parks and gardens is a curse in summer. If I am to make progress on this problem of physics, I must first address this problem of my own biology.

6 June: Chemistry is today's pursuit. I have secured medication in a greater dose than before.

7 June: Empirically, I appear to have determined that a more generous ingestion of cocaine is not the solution to my hay fever problem. I shall instead switch to increasing my intake of aspirin.

11 June: I am feeling most sorry, both for myself and the state of our discipline. It is as though my own ills are entangled with physics as a whole. There is little certainty or clarity, only contradictions and incompleteness. Whether at the scale of the atom or the galaxy, our understanding contradicts our intuition and our progress out of this darkness is pitiful.

Even Professor Einstein's magnificent general theory of relativity has its difficulties. Without a fix that lacks any theoretical origin, it predicts an expanding universe! There are even solutions that permitted dark stars whose gravity would be so large that nothing could escape! We are mired in questions and nonsense, all the while I am little more than coughs, sneezes and reddened eyes. What I might generously call my mind is barely deserving of the name.

I am consoled, at least, that in mathematics the story is not the same. Russell and Whitehead have shown that mathematics is complete and consistent – although I know of no one who has managed to read the whole proof. This result offers a firm bedrock I am sure mathematicians will continue to celebrate a hundred years from now.

15 June: I was en route to the department this morning when I entirely lost my bearings after taking a wrong turn from my usual route. Imagine knowing where I was going but not knowing where I was!

Just last week I had the opposite experience. My landlady accosted me just in front of the Friedhofskapelle Stadtfriedhof. I was as surprised to see her as we was to see me. "Good day, Professor Heisenberg." I long ago stopped reminding her that I was no professor, merely a Privatdozent. She means well. "Where are you heading?" And do you know, I had no idea! How I wish, though, that Born had let me travel to Helgoland.

16 June: As I walk – and sneeze – into the university this morning, I am caused to wonder from where answers to our quantum troubles might emerge. Bohr has great insight, so will it be from Copenhagen that an interpretation will appear? Or perhaps it will from Cambridge — Paul Dirac's thinking is particularly fresh.

For now, I wish an end to summer and the fog it has brought to my thinking, yet I also wonder whether we are asking more of nature than she is prepared to share with us. Perhaps it is our dearly held beliefs that hold us back. Perhaps nature and mathematics do not share those beliefs. Perhaps. There is an uncertainty within me that I find hard to articulate.

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Kevlin Henney is a software development consultant and writer based in Bristol, UK. Somewhere in his past is a degree in physics.

Explore more

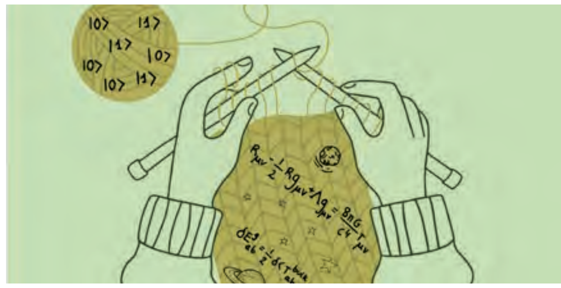
Qubits and pieces

Learn more about the history, mystery and applications of quantum physics in these features, all of which you can find on the *Physics World* website. In the digital issue you can click each picture to read – or scan the QR codes.

Thirty years of against measurement

Despite its many successes, physicists are still struggling to nail down a coherent interpretation of quantum mechanics, as it best represents "reality". **Jim Baggott** explores the arguments put forth by John Bell just before his death, and looks at theoretical and experimental evidence accumulated since.

Knitting space–time out of quantum entanglement



Clara Aldegunde goes on an intellectual journey to understand how quantum phenomena may thread together the fabric of space–time, giving rise to our reality.

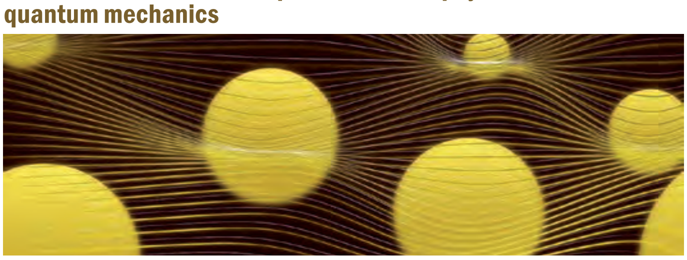
Can we use quantum computers to make music?

Computers and digital technology are central to the modern music industry – but what could quantum computers bring to the party? **Philip Ball** tunes in to an avant-garde band of musicians and scientists who are exploring how quantum computing can be used to make and manipulate music.

Why you shouldn't be worried about talk of a 'quantum winter'

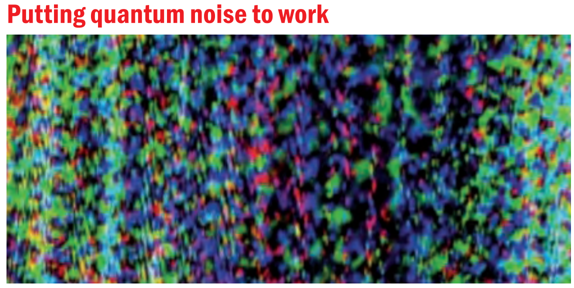
A recent fall in global private investment in quantum technology has led to suggestions that the sector is heading for a downturn. **James McKenzie** is unfazed and believes the future for the sector is bright. Investors, he thinks, are simply getting more tuned into this powerful emerging market.

How the Stern–Gerlach experiment made physicists believe in quantum mechanics



In 1922 the German physicists Otto Stern and Walther Gerlach carried out an experiment that gave an important credibility boost to the new-fangled notion of quantum mechanics. But as **Hamish Johnston** discovers, their now-famous experiment succeeded even if the physics on which it was based wasn't quite right.

Putting quantum noise to work



Could noise in a quantum system be used to do work? **Philip Ball** looks at new research that's attempting to make a feature of a fault, which may also link quantum mechanics to thermodynamics on a fundamental level.

Explore more

Enjoy our pick of the best recent quantum-themed *Physics World* podcasts.

Helgoland: leading physicists to gather on the tiny island where quantum mechanics was born

This *Physics World* podcast celebrates the centenary of Werner Heisenberg's trip to the North Sea island of Helgoland by exploring the latest advances in quantum science and technology with **Nathalie De Leon** of Princeton University, **Ana Maria Rey** from the University of Colorado Boulder, and **Jack Harris** from Yale University. All three experts, who are attending the Helgoland 2025 anniversary conference, discuss the latest developments in quantum sensing, quantum information and quantum computing.

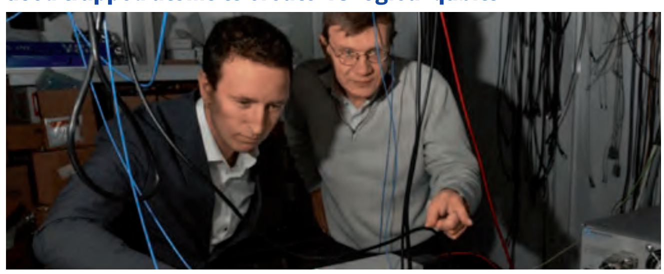
IYQ: our celebrations begin with a look at quantum networks and sensors

Turkish quantum physicist **Mete Atatüre**, who is head of the Cavendish Laboratory at the University of Cambridge in the UK, talks about hosting Quantour, the quantum light source that is IYQ's version of the Olympic torch. He also discusses his group's research on quantum sensors and quantum networks.

Quantum sensors monitor brain development in children

Margot Taylor – director of functional neuroimaging at Toronto's Hospital for Sick Children – explains how she uses optically-pumped magnetometers (OPMs) to do magnetoencephalography (MEG) studies of brain development in children. The OPM-MEG helmets are made by Cerca Magnetics and the UK-based company's managing director **David Woolger** joins the conversation to explain how the technology works. Finally, **Stuart Nicol**, chief investment officer at Quantum Exponential, gives his perspective on the medical sector.

Mikhail Lukin and Dolev Bluvstein explain how they used trapped atoms to create 48 logical qubits



Mikhail Lukin and **Dolev Bluvstein** from Harvard University in the US explain the crucial role that error correction is playing in the development of practical quantum computers. They also describe how atoms are moved around their quantum processor and why this coordinated motion let them make logical qubits with which they performed quantum computations.

Working in quantum tech: where are the opportunities for success?

Matthew Hutchings, chief product officer and co-founder of US firm SEEQC, talks about the increasing need for engineering positions in quantum tech – a sector that used to be dominated by people with a PhD in quantum physics. Meanwhile, **Araceli Venegas-Gomez**, chief executive of quantum-recruitment specialists QURECA, explains how she is building bridges between quantum information science and business.

Quantum science and technology thrives when industry and governments join forces

This podcast features **Celia Merzbacher**, executive director of the US-based Quantum Economic Development Consortium, who explains how she works with industry and governments to tackle gaps in quantum-related technologies, standards and workforces. Merzbacher, who has a research background, also shares her insights on the challenges of building a quantum workforce and explains why the strong coordination of academia, industry and governments is essential for future success.

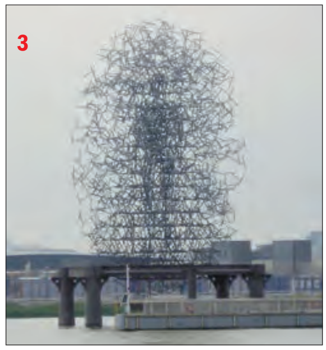
Test your quantum know-how

Quantum physics can be baffling but see how much you know in this quiz devised by **Matin Durrani**

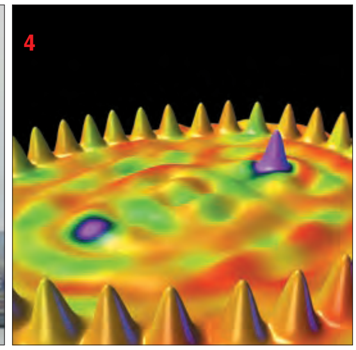
Jorge Cham; IOP Publishing

1 Can you name the mascot for IYQ 2025?

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



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



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

Andy Roberts IBM Research/Science Photo Library

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

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

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

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

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

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

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

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

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

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

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

● This quiz is for fun and there are no prizes. Answers are on the *Physics World* website.