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2025/2026

Quantum
Briefing 2.0

Centenary celebrations
Tales from Helgoland and beyond

Causal chaos
Superpositions and the order of time

Entangled ecosystems
Surveying today's quantum tech landscape

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Quantum Briefing 2.0

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William Phillips *Nobel laureate*

INTERNATIONAL YEAR OF
Quantum Science
and Technology

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IOP Publishing

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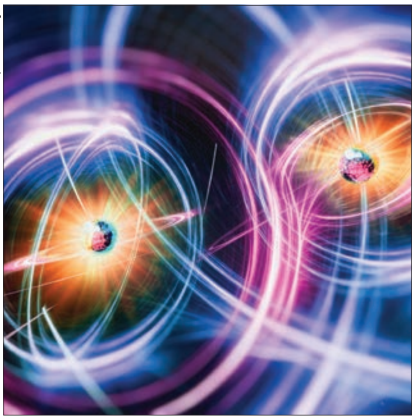

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Quantum for the future

Welcome to the 2025 *Physics World Quantum Briefing 2.0*, which wraps up the International Year of Quantum Science and Technology (IYQ) and looks ahead to a quantum-enhanced future

Celebrating 100 years since the advent of quantum mechanics, IYQ was designed to raise awareness of the impact of quantum physics and its myriad future applications. It certainly appears to have been a success with a global diary of quantum-themed public talks, scientific conferences, industry events and more.

The Institute of Physics (IOP), which publishes *Physics World*, is one of the IYQ's six founding members, and the UK and Ireland has certainly had a packed year. Highlights include the opening meeting hosted by the Royal Society in February; a week-long UK parliamentary exhibition on quantum run by the IOP in June; plus numerous hackathons and careers events.

I'm therefore delighted to introduce the 2025 *Physics World Quantum Briefing* 2.0, which follows on from the first edition published in May. Containing yet more quantum topics for you to explore, it's once again divided into "history", "mystery" and "industry".

Here, you can find out more about the contributions of Indian physicist Satyendra Nath Bose to quantum science (p11); explore weird phenomena such as causal order and quantum superposition (p20); and discover the latest applications of quantum computing (p37 and p44).

As IYQ draws to a close, the UK is giving it a worthy send-off with an entire "Quantum Week" in early November. Top of the bill is a two-day IOP conference – *Quantum Science and Technology: The First 100 Years; Our Quantum Future* – at the historic Royal Institution (RI) in London. The IOP and the National Physical Laboratory are hosting public events too, including a talk at the RI by quantum scientist and TV presenter Jim Al-Khalili.

A century after quantum mechanics was first formulated, many physicists are still undecided on some of the most basic foundational questions. There's no agreement on which interpretation of quantum mechanics holds strong; whether the wavefunction is merely a mathematical tool or a true representation of reality; or what impact an observer has on a quantum state.

Some of the biggest unanswered questions in physics – such as finding the quantum/classical boundary or reconciling gravity and quantum mechanics – lie at the heart of these conundrums. So as we look to the future of quantum – from its fundamentals to its technological applications – let us hope that some answers to these puzzles will become apparent, as we crack the quantum code to our universe.

Tushna Commissariat
Features editor, *Physics World*

Quantum tunnelling bags Nobel prize

The 2025 Nobel Prize for Physics has gone to John Clarke, Michel Devoret and John Martinis for the discovery of macroscopic tunnelling, as **Hamish Johnston** and **Michael Banks** report

John Clarke, Michel Devoret and John Martinis last month won the 2025 Nobel Prize for Physics "for the discovery of macroscopic quantum mechanical tunnelling and energy quantization in an electric circuit". The award includes a SEK 11m prize (£0.87m), which is shared equally by the winners. The prize will be presented at a ceremony in Stockholm on 10 December.

The trio carried out their prizewinning work in the mid-1980s at the University of California, Berkeley. At the time Devoret was a postdoc and Martinis was a graduate student – both working for Clarke, who is a Fellow of the Institute of Physics (IOP). They were looking for evidence of macroscopic quantum tunnelling (MQT) in a Josephson junction, which comprises two pieces of superconductor separated by an insulating barrier. In 1962 the British physicist Brian Josephson predicted how the Cooper pairs of electrons that carry current in a superconductor can tunnel across the barrier unscathed. This Josephson effect was confirmed experimentally in 1963.

The lowest-energy (ground) state of a superconductor is a macroscopic quantum state in which all Cooper pairs are described by a single quantum-mechanical wavefunction. In the late 1970s, the British-American physicist Anthony Leggett proposed that the tunnelling of this entire macroscopic state could be observed in a Josephson junction. The idea is to put the system into a metastable state in which electrical current flows without resistance across the junction – resulting in zero voltage across the junction. If the system is indeed a macroscopic quantum state, then it should be able to occasionally tunnel out of this metastable state, resulting in a voltage across the junction.

This tunnelling can be observed by increasing the current through the junction and measuring the current at which a voltage occurs – obtaining an average value over many such measurements. As the temperature of the device is reduced, this average current increases – something that is expected regardless of whether the system is in a macroscopic quantum state. However, at very low temperatures the average current becomes independent of temperature, which is the signature of macroscopic quantum tunnelling that Martinis, Devoret and Clarke were seeking.

Quantum pioneers (from left to right) John Clarke, Michel H Devoret and John M Martinis.
UC Berkeley; Yale University; UC Santa Barbara

As well as observing the signature of tunnelling, they were also able to show that the macroscopic quantum state exists in several different energy states. Such a multilevel system is essentially a macroscopic version of an atom or nucleus, with its own spectroscopic structure. Their challenge was to reduce the noise in their experimental apparatus, because noise has a similar effect as tunnelling on their measurements. The noise-control techniques developed by the trio to observe MQT and the fact that a Josephson junction can function as a macroscopic multilevel quantum system have led to the development of superconducting quantum bits (qubits) that form the basis of some nascent quantum computers.

During a press conference announcing the prize, Clarke noted that he was "stunned" upon hearing the news. "To put it mildly, it was the surprise of my life," noted Clarke. "It had never occurred to me that this might be the basis of a Nobel prize." As well as acknowledging the contributions of Devoret and Martinis, Clarke also said that their work was made possible by the work of Leggett and Josephson – previous Nobel winners themselves – who laid the groundwork for their work on tunnelling in superconducting circuits. At a Berkeley press conference later that day, Clarke noted that he was afforded time and resources such as lab space, students and equipment to carry out the work. He warned that current cuts to US science are an "immensely serious problem" that will cripple US science. "It is going to be disastrous if this continues," Clarke added.

This year's prize is also timely given that physicists are celebrating the International Year for Quantum Science and Technology. "It is wonderful in the International Year of Quantum to see this area of physics being recognized," says IOP chief executive Tom Grinyer. "The IOP is doubly proud to see one of our own celebrated by the Nobel committee and our congratulations extend to Michel Devoret and John Martinis for their important and remarkable work."

From the lab to industry

As well as having scientific significance, the trio's work has led to the development of nascent commercial quantum computers that employ superconducting circuits. Physicist and tech entrepreneur Ilana Wisby, who co-founded Oxford Quantum Circuits, told *Physics World* "It's such a brilliant and well-deserved recognition for the community," while Izhar Medalsy, co-founder and chief executive officer of the US-based Quantum Elements, added it is "remarkable that experiments performed four decades ago to probe fundamental questions about quantum mechanics at the macroscopic scale have become the basis for one of the leading platforms in the quest for practical quantum computing today".

Michael Hush, chief scientist of Q-CTRL based in Sydney, Australia, also offered his congratulations. "By proving that engineered superconducting systems could act as controllable 'artificial atoms', their work laid the essential foundation for the development of superconducting qubits, one of the leading platform for today's quantum computers," Hush notes. "This recognition not only honours their groundbreaking contributions to fundamental physics, but also highlights their profound impact on the technologies that are shaping the future of quantum information science."

AUDIO *Physics World*'s Hamish Johnston talks about this year's Nobel prize with Ilana Wisby – a quantum physicist, deep tech entrepreneur and former CEO of UK-based Oxford Quantum Circuits

Lives in science

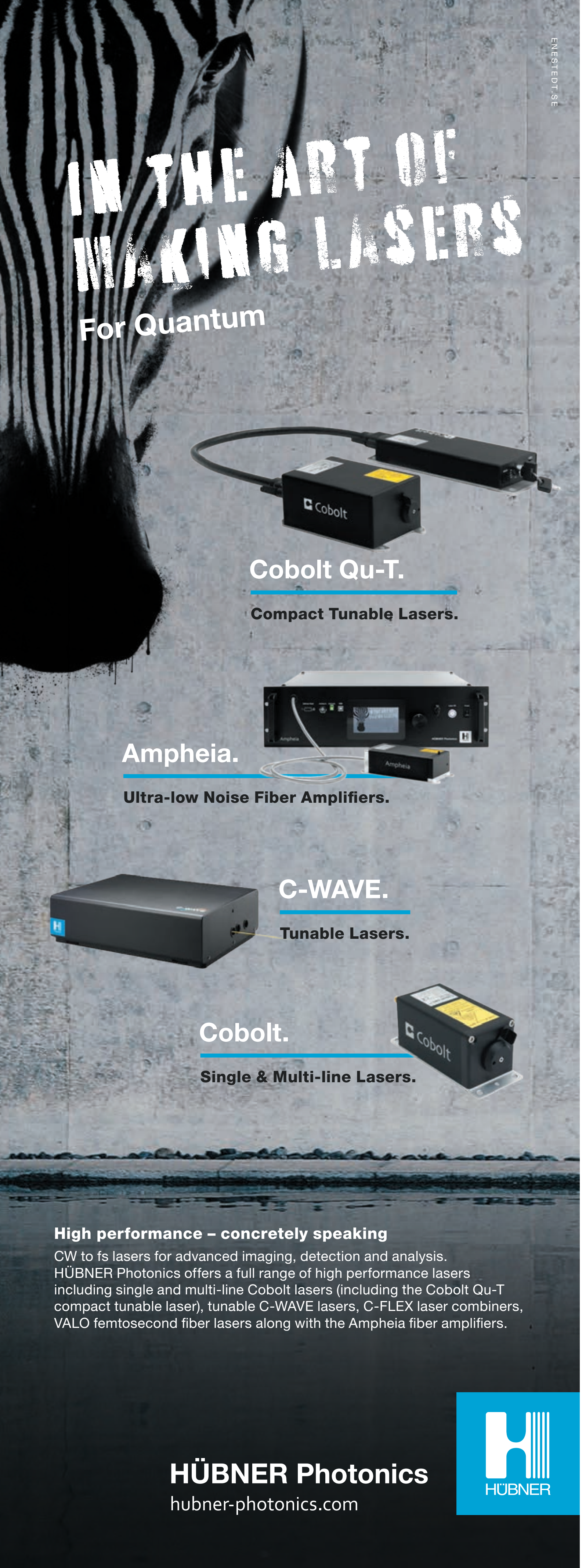
Clarke was born in 1942 in Cambridge, UK. He received his BA in physics from the University of Cambridge in 1964, staying on there to do a PhD, which he completed in 1968. He then moved to the University of California, Berkeley, to carry out a postdoc before joining the physics faculty in 1969 where he has remained since.

Devoret was born in Paris, France in 1953. He graduated from Ecole Nationale Superieure des Telecommunications in Paris in 1975 before earning a PhD from the University of Paris, Orsay, in 1982. He then moved to the University of California, Berkeley, to work in Clarke's group collaborating with Martinis who was a graduate student at the time. In 1984 Devoret returned to France to start his own research group at the Commissariat à l'Energie Atomique in Saclay (CEA-Saclay) before heading to the US to Yale University in 2002. In 2024 he moved to the University of California, Santa Barbara, and also became chief scientist at Google Quantum AI.

The trio's work laid the essential foundation for the development of superconducting qubits

Martinis was born in the US in 1958. He received a BS in physics in 1980 and a PhD in physics both from the University of California, Berkeley. He then carried out postdocs at CEA-Saclay and the National Institute of Standards and Technology in Boulder, Colorado, before moving to the University of California, Santa Barbara, in 2004. In 2014 Martinis and his team joined Google with the aim of building the first useful quantum computer before he moved to Australia in 2020 to join the start-up Silicon Quantum Computing. In 2022 he co-founded the company Qolab, of which he is currently the chief technology officer.

Hamish Johnston is an online editor of *Physics World*. **Michael Banks** is news editor of *Physics World*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Helgoland 2025: the quantum island of adventure

More than 300 top quantum physicists gathered on Helgoland in June for a conference that was billed as a highlight of the International Year of Quantum Science and Technology. Matin Durrani reveals what the meeting achieved

When Werner Heisenberg travelled to Helgoland in June 1925, he surely couldn't have imagined that more than 300 researchers would make the same journey exactly a century later. But his development of the principles of quantum mechanics on the tiny North Sea island proved so significant that the *crème de la crème* of quantum physics, including four Nobel laureates, attended a five-day conference on Helgoland in June to mark the centenary of his breakthrough.

Just as Heisenberg had done, delegates travelled to the German archipelago by boat, leading one person to joke that if the ferry from Hamburg were to sink, "that's basically quantum theory scuppered for a generation". Fortunately, the vessel survived the four-hour trip up the river Elbe and 50 km out to sea – despite strong winds almost leading to a last-minute cancellation. The physicists returned in one piece too, meaning the future of quantum physics is safe.

These days Helgoland is a thriving tourist destination, offering beaches, bird-watching and boating, along with cafes, restaurants and shops selling luxury goods (the island benefits from being duty-free). But even 100 years ago it was a popular resort, especially for hay-fever sufferers like Heisenberg, who took a leave of absence from his post-doc under Max Born in Göttingen to seek refuge from a particularly bad bout of the illness on the windy and largely pollen-free island.

More than five years in the making, Helgoland 2025 was organized by Florian Marquardt and colleagues at the Max Planck Institute for the Science of Light and Yale University quantum physicist Jack Harris, who said he was "very happy" with how the meeting turned out. As well as the quartet of Nobel laureates – Alain Aspect, Serge Haroche, David Wineland and Anton Zeilinger – there were many eager and enthusiastic early-career physicists who will be the future stars of quantum physics.

Questioning the foundations

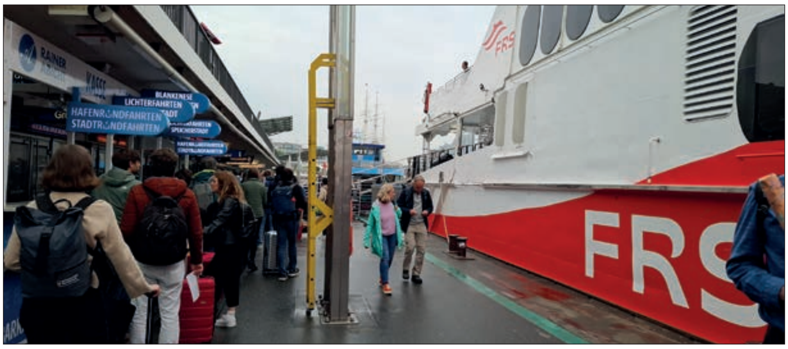
When quantum physics began 100 years ago, only a handful of people were involved in the field. As well as Heisenberg and Born, there were the likes of Erwin Schrödinger, Paul Dirac, Wolfgang Pauli, Niels Bohr and Pascual Jordan. If WhatsApp had existed back then, the protagonists would have fitted into their own small group chat (perhaps called "The Quantum Apprentices"). But these days quantum physics is a far bigger endeavour.

With 31 lectures, five panel debates and more than 100 posters, Helgoland 2025 had sessions covering everything from the fundamentals of quantum mechanics and quantum information to applied topics such as sensors and quantum computing. In fact, Harris said in an after-dinner speech on the conference's opening night in Hamburg that he and the organizing team could easily have "filled two or three solid programmes with people from whom we would have loved to hear".

Harris's big idea was to bring together theorists working on the foundational aspects of quantum mechanics with researchers applying those principles to quantum computing, sensing and communications. "[I hoped they] would enjoy talking to each other on an equal footing," he told me after the meeting. "These topics have a lot of overlap, but that overlap isn't always well-represented at conferences devoted to one or the other."

In terms of foundational questions, speakers covered issues such as entanglement, superposition, nonlocality, the meaning of measurement and the nature

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



All images: Matin Durrani

Quantum centenary After taking a ferry from Hamburg (top left), physicists at the Helgoland 2025 conference took part in talks, poster sessions and discussions in the island's Nordseehalle, where the four Nobel laureates in attendance (top right) signed a book marking the occasion (from left to right – Anton Zeilinger, Alain Aspect, Serge Haroche and David Wineland). While on the island, there was a visit to the plaque (centre left) that had been installed in 2000 by the Max Planck Society near the spot where Werner Heisenberg said he formulated the principles of quantum mechanics in June 1925.

Bahar Gholipour

Tracy Northup, Michelle Simmons and Peter Zoller talk about their views on this conference

AUDIO

Where it all began More than 300 quantum physicists attended the Helgoland 2025 conference on 9–14 June celebrating the centenary of quantum mechanics.

of information, particles, quantum states and randomness. Nicholas Gisin from the University of Geneva said physics is, at heart, all about extracting information from nature. Renato Renner from ETH Zurich discussed how to treat observers in quantum physics. Zeilinger argued that quantum states are states of knowledge – but, if so, do they exist only when measured?

Italian theorist and author Carlo Rovelli, who was constantly surrounded in the coffee breaks, gave a lecture on loop quantum gravity as a solution to marrying quantum physics with general relativity. In a talk on quantizing space–time, Juan Maldacena from the Institute for Advanced Study in Princeton discussed information loss and black holes, saying that a "white" black hole the size of a bacterium would be as hot as the Sun and emit so much light we could see it with the naked eye.

Markus Aspelmeyer from the University of Vienna spoke about creating non-classical (i.e. quantum) sources of gravity in table-top experiments and tackled the prospect of gravitationally induced entanglement. Jun Ye from the University of Colorado, Boulder, talked about improving atomic clocks for fundamental physics. Bill Unruh from the University of British Columbia discussed the nature of particles, concluding that: "A particle is what a particle detector detects".

It almost came as a relief when Gemma de les Coves from the Universitat Pompeu Fabra in Barcelona flashed up a slide joking: "I do not understand quantum mechanics."

Applying quantum ideas

Discussing foundational topics might seem self-indulgent given the burgeoning (and financially lucrative) applications of quantum physics. But those basic questions are not only intriguing in their own right – they also help to attract newcomers into quantum physics. What's more, practical matters like quantum computing, code breaking and signal detection are not just technical and engineering endeavours. "They hinge on our ability to understand those foundational questions," says Harris.

In fact, plenty of practical applications were discussed at Helgoland. As Michelle Simmons from the University of New South Wales pointed out, the last 25 years have been a "golden age" for experimental quantum physics. "We now have the tools that allow us to manipulate the world at the very smallest length scales," she said in an interview for the *Physics World Weekly* podcast. "We're able for the first time to try and control quantum states and see if we can use them for different types of information encoding or for sensing."

One presenter discussing applications was Jian-Wei Pan from the University of Science and Technology of China, who spoke about quantum computing and quantum communication across space, which relies on sustaining quantum entanglement over long distances and times. David Moore from Yale discussed some amazing practical experiments his group is doing using levitated, trapped silica microspheres as quantum sensors to detect what he called the "invisible" universe – neutrinos and perhaps even dark matter.

Nergis Mavalvala from the Massachusetts Institute of Technology, meanwhile, reminded us that gravitational-wave detectors, such as LIGO, rely on quantum physics to tackle the problem of "shot noise", which otherwise limits their performance. Nathalie de Leon from Princeton University, who admitted on the final day she was going a bit "stir crazy" on the island, discussed quantum sensing with diamond.

Outside influences

Helgoland 2025 proved that quantum physicists have much to shout about, but also highlighted the many challenges still lying in store. How can we move from systems with just a few quantum bits to hundreds or thousands? How can quantum error correction help make noisy quantum systems reliable? What will we do with an exponential speed-up in computing? Is there a clear border between quantum and classical physics – and, if so, where is it?

By cooping participants together on an island with such strong historical associations, Harris hopes that Helgoland 2025 will have catalysed new thinking. "I got to meet a lot of people I had always wanted to meet and re-connect with folks I'd been out of touch with for a long time," he said. "I had wonderful conversations that I don't think would have happened anywhere else. It is these kinds of person-to-person connections that often make the biggest impact."

> It is these kinds of person-to-person connections that often make the biggest impact
>
> Jack Harris, quantum physicist at Yale University

Occasionally, though, the outside world did encroach on the meeting. To a round of applause, Rovelli said that physicists must keep working with Russian scientists, and warned of the dangers of demonizing others. Pan, who had to give his talk on a pre-recorded video, said

> Big advances usually come from international collaboration or friendly competition
>
> Gerd Leuchs from the Max Planck Institute for the Science of Light

it was "with much regret" that he was prevented from travelling to Helgoland from China. There were a few rumbles about the conference being sponsored in part by the US Air Force Office of Scientific Research and the Army Research Office.

Quantum physicists would also do well to find out more about the philosophy of science. Questions like the role of the observer, the nature of measurement, and the meaning of non-locality are central to quantum physics but are philosophical as much as scientific. Even knowing the philosophy relevant to the early years of quantum physics is important. As Elise Crull from the City University of New York said: "Physicists ignore this early philosophy at their peril."

Towards the next century

The conference ended with a debate, chaired by Tracy Northup from the University of Innsbruck, on the next 100 years of quantum physics, where panellists agreed that the field's ongoing mysteries are what will sustain it. "When we teach quantum mechanics, we should not be hiding the open problems, which are what interest students," said Lorenzo Maccone from the University of Pavia in Italy. "They enjoy hearing there's no consensus on, say the Wigner's friend paradox. They seem engaged [and it shows] physics is not something dead."

The importance of global links in science was underlined too. "Big advances usually come from international collaboration or friendly competition," said panellist Gerd Leuchs from the Max Planck Institute for the Science of Light. "We should do everything we can to keep up collaboration. Scientists aren't better people but they share a common language. Maintaining links across borders dampens violence."

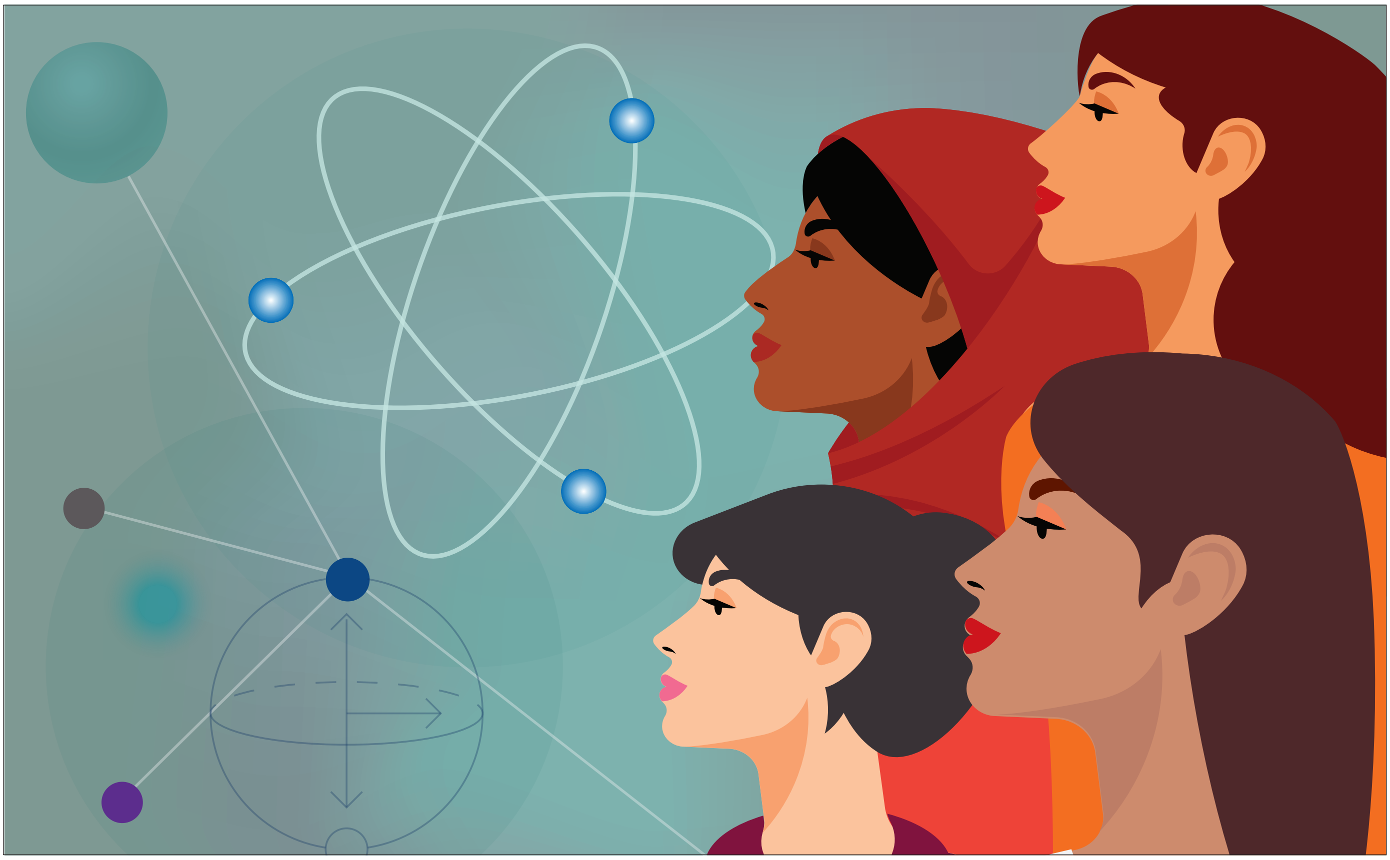
Leuchs also reminded the audience of the importance of scientists admitting they aren't always right. "Scientists are often viewed as being arrogant, but we love to be proved wrong and we should teach people to enjoy being wrong," he said. "If you want to be successful as a scientist, you have to be willing to change your mind. This is something that can be useful in the rest of society."

I'll leave the final word to Max Lock – a postdoc from the Technical University of Vienna – who is part of a new generation of quantum physicists who have grown up with the weird but entirely self-consistent world of quantum physics. Reflecting on what happened at Helgoland, Lock said he was struck most by the contrast between what was being celebrated and the celebration itself.

"Heisenberg was an audacious 23-year-old whose insight spurred on a community of young and revolutionary thinkers," he remarked. "With the utmost respect for the many years of experience and achievements that we saw on the stage, I'm quite sure that if there's another revolution around the corner, it'll come from the young members of the audience who are ready to turn the world upside down again." ■

- Tracy Northup and Michelle Simmons appear with fellow quantum physicist Peter Zoller on the 19 June 2025 episode of the *Physics World Weekly* podcast

India's women of quantum and the legacy of Satyendra Nath Bose


Alison Tovey, IOP Publishing

Satyendra Nath Bose didn't just make huge contributions to quantum science, he also welcomed women into what was at the time a male-dominated field. **Tanusri Saha-Dasgupta** and **Rupamanjari Ghosh** discuss Bose's scientific and social legacy, and celebrate the women now at the forefront of quantum science in India

The 1920s was an era of transformation. In the US, the "Roaring Twenties" saw industrial growth, the rise of consumerism, and huge social change, marked by jazz music, prohibition and flapper fashion. Europe, meanwhile, was recovering from the devastating First World War, and experiencing political and economic instability alongside flourishing artistic and intellectual movements. And India – which was still under British rule at the time – was embracing Mahatma Gandhi's policy of non-violence and civil disobedience, accelerating its nationalistic movement towards independence.

Amid worldwide cultural and sociopolitical change, another revolution was unfolding in science, particularly in our understanding of physical phenomena that cannot be explained by the classical laws of physics. Intense efforts were being made by European scientists to reconcile puzzling observations, and ground-breaking ideas were being introduced – such as Max Planck's hypothesis of "quanta" and Albert Einstein's quantization of electromagnetism. The first quantum revolution was flourishing.

In the midst of this excitement, a modest man from Bengal in undivided India, Satyendra Nath Bose, was teaching physics at Dacca (now Dhaka) University. He was greatly inspired by the new ideas in physics, and set about trying to solve the big inconsistency with the Plank distribution of black body radiation – the fact that it mixed classical and quantum concepts. Bose introduced the ground-breaking notion of indistinguishability of particles into the evolving quantum theory to rectify the problem, culminating in an equation describing the distribution of energy in the radiation from a black body purely based on quantum physics.

Bose's derivation of Planck's law impressed Einstein, who had also been trying to solve the problem. He translated the work and submitted it to *Zeitschrift für Physik* journal on Bose's behalf. Bose's novel quantum statistical approach later became known as Bose–Einstein sta-

Tanusri Saha-Dasgupta is a senior professor and director at S N Bose National Centre for Basic Sciences. **Rupamanjari Ghosh** is the former vice-chancellor of Shiv Nadar University, Delhi NCR, and a former professor of physics and dean at the School of Physical Sciences, Jawaharlal Nehru University, New Delhi

Photographer unknown

Legacy lives on Satyendra Nath Bose in London, 1925.

tistics. Einstein followed up with its extension to atoms and the prediction of Bose–Einstein condensates. Bose's work was a breakthrough for quantum mechanics, and there have since been many discoveries and multiple Nobel prizes awarded for work related to his research. He also laid the foundation for novel technologies that are central to today's "second quantum revolution". This exciting era encompasses themes such as quantum computing, communications, sensing and metrology, and materials and devices. Bose's scientific breakthroughs were not his only contributions to physics at the time.

Competent and capable

Bose lived in an era when women were not welcome in the scientific community in India, as was the case in much of the rest of the world. Infamously, in 1933 biochemist Kamala Sohonie – who went on to be the first Indian woman to get a PhD in a scientific discipline – was denied admission to the Indian Institute of Science by the then-director Chandrasekhara Venkata Raman. Best known for his work on light scattering, Raman believed that women were not competent enough to do scientific research. While Sohonie eventually did get a place, she had to fight hard for it, and Raman enforced certain restrictions. For example, she was on probation for a year and Raman had to approve her work before it could be officially recognized.

Bose on the other hand, did not make any distinction between men and women as far as scientific ability was concerned. In 1951 he welcomed PhD student Purnima

Leading lights

Co-authors of this article, Tanusri Saha-Dasgupta and Rupamanjari Ghosh, are leading quantum scientists in India.

Tanusri Saha-Dasgupta
Director and senior professor at S N Bose National Centre for Basic Sciences in West Bengal, Tanusri Saha-Dasgupta uses computational tools to predict and understand novel quantum systems. A recent objective of her research has been to study extreme sensitivity and colossal response of strongly correlated quantum materials to external perturbations to develop them as quantum sensors. Her research aims to find new quantum information platforms – including detectors and qubits – based on correlated multipolar materials as well as developing novel quantum sensor platforms.

Saha-Dasgupta has been fascinated by scientific research since childhood. Her father was a doctoral researcher in physics when she started school, and she was determined to be a scientist too. She studied physics at Presidency College in Kolkata for her bachelor's degree. In a class of 22 students, there were only four women, and coming from an all-girls school, it was a challenge to cope in the male-dominated environment. However, her passion for science helped her succeed. Saha-Dasgupta ranked first in her master's at the University of Calcutta, and carried out her PhD work at the S N Bose Centre affiliated to University of Calcutta.

Following her studies, she did postdocs at the aerospace lab ONERA in Paris, France, and later at the Max Planck Institute in Stuttgart, Germany. Studying abroad was not easy for Saha-Dasgupta, as it was filled with hurdles, including serious illness and being separated from her husband. However, her persistence paid off.

Saha-Dasgupta became the first female director at the S N Bose National Centre for Basic Sciences in 2021. She is a fellow of the American Physical Society and the World Academy of Sciences, as well as all three science academies in India. As a senior professor, Saha-Dasgupta has played a pivotal role in mentoring many students, and has been in a leadership position for several national and international decision-making bodies.

Rupamanjari Ghosh
Rupamanjari Ghosh has held multiple prominent positions during her career. She was a professor of physics and dean of the School of Physical Sciences at Jawaharlal Nehru University (JNU) in New Delhi, before moving to Shiv Nadar University (SNU), a new, privately funded research university in the Delhi region. Here she was director of the School of Natural Sciences, and then vice-chancellor of the university. Under her leadership, SNU received the title of "Institution of Eminence" from the government of India within just a few years of its existence.

Born and raised in Kolkata, Ghosh did her undergraduate and master's degrees at the University of Calcutta. Chosen for "outstanding scholarly ability and the promise of exceptional contributions to scholarship and teaching" she was awarded a Rush Rhees fellowship for her PhD studies at the University of Rochester, New York, in the US, where she was the only female PhD student to graduate under Leonard Mandel.

Ghosh is credited with the discovery of a new source of entangled photons using spontaneous parametric down-conversion, and the first experimental demonstration of two-photon interference exhibiting nonlocality. Her group at JNU has worked extensively on the critical issue of decoherence from a quantum to a classical state in specific models. She also has an international collaboration that explores the process of electromagnetically induced transparency – which is a promising approach for implementing quantum memory.

While science and technology are deeply intertwined, Ghosh emphasizes the importance of inventions in science, often arising from singular, deep ideas, that define the "what" of a problem. She is also a big advocate for equality in physics.

Ghosh continues to mentor the next generation of researchers as a governing or advisory council member at several institutions in India. She has also been extensively involved as an expert with the National Quantum Mission (NQM) of the government of India. Furthermore, she is currently the first and only international member on the advisory board of the Executive Leadership Academy at the University of California, Berkeley, US.

The tradition continues

The tradition of succession from guru to disciple set up by Satyendra Nath Bose continues. The students of Tanusri Saha-Dasgupta and Rupamanjari Ghosh (see box on opposite page) inspired by their passion have now made their mark as established researchers.

Swastika Chatterjee

Swastika Chatterjee is an associate professor at the Indian Institute of Science Education and Research in Kolkata. Her research focuses on understanding quantum effects in Earth phenomena, such as the planet's magnetism and dynamo motion.

Chatterjee completed her undergraduate degree in physics with chemistry and maths at the University of Delhi, before specializing in condensed-matter physics for her master's. She went on to do her PhD under Tanusri Saha-Dasgupta at the S N Bose National Centre for Basic Science. Chatterjee got married during her studies, and she submitted her thesis while expecting her child. Her daughter was born just a few days later, and trying to balance motherhood and her career posed a significant challenge, but she succeeded through perseverance and determination. "The workplace environment has evolved significantly over the last decade, thanks to our academic predecessors who fought their way out," she says.

Joyee Ghosh

An associate professor of physics at the Indian Institute of Technology, Delhi, Joyee Ghosh is working to understand photon–atom interactions at the single-particle level, to be used in quantum networks. Her team's research involves "trusted-node-free" secure quantum communication, based on free-space and fibre-based entangled photon sources.

Ghosh grew up in Kolkata and then got her master's and PhD degrees from Jawaharlal Nehru University (JNU), under the supervision of Rupamanjari Ghosh. She went on to do postdoctoral research in Spain as a Marie Curie fellow, and in Germany as an Alexander von Humboldt fellow.

"My journey so far underscores the tenacity and positivity required by women physicists in India to navigate systemic challenges, secure funding and gain recognition in a complex and competitive scientific landscape," says Ghosh. "I have been fortunate to learn from great teachers and work in some of the best experimental research facilities."

Sinha to his group at the University of Calcutta. Despite being the only woman in the team, Sinha succeeded in leaving her indelible imprint on a male-dominated world, helped by the constant guidance and encouragement she received from Bose.

Sinha's research was on crystallographic and thermal analysis of clay samples taken from all over India. She built sophisticated X-ray instruments using military scrap equipment sold on the streets of Calcutta (now Kolkata) after the Second World War. In 1956 Sinha was awarded her doctorate, becoming the first woman to earn a PhD in physics from Calcutta University (and likely the first woman to get a PhD in physics from an institution in India).

She went on to conduct research in biophysics at Stanford University in the US, and found similarities between clay structure and DNA structure, providing pioneering thoughts on the origin of life. Sinha further broke gender stereotypes by doing masonry work, carpentry and even playing the tabla (a pair of hand drums). Bose was equally supportive of Asima Chatterjee, who started her research on medicinal plant extracts with Bose, and conducted the first small-molecule X-ray diffraction, which was ground-breaking work.

Breaking through

While times have changed and women today have more freedom to pursue science, technology, engineering and mathematics (STEM), these areas continue to be dominated by men. India produces the highest percentage of female STEM graduates in the world (43%), but women make up only 14% of the STEM workforce in the country and 18.6% of those directly involved in research and development activities.

The representation of women in the science and technology sector remains strikingly low, both in terms of job applicants and leadership roles. For example, a survey by the Council of Scientific Industrial Research (CSIR) in 2022 revealed that no woman had held the role of director general of CSIR until August of that year when chemical engineer Nallathamby Kalaiselvi became the first woman to lead the institute – a role that she still holds. Indeed, only five of the 35 CSIR labs were led by women at the time of the survey.

Gender bias and traditional role segregation are some of the key reasons why women remain under-represented in STEM careers in India. Several studies have found that women leave the workforce at key phases in their life – notably when they have children – and are also often rejected when seeking jobs because of gender discrimination.

Gender bias and traditional role segregation are some of the key reasons why women remain under-represented in STEM careers in India. However, the picture is changing rapidly

At the quantum frontier

Women at the forefront of quantum science in India today. This list is far from exhaustive, but it offers a glimpse of the broader picture.

Aditi Sen De

Aditi Sen De is a professor of physics at the Harish Chandra Research Institute in Allahabad. Her research exploits quantum mechanical principles to design quantum technologies, such as quantum communication networks, quantum thermal machines, and measurement-based quantum computers. She also characterizes resources responsible for achieving quantum technologies superior to their day-to-day versions.

Sen De was greatly inspired by her mother, a mathematics teacher, and developed a passion for teaching from an early age. "I used to teach using a small blackboard at home, imagining a classroom full of students," she explains. She completed her bachelor's degree at India's oldest women's college, Bethune College in Kolkata, before pursuing her interest in quantum and statistical physics at the University of Calcutta for her master's. Alongside her husband – they grew together both personally and professionally – she continued her scientific journey in Europe, completing her PhD at the University of Gdansk in Poland, and then doing postdoctoral research in Germany and Spain.

In 2018 Sen De was awarded the Shanti Swarup Bhatnagar Prize for Science and Technology (now the Vigyan Yuva – Shanti Swarup Bhatnagar Award). Given by the Indian government to recognize talented young scientists in all disciplines, the prize is one of the most prestigious scientific accolades in India. First awarded in 1958, only two women have ever received this honour in the physical sciences category (now physics), out of 103 recipients – a stark reflection of the gender imbalance.

Urbasi Sinha

The only other woman to receive the Bhatnagar award is Urbasi Sinha, a professor at the Raman Research Institute in Bangalore. Her research spans experimental studies on photonic quantum information processing, secure quantum communication, and precision tests of quantum mechanics.

Sinha's scientific journey was shaped by the constant support of her non-scientist parents, whose encouragement sparked her passion for discovery. After doing her undergraduate degree at Jadavpur University in Kolkata, Sinha went on to do a master's and PhD at the University of Cambridge, UK. She has gained significant international recognition for her work, with recent honours including the Canada Excellence Research Chair in Photonic Quantum Science and Technologies, the Gates Cambridge Impact Prize, and the Royal Academy of Engineering UK's Distinguished International Associateship. Sinha has also co-founded a quantum start-up, QuSyn Technologies, and leads a technical group under the NQM.

Meanwhile, as a mother raising a daughter, Sinha maintains a sense of work–life integration by being fully present – giving her complete attention to whatever requires it, whether personal or professional.

"Women in academia are breaking barriers as institutions embrace diversity," says Sinha. "While explicit obstacles fall through targeted initiatives, the academic community now faces the vital challenge of identifying subtle biases woven into institutional fabric. This evolving awareness promises a future where talent thrives regardless of gender, transforming scholarship through diverse perspectives."

Usha Devi A R

A professor at Bangalore University, Usha Devi A R is a theorist who has contributed to formulating figures of merit for non-classicality of photonic states – which are crucial for metrology, quantum target detection, quantum digital reading and more. Her team has put forth geometric visualization of spin states, which works like a fingerprint for entanglement and spin-squeezing, needed in metrology.

Devi was born in Thirthahalli town in Karnataka, where she completed her undergraduate degree in sciences. She was top of her class and received a gold medal for her master's in physics from Mysore University, where she also completed her PhD in 1998. She received the IPA young physicist award in 1997, and was a visiting scientist in Barry Sander's research group at Macquarie University in Sydney, Australia, in 2003. She also worked in Sandu Popescu's research group at the University of Bristol, UK, under a Commonwealth Academic Fellowship in 2008.

Working as a faculty member at a state-funded university comes with persistent challenges, such as limited resources for research and teaching, and sometimes outdated administrative priorities. "In quantum mechanics, we embrace uncertainty," Devi says. "In academia, we challenge it – especially as women physicists from state universities."

Kasturi Saha

Kasturi Saha is an associate professor at the Indian Institute of Technology (IIT) Bombay (Mumbai). She is the project director of Qmet Tech Foundation, the quantum sensing and metrology hub established by IIT Bombay under the National Quantum Mission (NQM) of the Government of India. She is the only female project director among the four NQM hubs established.

Saha was raised in the lively heart of Kolkata's Wellington Square, in a family filled with engineers and doctors. Drawn to the elegance of physics, she chose it as her major, inspired by the Nobel-winning work on Bose–Einstein condensates. Although she aspired to become a scientist, her decision was initially met with concern and scepticism from her family, who were worried about the challenges of pursuing a career in science – especially as female representation was (and still is) limited.

Despite their concerns, Saha's parents stood firmly by her side, supporting her throughout every step of her academic journey. After her undergraduate physics degree from St Stephen's College in Delhi, Saha moved to IIT Delhi for her master's, and then went to Cornell University in the US for her PhD. As she progressed through her degrees, the gender gap became increasingly apparent, with a sharp decline in the number of women.

Training to be an experimental physicist brought its own set of biases – people often assumed Saha couldn't handle technical tasks or heavy equipment. These subtle yet persistent doubts made her hyper-aware of her identity – she even stopped wearing pink T-shirts during her PhD. Yet, she persisted, bolstered by mentors including Michal Lipson and Paola Cappellaro.

However, the picture is changing rapidly, aided by educational initiatives and grassroots movements advocating for gender equity. The quickly growing quantum sector is no different, and the need for quantum education is greater than ever, as a shortage of trained researchers is being felt globally.

One person hoping to inspire and educate women and girls about quantum computing is Singapore-based researcher Nithyasri Srivathsan, who founded She-Quantum in 2020. The initiative has built an e-learning platform offering lectures, quantum computing courses and other educational resources, as well as articles and interviews with experts. It was listed by *The Quantum Insider* as one of the "9 Educational Platforms to get the Quantum Workforce Up & Running", alongside IBM, Microsoft and MIT xPRO among others.

Another example is Women for Quantum (W4Q), which was set up by a group of female physics professors, mostly based in Europe and Japan, who work in the field of quantum optics, quantum many-body physics and quantum information. In its manifesto, the initiative highlights the "unsatisfactory current situation of women in quantum physics" and calls for a joint effort to make real change in the field.

Celebrating success

The good news is that such efforts seem to be paying off. According to the latest All India Survey on Higher Education (AISHE) (2020–2021) women make up 42.3% of undergraduate, postgraduate, MPhil, and PhD places in STEM education. There has also been a surge in women in all fields of STEM, including quantum science, where they are making significant contributions to the second quantum revolution.

To celebrate the growing presence of women at the forefront of quantum science in India, the S N Bose National Centre for Basic Sciences in Kolkata arranged an international conference in July 2024 on Women in Quantum Science and Technologies. The meeting was part of celebrations marking the 100th anniversary of Bose's seminal work, highlighting that his legacy encompasses both quantum science and gender equality in physics.

The three-day conference consisted of six talks from accomplished female scientists, two panel discussions, three special lectures, 10 invited talks from early-career women working across quantum science and technologies, and a poster session by PhD students. The panel discussions focused on the challenges faced by women in higher education and ways to overcome them, as well as opportunities for women in the quantum arena. Speakers included Rupamanjari Ghosh, Aditi Sen De, Indrani Bose, Anjana Devi, Shohini Ghose and Efrat Shimshoni.

Such events highlight the achievements of women in the field, providing a platform for sharing research and inspiring future generations. This visibility is crucial for normalizing women's participation in science and encouraging girls to pursue careers in physics and related disciplines.

With the second quantum revolution in progress, and the next likely to be driven by commercial innovations in areas such as cybersecurity, eco-materials and medical advancements, it is important to ensure that these breakthroughs do not reinforce societal inequalities. For that, we need women, and other under-represented groups in physics, to be encouraged into the field to ensure a diverse range of ideas.

S N Bose National Centre

Opportunity for change Women in Quantum Science and Technologies was a three-day conference held in Kolkata in July 2024.

To this end, in the box opposite we highlight some women at the forefront of quantum science in India.

Beyond academia

Impressive women in quantum science are not limited to academia. Government departments and industry in India can boast of some prominent female leaders. For example, Anindita Banerjee is a product manager for quantum technology projects at the Centre for Development of Advanced Computing (CDACINDIA), a premier research and development organization founded by the Ministry of Electronics and Information Technology. Anupama Ray is an award-winning senior research scientist at IBM Research in Bangalore, where she focuses on developing quantum machine learning algorithms. Meanwhile at Microsoft India and South Asia, Rohini Srivathsa is the chief technology officer, responsible for driving technology innovation and growth across industry and the government.

In addition to the accomplished Indian women working in quantum in their home country, there are several who have built successful careers abroad. Notable cases are Anjana Devi, director of the Institute for Materials Chemistry at the Leibniz Institute for Solid State and Materials Research, Dresden, Germany; Nandini Trivedi, professor of physics at Ohio State University, US; Nilanjana Datta, professor in quantum information theory at the University of Cambridge, UK; Vidya Madhavan, professor of physics at the University of Illinois Urbana-Champaign, US; Shohini Ghose, professor of physics and computer science, and director of research and programmes for the Centre for Women in Science at Wilfrid Laurier University in Waterloo, Canada, and chief technology officer at Quantum Algorithms Institute.

The rise of women in quantum science in India is a tribute to Bose's legacy, and a sign of a more inclusive and dynamic future. To sustain this momentum, we must create ecosystems that support curiosity, collaboration and equal opportunity – ensuring that every brilliant mind, regardless of gender, has the chance to transform the world.

● *All portrait photos in this article were kindly supplied by their subjects*

Entangled histories

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

AIP Emilio Segrè Visual Archives, Physics Today Collection; AIP Emilio Segrè Visual Archives, Lisa Lisco, gift of Jost Lemmerich; Lohrisch-Achilles/ Bremen State Archives; Atomic Heritage Foundation; AIP Emilio Segrè Visual Archives, Wheeler Collection; IAEA ImageBank

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

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

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

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

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

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

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

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

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

Lost physics

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

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

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

Calculate, don't think

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

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

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

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

Quantum physics is a unique field, and women played a crucial and distinctive role in its formation

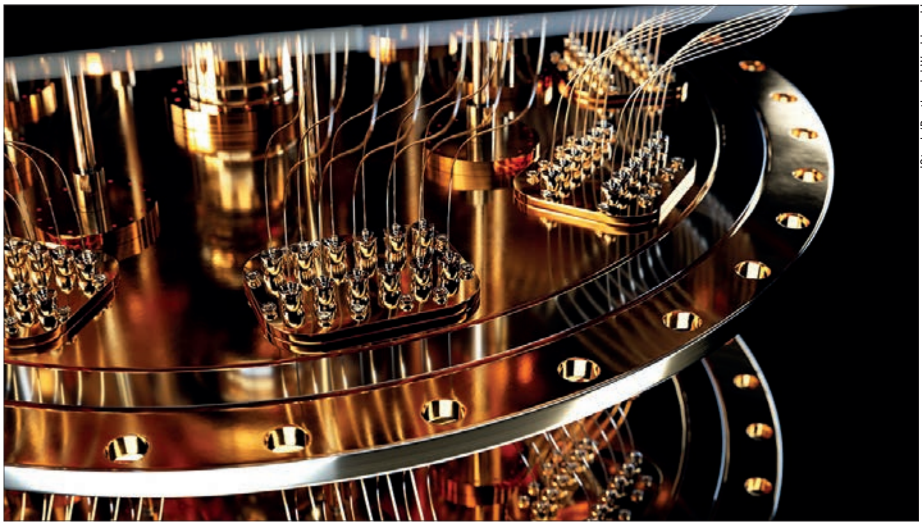
Jennifer Carter is a lecturer in the Department of Philosophy at Stony Brook University, NY, US

Performance metrics and benchmarks point the way to practical quantum advantage

The UK's National Physical Laboratory is leading a 'deep-dive' research initiative on performance metrics and benchmarking for quantum computers. It's a foundational piece of work that will ultimately help to fast-track technology translation, innovation and commercialization

From quantum utility today to quantum advantage tomorrow: incumbent technology companies – among them Google, Amazon, IBM and Microsoft – and a wave of ambitious start-ups are on a mission to transform quantum computing from applied research endeavour to mainstream commercial opportunity. The end-game: quantum computers that can be deployed at-scale to perform computations significantly faster than classical machines while addressing scientific, industrial and commercial problems beyond the reach of today's high-performance computing systems.

Meanwhile, as technology translation gathers pace across the quantum supply chain, government laboratories and academic scientists must maintain their focus on the "hard yards" of precompetitive research. That means prioritizing foundational quantum hardware and software technologies, underpinned by theoretical understanding, experimental systems, device design and fabrication – and pushing out along all these R&D pathways simultaneously.



iStock/Bartlomiej Wroblewski

Quantum connections Measurement scientists are seeking to understand and quantify the relative performance of quantum computers from different manufacturers as well as across the myriad platform technologies.

Bringing order to disorder

Equally important is the requirement to understand and quantify the relative performance of quantum computers from different manufacturers as well as across the myriad platform technologies – among them superconducting circuits, trapped ions, neutral atoms as well as photonic and semiconductor processors. A case study in this regard is a broad-scope UK research collaboration that, for the past four years, has been reviewing, collecting and organizing a holistic taxonomy of metrics and benchmarks to evaluate the performance of quantum computers against their classical counterparts as well as the relative performance of competing quantum platforms.

Funded by the National Quantum Computing Centre (NQCC), which is part of the UK National Quantum Technologies Programme (NQTP), and led by scientists at the National Physical Laboratory (NPL), the UK's National Metrology Institute, the cross-disciplinary consortium has taken on an endeavour that is as sprawling as it is complex. The challenge lies in the diversity of quantum hardware platforms in the mix; also the emergence of two different approaches to quantum computing – one being a gate-based framework for universal quantum computation, the other an analogue approach tailored to outperforming classical computers on specific tasks.

"Given the ambition of this undertaking, we tapped into a deep pool of specialist domain knowledge and expertise provided by university colleagues at Edinburgh, Durham, Warwick and several other centres-of-excellence in quantum," explains Ivan Rungger, a principal scientist at NPL, professor in computer science at Royal Holloway, University of London, and lead scientist on the quantum benchmarking project. That core group consulted widely within the research community and with quantum technology companies across the nascent supply chain. "The resulting study," adds Rungger, "positions transparent and objective benchmarking as a critical enabler for trust, comparability and commercial adoption of quantum technologies, aligning closely with NPL's mission in quantum metrology and standards."

Not all metrics are equal – or mature

For context, a number of performance metrics used to benchmark classical computers can also be applied directly to quantum computers, such as the speed of operations, the number of processing units, as well as the probability of errors to occur in the computation. That only goes so far, though, with all manner of dedicated metrics emerging in the past decade to benchmark the performance of quantum computers – ranging from their individual hardware components to entire applications.

Complexity reigns, it seems, and navigating the extensive literature can prove overwhelming, while the levels of maturity for different metrics varies significantly. Objective comparisons aren't straightforward either – not least because variations of the same metric are commonly deployed; also the data disclosed together with a reported metric value is often not sufficient


NPL

Made to measure NPL's Institute for Quantum Standards and Technology (above) is the UK's national metrology institute for quantum science.

to reproduce the results.

"Many of the approaches provide similar overall qualitative performance values," Rungger notes, "but the divergence in the technical implementation makes quantitative comparisons difficult and, by extension, slows progress of the field towards quantum advantage."

The task then is to rationalize the metrics used to evaluate the performance for a given quantum hardware platform to a minimal yet representative set agreed across manufacturers, algorithm developers and end-users. These benchmarks also need to follow some agreed common approaches to fairly and objectively evaluate quantum computers from different equipment vendors.

With these objectives in mind, Rungger and colleagues conducted a deep-dive review that has yielded a comprehensive collection of metrics and benchmarks to allow holistic comparisons of quantum computers, assessing the quality of hardware components all the way to system-level performance and application-level metrics.

Drill down further and there's a consistent format for each metric that includes its definition, a description of the methodology, the main assumptions and limitations, and a linked open-source software package implementing the methodology. The software transparently demonstrates the methodology and can also be used in practical, reproducible evaluations of all metrics.

"As research on metrics and benchmarks progresses, our collection of metrics and the associated software for performance evaluation are expected to evolve," says Rungger. "Ultimately, the repository we have put together will provide a 'living' online resource, updated at regular intervals to account for community-driven developments in the field."

From benchmarking to standards

Innovation being what it is, those developments are well under way. For starters, the importance of objective and relevant performance benchmarks for quantum computers has led several international standards bodies to initiate work on specific areas that are ready for standardization – work that, in turn, will give manufacturers, end-users and investors an informed evaluation of the performance of a range of quantum computing components, subsystems and full-stack platforms.

What's evident is that the UK's voice on metrics and benchmarking is already informing the collective conversation around standards development. "The quantum computing community and international standardization bodies are adopting a number of concepts from our approach to benchmarking standards," notes Deep Lall, a quantum scientist in Rungger's team at NPL and lead author of the study. "I was invited to present our work to a number of international standardization meetings and scientific workshops, opening up widespread international engagement with our research and discussions with colleagues across the benchmarking community."

He continues: "We want the UK effort on benchmarking and metrics to shape the broader international effort. The hope is that the collection of metrics we have pulled together, along with the associated open-source software provided to evaluate them, will guide the development of standardized benchmarks for quantum computers and speed up the progress of the field towards practical quantum advantage."

That's a view echoed – and amplified – by Cyrus Larijani, NPL's head of quantum programme. "As we move into the next phase of NPL's quantum strategy, the importance of evidence-based decision making becomes ever-more critical," he concludes. "By grounding our strategic choices in robust measurement science and real-world data, we ensure that our innovations not only push the boundaries of quantum technology but also deliver meaningful impact across industry and society."

The headline take from NQCC

Quantum computing technology has reached the stage where a number of methods for performance characterization are backed by a large body of real-world implementation and use, as well as by theoretical proofs. These mature benchmarking methods will benefit from commonly agreed-upon approaches that are the only way to fairly, unambiguously and objectively benchmark quantum computers from different manufacturers.

"Performance benchmarks are a fundamental enabler of technology innovation in quantum computing," explains Konstantinos Georgopoulos, who heads up the NQCC's quantum applications team and is responsible for the centre's liaison with the NPL benchmarking consortium. "How do we understand performance? How do we compare capabilities? And, of course, what are the metrics that help us to do that? These are the leading questions we addressed through the course of this study.

"If the importance of benchmarking is a given, so too is collaboration and the need to bring research and industry stakeholders together from across the quantum ecosystem. "I think that's what we achieved here," says Georgopoulos. "The long list of institutions and experts who contributed their perspectives on quantum computing was crucial to the success of this project. What we've ended up with are better metrics, better benchmarks, and a better collective understanding to push forward with technology translation that aligns with end-user requirements across diverse industry settings."

Further reading

Deep Lall *et al*. 2025: A review and collection of metrics and benchmarks for quantum computers: definitions, methodologies and software https://arxiv.org/abs/2502.06717.

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National Physical Laboratory

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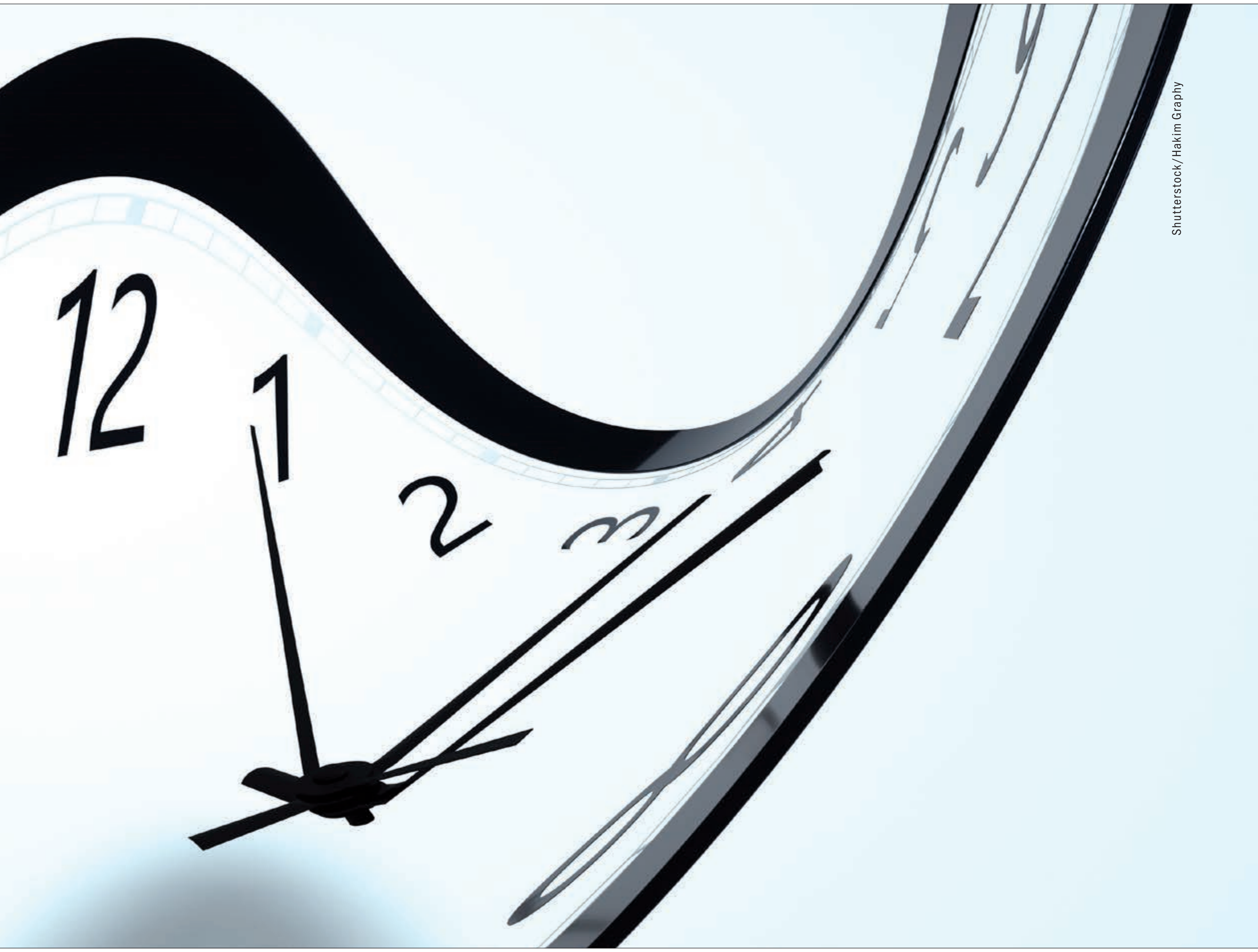
How quantum physics is challenging causality

Hamish Johnston is an online editor of *Physics World*

In the fourth of our series of truly weird quantum effects, **Hamish Johnston** becomes a casual observer of the bizarre situation in which the causal order of events are in a quantum superposition

The concept of cause and effect plays an important role in both our everyday lives, and in physics. If you set a ball down in front of a window and kick it hard, a split-second later the ball will hit the window and smash it. What we don't observe is a world where the window smashes on its own, thereby causing the ball to be kicked – that would seem rather nonsensical. In other words, kick before smash, and smash before kick, are two different physical processes each having a unique and definite causal order.

But, does definite causal order also reign supreme in the quantum world, where concepts like position and time can be fuzzy? Most physicists are happy to accept



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the paradox of Schrödinger's cat – a thought experiment in which a cat hidden in a box is simultaneously dead and alive at the same time, until you open the box to check. Schrödinger's cat illustrates the quantum concept of "superposition", whereby a system can be in two or more states at the same time. Only when a measurement is made (by opening the box), does the system collapse into one of its possible states.

But could two (or more) causally distinct processes occur at the same time in the quantum world? The answer, perhaps shockingly, is yes and this paradoxical phenomenon is called indefinite causal order (ICO).

Stellar superpositions and the order of time

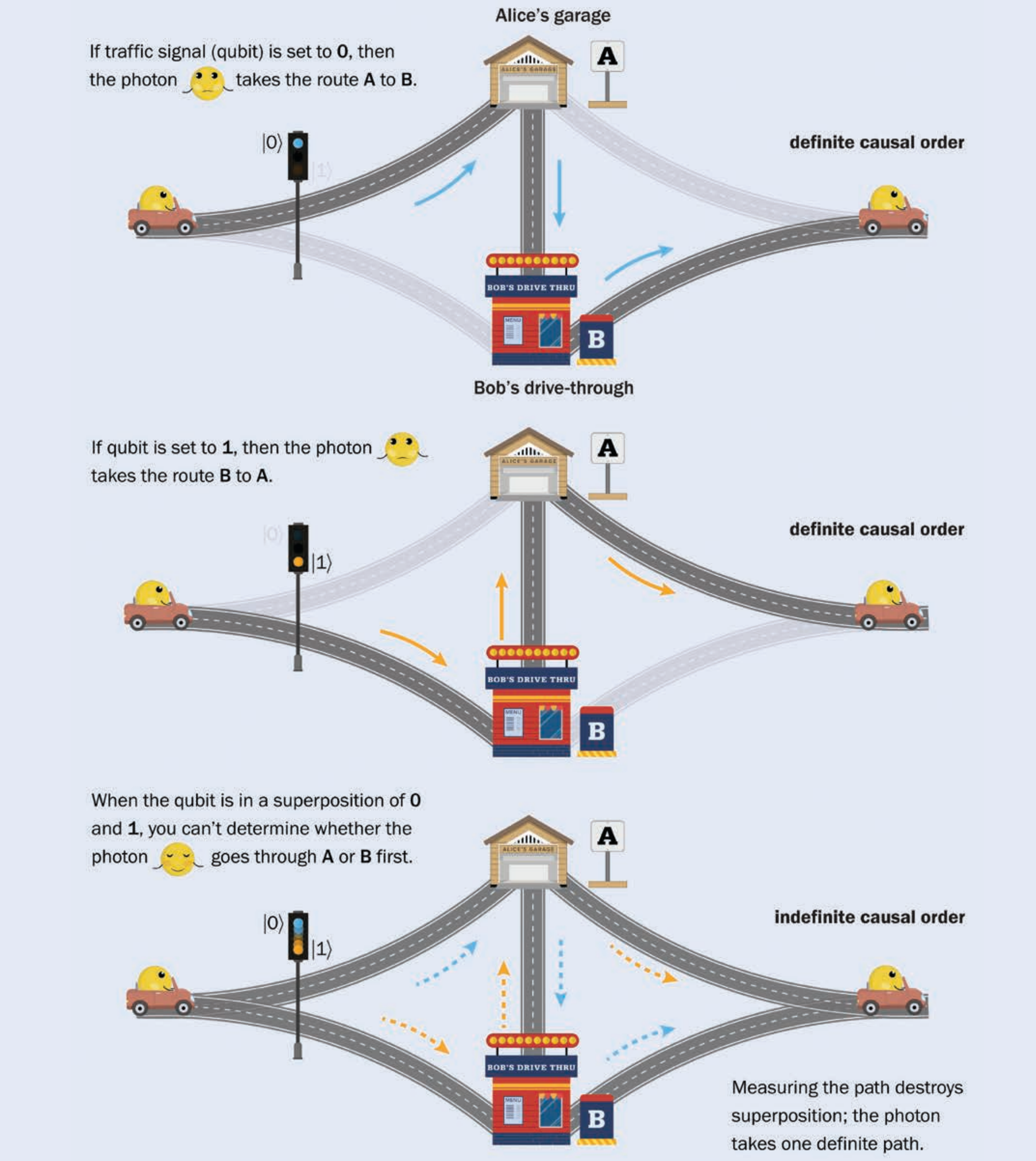
It turns out that different causal processes can also exist in a superposition. One example is a thought experiment called the "gravitational quantum switch", which was proposed in 2019 by Magdalena Zych of the University of Queensland and colleagues (*Nat. Comms* **10** 3772). This features our favourite quantum observers Alice and Bob, who are in the vicinity of a very large mass, such as a star. Alice and Bob both have initially synchronized clocks and in the quantum world, these clocks would continue to run at identical rates. However, Einstein's general theory of relativity dictates that the flow of time is influenced by the distribution of matter in the vicinity of Alice and Bob. This means that if Alice is closer to the star than Bob, then her clock will run slower than Bob's, and vice versa.

Like with Schrödinger's cat, quantum mechanics allows the star to be in a superposition of spatial states; meaning that in one state Alice is closer to the star than Bob, and in the other Bob is closer to the star than Alice. In other words, this is a superposition of a state in which Alice's clock runs slower than Bob's, and a state in which Bob's clock runs slower than Alice's.

Alice and Bob are both told they will receive a message at a specific time (say noon) and that they would then pass that message on to the their counterpart. If Alice's clock is running faster than Bob's then she will receive the message first, and then pass it on to Bob, and vice versa. This superposition of Alice to Bob with Bob to Alice is an example of indefinite causal order.

Now, you might be thinking "so what" because this

1 Simultaneous paths



In this illustration of a quantum switch a photon (driving a car) can follow two different paths, each with a different causal order. One path (top) leads to Alice's garage followed by a visit to Bob's drive thru. The second path (middle) visits Bob first, and then Alice. The path taken by the photon is determined by a control qubit that is represented by a traffic light. If the value of the qubit is "0" then the photon visits Alice First; if the qubit is "1" then the photon visits Bob first. Both of these scenarios have definite causal order.

However, the control qubit can exist in a quantum superposition of "0" and "1" (bottom). In this superposition, the path followed by the photon – and therefore the temporal order in which it visits Alice and Bob – is not defined. This is an example of indefinite causal order. Of course, any attempt to identify exactly which path the photon goes through initially will destroy the superposition (and therefore the ICO) and the photon will take only one definite path.

seems to be a trivial example. But it becomes more interesting if you replace the message with a quantum particle like a photon; and have Alice and Bob perform different operations on that photon. If the two operations do not commute – such as rotations of the photon polarization in the X and Z planes – then the order in which the operations are done will affect the outcome.

As a result, this "gravitational quantum switch" is a superposition of two different causal processes with two different outcomes. This means that Alice and Bob could do more exotic operations on the photon, such as "measure-and-reprepare" operations (where a quantum system is first measured, and then, based on the measurement outcome, a new quantum state is prepared). In this case Alice measures the quantum state of the received photon and prepares a photon that she sends to Bob (or vice versa).

Much like Schrödinger's cat, a gravitational quantum switch cannot currently be realized in the lab. But, never say never. Physicists have been able to create experimental analogues of some thought experiments, so who knows what the future will bring. Indeed, a gravitational quantum switch could provide important information regarding a quantum description of gravity – something that has eluded physicists ever since quantum mechanics and general relativity were being developed in the early 20th century.

Switches and superpositions

Moving on to more practical ICO experiments, physicists have already built and tested light-based quantum switches in the lab. Instead of having the position of the star determining whether Alice or Bob go first, the causal order is determined by a two-level quantum state – which can have a value of 0 or 1. If this control state is 0, then Alice goes first and if the control state is 1, then Bob goes first. Crucially, when the control state is in a superposition of 0 and 1 the system shows indefinite causal order (see figure 1).

The first such quantum switch was created by in 2015 by Lorenzo Procopio (now at Germany's University of Paderborn) and colleagues at the Vienna Center for Quantum Science and Technology (*Nat. Comms* **6** 7913). Their quantum switch involves firing a photon at a beam splitter, which puts the photon into a superposition of a photon that has travelled straight through the splitter (state 0) and a photon that has been deflected by 90 degrees (state 1). This spatial superposition is the control state of the quantum switch, playing the role of the star in the gravitational quantum switch.

State 0 photons first travel to an Alice apparatus where a polarization rotation is done in a specific direction (say X). Then the photons are sent to a Bob apparatus where a non-commuting rotation (say Z) is done. Conversely, the photons that travel along the state 1 path encounter Bob before Alice.

Finally, the state 0 and state 1 paths are recombined at a second beamsplitter, which is monitored by two photon-detectors. Because Alice-then-Bob has a different effect on a photon than does Bob-then-Alice, interference can occur between recombined photons. This interference is studied by systematically changing certain aspects of the experiment. For example, by changing Alice's direction of rotation or the polarization of the incoming photons.

A gravitational quantum switch could provide important information regarding a quantum description of gravity

In 2017 quantum-information researcher Giulia Rubino, then at the Vienna Center for Quantum Science and Technology, teamed up with Procopia and colleagues to verify ICO in their quantum switch using a "causal witness" (*Sci. Adv.* **3** e1602589). This involves doing a specific set of experiments on the quantum switch and calculating a mathematical entity (the causal witness) that reveals whether a system has definite or indefinite causal order. Sure enough, this test revealed that their system does indeed have ICO. Since then, physicists working in several independent labs have successfully created their own quantum switches.

Computational speed up?

While this effect might still seem somewhat obscure, in 2019, an international team led by the renowned Chinese physicist Jian-Wei Pan showed that a quantum switch can be very useful for doing computations that are distributed between two parties (*Phys. Rev. Lett.* **122** 120504). In such a scenario a string of data is received and then processed by Alice, who then passes the results on to Bob for further processing. In an experiment using photons, they showed that ICO delivers an exponential speed-up of the rate at which longer strings are processed – compared to a system with no ICO.

Physicists are also exploring if ICO could be used to enhance quantum metrology. Indeed, recent calculations by Oxford University's Giulio Chiribella and colleagues suggest that it could lead to a significant increase in precision when compared to techniques that involve states with definite causal order (*Phys. Rev. Lett.* 1**24** 190503).

While other applications could be possible, it is often difficult to work out whether ICO offers the best solution to a specific problem. For example, physicists had thought a quantum switch offered an advantage when it comes to communicating along a noisy channel, but it turns out that some configurations of Alice and Bob with definite causal order were just as good as an ICO.

Beyond the quantum switch, there are other types of circuits that would display ICO. These include "quantum circuits with quantum control of causal order", which have yet to be implemented in the lab because of their complexity.

But despite the challenges in creating ICO systems and proving that they outperform other solutions, it looks like ICO is set to join ranks of other weird phenomena such as superposition and entanglement that have found practical applications in quantum technologies. ■

William Phillips: a passion for quantum physics

William Phillips, who shared the Nobel Prize for Physics for his work on laser cooling, talks to Margaret Harris about his life in science, the weirdness of entanglement, and the future of quantum tech

William Phillips is a pioneer in the world of quantum physics. After graduating from Juniata College in Pennsylvania in 1970, he did a PhD with Dan Kleppner at the Massachusetts Institute of Technology (MIT), where he measured the magnetic moment of the proton in water. In 1978 Phillips joined the National Bureau of Standards in Gaithersburg, Maryland, now known as the National Institute of Standards and Technology (NIST), where he is still based.

Phillips shared the 1997 Nobel Prize for Physics with Steven Chu and Claude Cohen-Tannoudji for their work on laser cooling. The technique uses light from precisely tuned laser beams to slow atoms down and cool them to just above absolute zero. As well as leading to more accurate atomic clocks, laser cooling proved vital for the creation of Bose–Einstein condensates – a form of matter where all constituent particles are in the same quantum state.

To mark the International Year of Quantum Science and Technology in 2025, *Physics World* online editor Margaret Harris sat down with Phillips in Gaithersburg to talk about his life and career in physics.

"Deliciously weird" How William Phillips views quantum physics.

Listen to the full version of our interview with Bill Phillips

AUDIO

How did you become interested in quantum physics?

As an undergraduate, I was invited by one of the professors at my college to participate in research he was doing on electron spin resonance. We were using the flipping of unpaired spins in a solid sample to investigate the structure and behaviour of a particular compound. Unlike a spinning top, electrons can spin only in two possible orientations, which is pretty weird and something I found really fascinating. So I was part of the quantum adventure even as an undergraduate.

What did you do after graduating?

I did a semester at Argonne National Laboratory outside Chicago, working on electron spin resonance with two physicists from Argentina. Then I was invited by Dan Kleppner – an amazing physicist – to do a PhD with him at the Massachusetts Institute of Technology. He really taught me how to think like a physicist. It was in his lab that I first encountered tuneable lasers, another wonderful tool for using the quantum properties of matter to explore what's going on at the atomic level.

Quantum mechanics is often viewed as being weird, counter-intuitive and strange. Is that also how you felt?

I'm the kind of person entranced by everything in the natural world. But even in graduate school, I don't think I understood just how strange entanglement is. If two particles are entangled in a particular way, and you measure one to be spin "up", say, then the other particle will necessarily be spin "down" – even though there's no connection between them. Not even a signal travelling at the speed of light could get from one particle to the other to tell it, "You'd better be 'down' because the first one was measured to be 'up'." As a graduate student I didn't understand how deliciously weird nature is because of quantum mechanics.

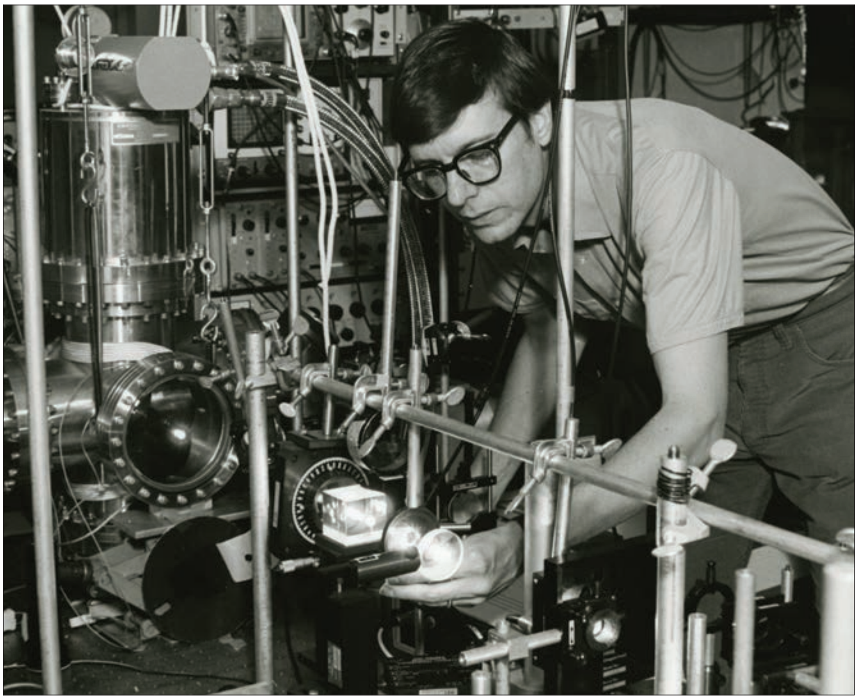
Is entanglement the most challenging concept in quantum mechanics?

It's not that hard to understand entanglement in a formal sense. But it's hard to get your mind wrapped around it because it's so weird and distinct from the kinds of things that we experience on a day-to-day basis. The thing that it violates – local realism – seems so reasonable. But experiments done first by John Clauser and then Alain Aspect and Anton Zeilinger, who shared the Nobel Prize for Physics in 2022, basically proved that it happens.

What quantum principle has had the biggest impact on your work?

Superposition has enabled the creation of atomic clocks of incredible precision. When I first came to NIST in 1978, when it was still called the National Bureau of Standards, the very best clock

NIST



Chilling out William Phillips working on laser-cooling experiments in his laboratory circa 1986.

in the world was in our labs in Boulder, Colorado. It was good to one part in 10^{13}.

Because of Einstein's general relativity, clocks run slower if they're deeper in a gravitational potential. The effect isn't big: Boulder is about 1.5 km above sea level and a clock there would run faster than a sea level clock by about 1.5 parts in 10^{13}. So if you had two such clocks – one at sea level and one in Boulder – you'd barely be able to resolve the difference. Now, at least in part because of the laser cooling and trapping ideas that my group and I have worked on, one can resolve a difference of less than 1 mm with the clocks that exist today. I just find that so amazing.

What research are you and your colleagues at NIST currently involved in?

Our laboratory has been a generator of ideas and techniques that could be used by people who make atomic clocks. Jun Ye, for example, is making clocks from atoms trapped in a so-called optical lattice of overlapping laser beams that are better than one part in 10^{18} – two orders of magnitude better than the caesium clocks that define the second. These newer types of clocks could help us to redefine the second.

We're also working on quantum information. Ordinary digital information is stored and processed using bits that represent 0 or 1. But the beauty of qubits is that they can be in a superposition state, which is both 0 and 1. It might sound like a disaster because one of the great strengths of binary information is there's no uncertainty; it's one thing or another. But putting quantum bits into superpositions means you can do a problem in a lot fewer operations than using a classical device.

In 1994, for example, Peter Shor devised an algorithm that can factor numbers quantum mechanically much faster, or using far fewer operations, than with an ordinary classical computer. Factoring is a "hard problem", meaning that the number of operations to solve it grows exponentially with the size of the number. But if you do it quantum mechanically, it doesn't grow exponentially – it becomes an "easy" problem, which I find absolutely amazing. Changing the hardware on which you do the calculation changes the complexity class of a problem.

How might that change be useful in practical terms?

Shor's algorithm is important because of public key encryption, which we use whenever we buy something online with a credit card. A company sends your computer a big integer number that they've generated by multiplying two smaller numbers together. That number is used to encrypt your credit card number. Somebody trying to intercept the transmission can't get any useful information because it would take centuries to factor this big number. But if an evildoer had a quantum computer, they could factor the number, figure out your credit card and use it to buy TVs or whatever evildoers buy.

Now, we don't have quantum computers that can do this yet – they can't even do simple problems, let alone factor big numbers. But if somebody did do that, they could decrypt messages that do matter, such as diplomatic or military secrets. Fortunately, quantum mechanics comes to the rescue through something called the no-cloning theorem. These quantum forms of encryption prevent an eavesdropper from intercepting a message, duplicating it and using it – it's not allowed by the laws of physics.

Quantum processors can be made from different qubits – not just cold atoms but trapped ions, superconducting circuits and others, too. Which do you think will turn out best?

My attitude is that it's too early to settle on one particular platform. It may well be that the final quantum computer is a hybrid device, where computations are done on one platform and storage is done on another. Superconducting quantum computers are fast, but they can't store information for long, whereas atoms and ions can store information for a really long time – they're robust and isolated from the environment, but are slow at computing. So you might use the best features of different platforms in different parts of your quantum computer.

But what do I know? We're a long way from having quantum computers that can do interesting problems faster than classical device. Sure, you might have heard somebody say they've used a quantum computer to solve a problem that would take a classical device a septillion years. But they've probably chosen a problem that was easy for a quantum computer and hard for a classical computer – and it was probably a problem nobody cares about.

When do you think we'll see quantum computers solving practical problems?

People are definitely going to make money from factoring numbers and doing quantum chemistry. Learning how molecules behave could make a big difference to our lives. But none of this has happened yet, and we may still be pretty far away from it. In fact, I have proposed a bet with my colleague Carl Williams, who says that by 2045 we will have a quantum computer that can factor numbers that a classical computer of that time cannot. My view is we won't. I expect to be dead by then. But I hope the bet will encourage people to solve the problems to make this work, like error correction. We'll also put up money to fund a scholarship or a prize.

What do you think quantum computers will be most useful for in the nearer term?

What I want is a quantum computer that can tackle problems such as magnetism. Let's say you have a 1D chain of atoms with spins that can point up or down. Quantum magnetism is a hard problem because with n spins there are 2^n possible states and calculating the overall magnetism of a chain of more than a few tens of spins is impossible for a brute-force classical computer. But a quantum computer could do the job.

There are quantum computers that already have lots of qubits but you're not going to get a reliable answer from them. For that you have to do error correction by assembling physical qubits into what's known as a logical qubit. They let you determine whether an error has happened and fix it, which is what people are just starting to do. It's just so exciting right now.

What development in quantum physics should we most look out for?

The two main challenges are: how many logical qubits we can entangle with each other; and for how long they can maintain their coherence. I often say we need an "immortal" qubit, one that isn't killed by the environment and lasts long enough to be used to do an interesting calculation. That'll determine if you really have a competent quantum computer.

Reflecting on your career so far, what are you most proud of?

Back in around 1988, we were just fooling around in the lab trying to see if laser cooling was working the way it was supposed to. First indications were: everything's great. But then we discovered that the temperature to which you could laser cool atoms was lower than everybody said was possible based on the theory at that time. This is called sub-Doppler laser cooling, and it was an accidental discovery; we weren't looking for it.

People got excited and our friends in Paris at the École Normale came up with explanations for what was going on. Steve Chu, who was at that point at Stanford University, was also working on understanding the theory behind it, and that really changed things in an important way. In fact, all of today's laser-cooled caesium atomic clocks use that feature that the temperature is lower than the original theory of laser cooling said it was.

Another thing that has been particularly important is Bose–Einstein condensation, which is an amazing process that happens because of a purely quantum-mechanical feature that makes atoms of the same kind fundamentally indistinguishable. It goes back to the work of Satyendra Nath Bose, who 100 years ago came up with the idea that photons are indistinguishable and therefore that the statistical mechanics of photons would be different from the usual statistical mechanics of Boltzmann or Maxwell.

Bose–Einstein condensates, where almost all the atoms are in the same quantum state, were facilitated by our discovery that the temperature could be so much lower. To get this state, you've got to cool the atoms to a very low temperature – and it helps if the atoms are colder to start with.

Did you make any other accidental discoveries?

We also accidentally discovered optical lattices. In 1968 a Russian physicist named Vladilen Letokhov came up with the idea of trapping atoms in a standing wave of light. This was 10 years before laser cooling arrived and made it possible to do such a thing, but it was a great idea because the atoms are trapped over such a small distance that a phenomenon called Dicke narrowing gets rid of the Doppler shift.

Everybody knew this was a possibility, but we weren't looking for it. We were trying to measure the temperature of the atoms in the laser-cooling configuration, and the idea we came up with was to look at the Doppler shift of the scattered light. Light comes in, and if it bounces off an atom that's moving, there'll be a Doppler shift, and we can measure that Doppler shift and see the

AIP Emilio Segrè Visual Archives

Sharing the excitement William Phillips performing a demo during a lecture at the Sigma Pi Sigma Congress in 2000.

distribution of velocities.

So we did that, and the velocity distribution just floored us. It was so odd. Instead of being nice and smooth, there was a big sharp peak right in the middle. We didn't know what it was. We thought briefly that we might have accidentally made a Bose–Einstein condensate, but then we realized, no, we're trapping the atoms in an optical lattice so the Doppler shift goes away.

It wasn't nearly as astounding as sub-Doppler laser cooling because it was expected, but it was certainly interesting, and it is now used for a number of applications, including the next generation of atomic clocks.

How important is serendipity in research?

Learning about things accidentally has been a recurring theme in our laboratory. In fact, I think it's an important thing for people to understand about the way that science is done. Often, science is done not because people are working towards a particular goal but because they're fooling around and see something unexpected. If all of our science activity is directed toward specific goals, we'll miss a lot of really important stuff that allows us to get to those goals. Without this kind of curiosity-driven research, we won't get where we need to go.

In a nutshell, what does quantum meant to you?

Quantum mechanics was the most important discovery of 20th-century physics. Wave–particle duality, which a lot of people would say was the "ordinary" part of quantum mechanics, has led to a technological revolution that has transformed our daily lives. We all walk around with mobile phones that wouldn't exist were it not for quantum mechanics. So for me, quantum mechanics is this idea that waves are particles and particles are waves. ■

- You can listen to the full version of this interview on the *Physics World Weekly* podcast of 4 April 2025

Margaret Harris is an online editor of *Physics World*

Why quantum technology is driving quantum fundamentals

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Quantum physics is full of scientific and philosophical mysteries, the answers to which could well emerge from the field's commercial applications. **Elise Crull** (a philosopher), **Artur Ekert** (an academic) and **Stephanie Simmons** (an industrialist) examine the complex interplay between applications and fundamentals in conversation with Hamish Johnston

Hamish Johnston is an online editor of *Physics World*

Science and technology go hand in hand but it's not always true that basic research leads to applications. Many early advances in thermodynamics, for example, followed the opposite path, emerging from experiments with equipment developed by James Watt, who was trying to improve the efficiency of steam engines. In a similar way, much progress in optics and photonics only arose after the invention of the laser.

The same is true in quantum physics, where many of the most exciting advances are occurring in companies building quantum computers, developing powerful sensors, or finding ways to send information with complete security. The cutting-edge techniques and equipment developed to make those advances then, in turn, let us understand the basic scientific and philosophical questions of quantum physics.

Quantum entanglement, for example, is no longer an academic curiosity, but a tangible resource that can be exploited in quantum technology. But because businesses are now applying this resource to real-world problems, it's becoming possible to make progress on basic questions about what entanglement is. It's a case of technological applications leading to fundamental answers, not the other way round.

As part of our Physics World Live series of online events, Elise Crull (a philosopher), Artur Ekert (an

Quantum panellists From left: Elise Crull, Artur Ekert and Stephanie Simmons.

academic) and Stephanie Simmons (an industrialist) came together to discuss the complex interplay between quantum technology and quantum foundations. Elise Crull, who trained in physics, is now associate professor of philosophy at the City University of New York. Artur Ekert is a quantum physicist and cryptographer at the University of Oxford, UK, and founding director of the Center for Quantum Technologies in Singapore. Stephanie Simmons is chief quantum officer at Photonic, co-chair of Canada's Quantum Advisory Council, and associate professor of physics at Simon Fraser University in Vancouver.

Presented here is an edited extract of their discussion, which you can watch in full online.

Can you describe the interplay between applications of quantum physics and its fundamental scientific and philosophical questions?

Stephanie Simmons: Over the last 20 years, research funding for quantum technology has risen sharply as people have become aware of the exponential speed-ups that lie in store for some applications. That commercial potential has brought a lot more people into the field and made quantum physics much more visible. But in turn, applications have also let us learn more about the fundamental side of the subject.

They have, for example, forced us to think about what quantum information really means, how it can be treated as a resource, and what constitutes intelligence versus consciousness. We're learning so much at a fundamental level because of those technological advances. Similarly, understanding those foundational aspects lets us develop technology in a more innovative way.

If you think about conventional, classical supercomputers, we use them in a distributed fashion, with lots of different nodes all linked up. But how can we achieve that kind of "horizontal scalability" for quantum computing? One way to get distributed quantum technology is to use entanglement, which isn't some kind of afterthought but the core capability.

We're learning so much at a fundamental level because of technological advances

Stephanie Simmons

How do you manage entanglement, create it, distribute it and distil it? Entanglement is central to next-generation quantum technology but, to make progress, you need to break free from previous thinking. Rather than thinking along classical lines with gates, say, an "entanglement-first" perspective will change the game entirely.

Artur Ekert: As someone more interested in the foundations of quantum mechanics, especially the nature of randomness, technology has never really been my concern. However, every single time I've tried to do pure research, I've failed because I've discovered it has interesting links to technology. There's always someone saying: "You know, it can be applied to this and that."

Think about some of the classic articles on the foundations of quantum physics, such as the 1935 Einstein–Podolsky–Rosen (EPR) paper suggesting that quantum mechanics is incomplete. If you look at them from the perspective of data security, you realize that some concepts – such as the ability to learn about a physical property without disturbing it – are relevant to cryptography. After all, it offers a way into perfect eavesdropping.

So while I enjoy the applications and working with colleagues on the corporate side, I have something of a love–hate relationship with the technological world.

Elise Crull: These days physicists can test things that they couldn't before – maybe not the really weird stuff like indefinite causal ordering but certainly quantum metrology and the location of the quantum-classical boundary. These are really fascinating areas to think about and I've had great fun interacting with physicists, trying to fathom what they mean by fundamental terms like causality.

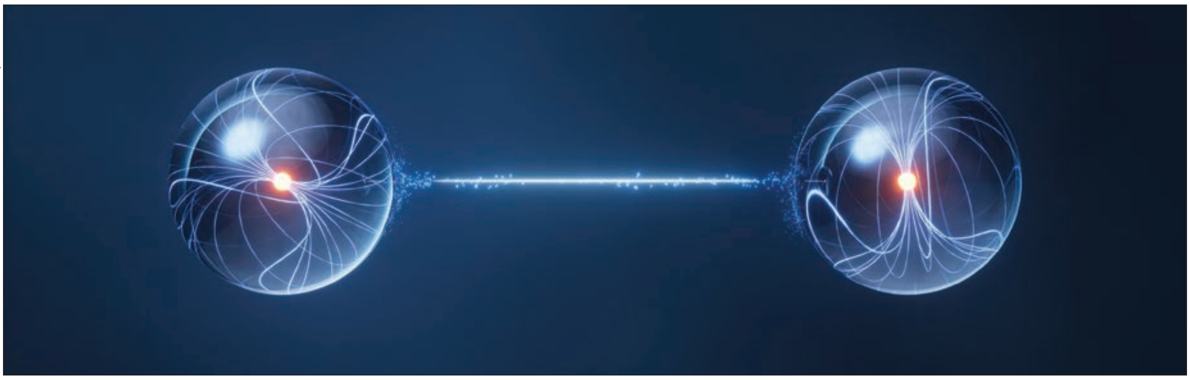
Was Schrödinger right to say that it's entanglement that forces our entire departure from classical lines of thought? What counts as non-classical physics and where is the boundary with the quantum world? What kind of behaviour is – and is not – a signature of quantum phenomena? These questions make it a great time to be a philosopher.

Do you have a favourite quantum experiment or quantum technology that's been developed over the last few decades?

Artur Ekert: I would say the experiments of Alain Aspect in Orsay in the early 1980s, who built on the earlier work of John Clauser, to see if there is a way to violate Bell inequalities. When I was a graduate student in Oxford, I found the experiment absolutely fascinating, and I was surprised it didn't get as much attention at the time as I thought it should. It was absolutely mind-blowing that nature is inherently random and refutes the notion of local "hidden variables".

There are, of course, many other beautiful experiments in quantum physics. There are cavity quantum electrodynamic and ion-trap experiments that let physicists go from controlling a bunch of atoms to individual atoms or ions. But to me the Aspect experiment was different because it didn't confirm something that we'd already experienced. As a student I remember thinking: "I don't understand this; it just doesn't make sense. It's mind-boggling."

Elise Crull: The Bell-type experiments are how I got interested in the philosophy of quantum mechanics. I wasn't around when Aspect did his first experiments, but



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Fundamental benefits
Despite being so weird, quantum entanglement is integral to practical applications of quantum mechanics.

at the recent Helgoland conference marking the centenary of quantum mechanics, he was on stage with Anton Zeilinger debating the meaning of Bell violations. So, it's an experiment that's still unsettled almost 50 years later and we have different stories involving causality to explain it.

I'm also interested in how physicists are finding clever ways to shield systems from decoherence, which is letting us see quantum phenomena at higher and higher levels. It seems the game is to go from a single qubit or small quantum systems to many-body quantum systems and to look at the emergent phenomena there. I'm looking forward to seeing further results.

Stephanie Simmons: I'm particularly interested in large quantum systems, which will let us do wonderful things like error correction and offer exponential speed-ups on algorithms and entanglement distribution for large distances. Having those capabilities will unlock new technology and let us probe the measurement problem, which is the core of so many of the unanswered questions in quantum physics.

Figuring out how to get reliable quantum systems out of noisy quantum systems was not at all obvious. It took a good decade for various teams around the world to do that. You're pushing the edges of performance but it's a really fast-moving space and I would say quantum-error correction is the technology that I think is most underappreciated.

What are the barriers to scaling up quantum devices so they can be commercially successful?

Stephanie Simmons: To unleash exponential speed-ups in chemistry or cybersecurity, we will need quantum computers with 400 to 2000 application-grade logical qubits. They will need to perform to a certain degree of precision, which means you need error correction. The overheads will be high but we've raised a lot of money on the assumption that it all pans out, though there's no reason to think there's a limit.

I don't feel like there's anything that would bar us from hitting that kind of commercial success. But when you're building things that have never been built before, there are always "unknown unknowns", which is kind of fun. There's always the possibility of seeing some kind of interesting emergent phenomenon when we build very large quantum systems that don't exist in nature.

> The game is to go from a single qubit or small quantum systems to many-body quantum systems and to look at the emergent phenomena there
>
> Elise Crull

How large could a quantum object or system be? And if we ever built it, what new fundamental information about quantum mechanics would it tell us?

Artur Ekert: Technology has driven progress in our understanding of the quantum world. We've gone from being able to control zillions of atoms in an ensemble to just one but the challenge is now to control more of them – two, three or four. It might seem paradoxical to have gone from many to one and back to many but the difference is that we can now control those quantum states. We can engineer those interactions and look at emerging phenomena. I don't believe there will be a magic number where quantum will stop working – but who knows? Maybe when we get to 42 atoms the world will be different.

Elise Crull: It depends what you're looking for. To detect gravitational waves, LIGO already uses Weber bars, which are big aluminium rods – weighing about a tonne – that vibrate like quantum oscillators. So we already have macroscopic systems that need to be treated quantum mechanically. The question is whether you can sustain entanglement longer and over greater distance.

Artur Ekert: To build a quantum computer, we have to create enough logical qubits and make them interact, which requires an amazing level of precision and degree of control. There's no reason why we shouldn't be able to do that, but what would be fascinating is if – in the process of doing so – we discovered there is a fundamental limit.

So while I support all efforts to build quantum computers, I'd almost like them to fail because we might then discover something that refutes quantum physics. After all, building a quantum computer is probably the most complicated and sophisticated experiment in quantum physics. It's more complex than the whole of the Apollo project that sent astronauts to the Moon: the degree of precision of every single component that is required is amazing.

If quantum physics breaks down at some point, chances are it'll be in this kind of experiment. Of course, I wish all my colleagues investing in quantum computing get a good return for their money, but I have this hidden agenda. Failing to build a quantum computer would be a success for science: it would let us learn something

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Large potential After successfully being able to figure out how to control single atoms at a time, quantum physicists now want to control large groups of atoms – but is there a limit to how big quantum objects can be?

new. In fact, we might even end up with an even more powerful "post-quantum" computer.

Surely the failure of quantum mechanics, driven by those applications, would be a bombshell if it ever happened?

Artur Ekert: People seeking to falsify quantum prediction are generally looking at connections between quantum and gravity so how would you be able to refute quantum physics with a quantum computer? Would it involve observing no speed-up where a speed-up should be seen, or would it be failure of some other sort?

My gut feeling is make this quantum experiment as complex and as sophisticated as you want, scale it up to the limits, and see what happens. If it works as we currently understand it should work, that's fine, we'll have quantum computers that will be useful for something. But if it doesn't work for some fundamental reason, it's also great – it's a win–win game.

> While I support all efforts to build quantum computers, I'd almost like them to fail because we might then discover something that refutes quantum physics
>
> Artur Ekert

Are we close to the failure of quantum mechanics?

Elise Crull: I think Arthur has a very interesting point. But we have lots of orders of magnitude to go before we have a real quantum computer. In the meantime, many people working on quantum gravity – whether string theory or canonical quantum gravity – are driven by their deep commitment to the universality of quantization.

There are, for example, experiments being designed by some to disprove classical general relativity by entangling space–time geometries. The idea is to kick out certain other theories or find upper and lower bounds on a certain theoretical space. I think we will make a lot of progress by not by trying to defeat quantum mechanics but to look at the "classicality" of other field theories and try to test those.

How will quantum technology benefit areas other than, say, communication and cryptography?

Stephanie Simmons: History suggests that every time we commercialize a branch of physics, we aren't great at predicting where that platform will go. When people invented the first transistor, they didn't anticipate the billions that you could put onto a chip. So for the new generation of people who are "quantum native", they'll have access to tools and concepts with which they'll quickly become familiar.

You have to remember that people think of quantum mechanics as counterintuitive. But it's actually the most self-consistent set of physics principles. Imagine if you're a character in a video game and you jump in midair; that's not reality, but it's totally self-consistent. Quantum is exactly the same. It's weird, but self-consistent. Once you get used to the rules, you can play by them.

I think that there's a real opportunity to think about chemistry in a much more computational sense. Quantum computing is going to change the way people talk about chemistry. We have the opportunity to rethink the way chemistry is put together, whether it's catalysts or heavy elements. Chemicals are quantum-mechanical objects – if you had 30 or 50 atoms, with a classical computer it would just take more bits than there are atoms in the universe to work out their electronic structure.

Has industry become more important than academia when it comes to developing new technologies?

Stephanie Simmons: The grand challenge in the quantum world is to build a scaled-up, fault-tolerant, exponentially sped-up quantum system that could simultaneously deliver the repeaters we need to do all the entanglement distribution technologies. And all of that work, or at least a good chunk of it, is in companies. The focus of that development has left academia.

Sure, there are still contributions from academia, but there is at least 10 times as much going on in industry tackling these ultra-complicated, really complex system engineering challenges. In fact, tackling all those unknown unknowns, you actually become a better "quantum engineer". Industry is the most fast-moving place to be in quantum at the moment, and things will emerge that will surprise people.

Artur Ekert: We can learn a lot from colleagues who work in the commercial sector because they ask different kinds of questions. My own first contact was with John Rarity and Paul Tabster at the UK Defence Evaluation and Research Agency, which became QinetiQ after privatization. Those guys were absolutely amazing and much more optimistic than I was about the future of quantum technologies. Paul in particular is an unsung hero of quantum tech. He showed me how you can think not in terms of equations, but devices – blocks you can put together, like quantum LEGO.

Over time, I saw more and more of my colleagues, students and postdocs going into the commercial world. Some even set up their own companies and I have a huge respect for my colleagues who've done that. I myself am involved with Speqtral in Singapore, which

> **Industry is the most fast-moving place to be in quantum at the moment, and things will emerge that will surprise people** Stephanie Simmons


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Competitive edge Most efforts to build quantum computers are now in industry, not academia.

does satellite quantum communication, and I'm advising a few other firms too.

Most efforts to build quantum devices are now outside academia. In fact, it has to be that way because universities are not designed to build quantum computers, which requires skills and people not found in a typical university. The only way to work out what quantum is good for is through start-up companies. Some will fail; but some will survive – and the survivors will be those that bet on the right applications of quantum theory.

What technological or theoretical breakthrough do you most hope to see that make the biggest difference?

Elise Crull: I would love someone to design an experiment to entangle space–time geometries, which would be crazy but would definitely kick general relativity off the table. It's a dream that I'd love to see happen.

Stephanie Simmons: I'm really keen to see distributed logical qubits that are horizontally scalable.

Artur Ekert: On the practical side, I would like to see real progress in quantum-error-correcting codes and fault-tolerant computing. On the fundamental side, I'd love experiments that provide a better understanding of the nature of randomness and its links with special relativity.

● This article is based on the 17 June 2025 Physics World Live event, which you can watch on demand on our website

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.

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."

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

Quantum physics is at a crossroads

Ana María Cetto and **Luis de la Peña** say that as quantum science advances, it is crucial not to lose sight of its conceptual foundations

One hundred years after its birth, quantum mechanics remains one of the most powerful and successful theories in all of science. From quantum computing to precision sensors, its technological impact is undeniable – and one reason why 2025 is being celebrated as the International Year of Quantum Science and Technology.

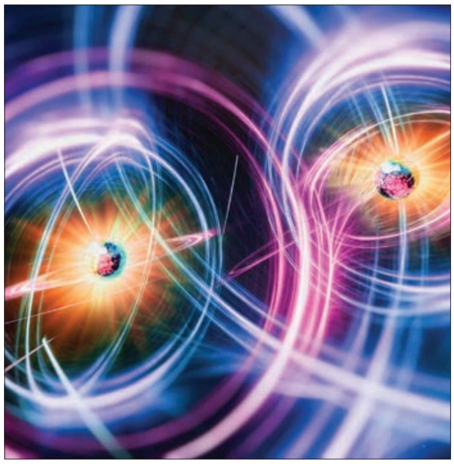
Yet as we celebrate these achievements, we should still reflect on what quantum mechanics reveals about the world itself. What, for example, does this formalism actually tell us about the nature of reality? Do quantum systems have definite properties before we measure them? Do our observations create reality, or merely reveal it?

These are not just abstract, philosophical questions. Having a clear understanding of what quantum theory is all about is essential to its long-term coherence and its capacity to integrate with the rest of physics. Unfortunately, there is no scientific consensus on these issues, which continue to provoke debate in the research community.

That uncertainty was underlined by a recent global survey of physicists about quantum foundational issues, conducted by *Nature* (**643** 1157). It revealed a persistent tension between "realist" views, which seek an objective, visualizable account of quantum phenomena, and "epistemic" views that regard the formalism as merely a tool for organizing our knowledge and predicting measurement outcomes.

Only 5% of the 1100 people who responded to the *Nature* survey expressed full confidence in the Copenhagen interpretation, which is still prevalent in textbooks and laboratories. Further divisions were revealed over whether the wavefunction is a physical entity, a mere calculation device, or a subjective reflection of belief. The lack of agreement on such a central feature underscores the theoretical fragility underlying quantum mechanics.

More broadly, 75% of respondents believe that quantum theory will eventually be replaced, at least partially, by a more complete framework. Encouragingly, 85% agree that attempts to interpret the theory in intuitive or physical terms are valuable. This willingness to explore alternatives reflects the intellectual vitality of the field but also underscores the inadequacy of current approaches.



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Physical puzzles While quantum mechanics works impressively in practice, the theory remains conceptually opaque to many.

Beyond interpretation

We believe that this interpretative proliferation stems from a deeper problem, which is that quantum mechanics lacks a well-defined physical foundation. It describes the statistical outcomes of measurements, but it does not explain the mechanisms behind them. The concept of causality has been largely abandoned in favour of operational prescriptions such that quantum theory works impressively in practice but remains conceptually opaque.

In our view, the way forward is not to multiply interpretations or continue debating them, but to pursue a deeper physical understanding of quantum phenomena. One promising path is stochastic electrodynamics (SED), a classical theory augmented by a random electromagnetic background field, the real vacuum or zero-point field discovered by Max Planck as early as 1911. This framework restores causality and locality by explaining quantum behaviour as the statistical response of particles to this omnipresent background field.

Over the years, several researchers from different lines of thought have contributed to SED. Since our early days with Trevor Marshall, Timothy Boyer and others, we have refined the theory to the point that it can now account for the emergence of features that are considered building blocks of quantum formalism, such as the basic commutator and Heisenberg inequalities.

Particles acquire wave-like properties not by intrinsic duality, but as a consequence of their interaction with the vacuum field. Quantum fluctuations, interference patterns and entanglement emerge from this interaction, without the need to resort to non-local influences or observer-dependent realities. The SED approach is not merely mechanical, but rather electrodynamic.

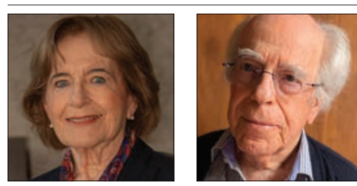
Coherent thoughts

We're not claiming that SED is the final word. But it does offer a coherent picture of microphysical processes based on physical fields and forces. Importantly, it doesn't abandon the quantum formalism but rather reframes it as an effective theory – a statistical summary of deeper dynamics. Such a perspective enables us to maintain the successes of quantum mechanics while seeking to explain its origins.

For us, SED highlights that quantum phenomena can be reconciled with concepts central to the rest of physics, such as realism, causality and locality. It also shows that alternative approaches can yield testable predictions and provide new insights into long-standing puzzles. One phenomenon lying beyond current quantum formalism that we could now test, thanks to progress in experimental physics, is the predicted violation of Heisenberg's inequalities over very short time periods.

As quantum science continues to advance, we must not lose sight of its conceptual foundations. Indeed, a coherent, causally grounded understanding of quantum mechanics is not a distraction from technological progress but a prerequisite for its full realization. By turning our attention once again to the foundations of the theory, we may finally complete the edifice that began to rise a century ago.

The centenary of quantum mechanics should be a time not just for celebration but critical reflection too.



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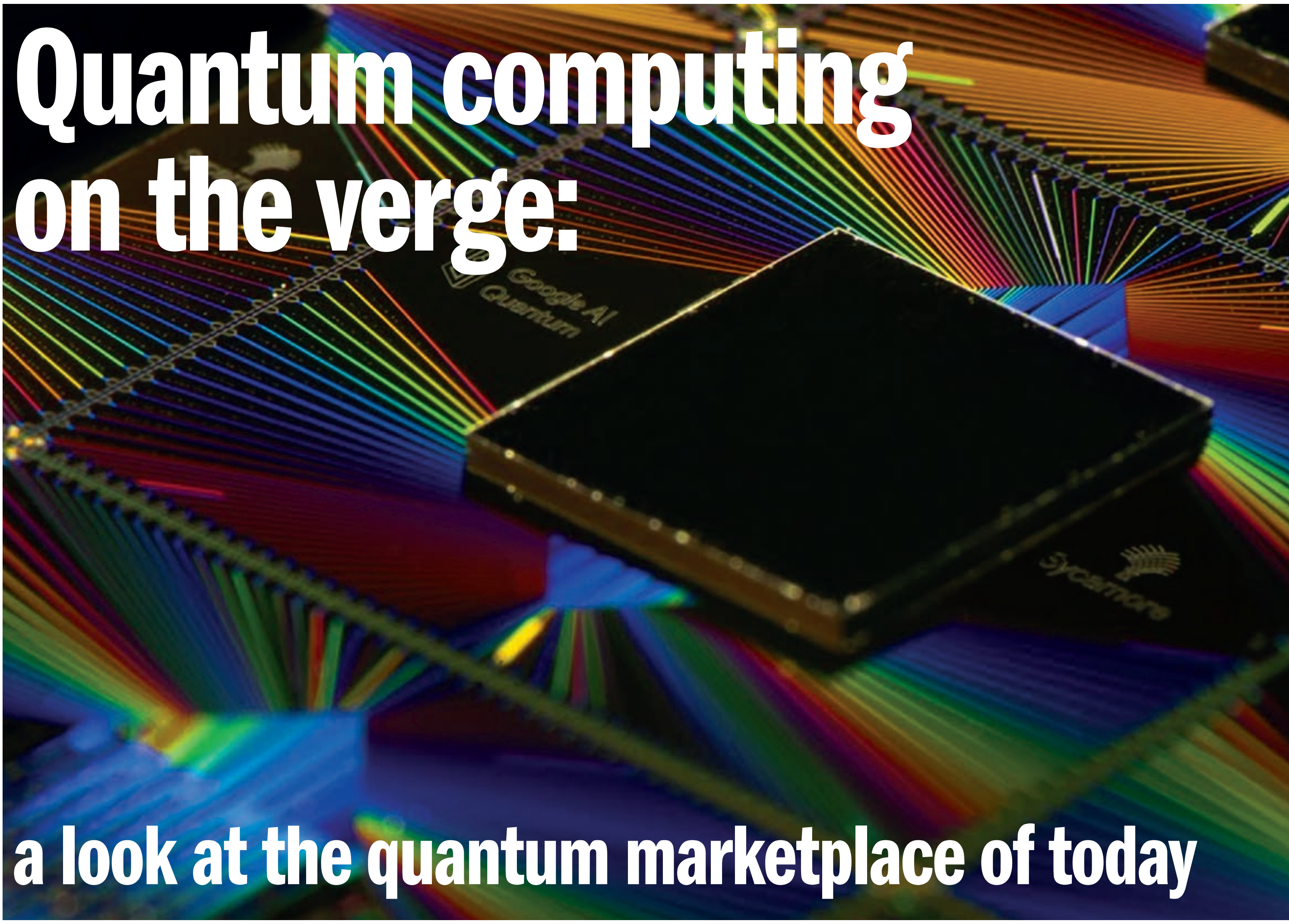
Quantum computing on the verge: a look at the quantum marketplace of today



Google Quantum AI

Quantum computing is booming in the world of business, with about 400 competing companies, lots of rival qubit platforms and varying measures of merit. Philip Ball explores how the quantum tech landscape is developing

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

"I'd be amazed if quantum computing produces anything technologically useful in ten years, twenty years, even longer." So wrote University of Oxford physicist David Deutsch – often considered the father of the theory of quantum computing – in 2004. But, as he added in a caveat, "I've been amazed before."

We don't know how amazed Deutsch, a pioneer of quantum computing, would have been had he attended a meeting at the Royal Society in London in February on "the future of quantum information". But it was tempting to conclude from the event that quantum computing has now well and truly arrived, with working machines that harness quantum mechanics to perform computations being commercially produced and shipped to clients. Serving as the UK launch of the International Year of Quantum Science and Technology (IYQ) 2025, it brought together some of the key figures of the field to spend two days discussing quantum computing as something like a mature industry, even if one in its early days.

Werner Heisenberg – who worked out the first proper theory of quantum mechanics 100 years ago – would surely have been amazed to find that the formalism he and his peers developed to understand the fundamental behaviour of tiny particles had generated new ways of manipulating information to solve real-world problems in computation. So far, quantum computing – which exploits phenomena such as superposition and entanglement to potentially achieve greater computational power than the best classical computers can muster – hasn't tackled any practical problems that can't be solved classically.

Although the fundamental quantum principles are well-established and proven to work, there remain many hurdles that quantum information technologies have to clear before this industry can routinely deliver resources with transformative capabilities. But many researchers think that moment of "practical quantum advantage" is fast approaching, and an entire industry is readying itself for that day.

Entangled marketplace

So what are the current capabilities and near-term prospects for quantum computing?

The first thing to acknowledge is that a booming

Many researchers believe that no single qubit type will ever dominate

quantum-computing market exists. Devices are being produced for commercial use by a number of tech firms, from the likes of IBM, Google, Canada-based D-Wave, and Rigetti who have been in the field for a decade or more; to relative newcomers like Nord Quantique (Canada), IQM (Finland), Quantinuum (UK and US), Orca (UK) and PsiQuantum (US), Silicon Quantum Computing (Australia). See box, "The global quantum ecosystem".

A supply chain is also organically developing, which includes manufacturers of specific hardware components, such as Oxford Instruments and Quantum Machines and software developers like Riverlane, based in Cambridge, UK, and QC Ware in Palo Alto, California. Supplying the last link in this chain are a range of eager end-users, from finance companies such as J P Morgan and Goldman Sachs to pharmaceutical companies such as AstraZeneca and engineering firms like Airbus. Quantum computing is already big business, with around 400 active companies and current global investment estimated at around $2 billion.

But the immediate future of all this buzz is hard to assess. When the chief executive of computer giant Nvidia announced at the start of 2025 that "truly useful" quantum computers were still two decades away, the previously burgeoning share prices of some leading quantum-computing companies plummeted. They have since recovered somewhat, but such volatility reflects the fact that quantum computing has yet to prove its commercial worth.

The field is still new and firms need to manage expectations and avoid hype while also promoting an optimistic enough picture to keep investment flowing in. "Really amazing breakthroughs are being made," says physicist Winfried Hensinger of the University of Sussex, "but we need to get away from the expectancy that [truly useful] quantum computers will be available tomorrow."

The current state of play is often called the "noisy intermediate-scale quantum" (NISQ) era. That's because the "noisy" quantum bits (qubits) in today's devices are prone to errors for which no general and simple correction process exists. Current quantum computers can't therefore carry out practically useful computations that could not be done on classical high-performance computing (HPC) machines. It's not just a matter of better engineering either; the basic science is far from done.

"We are right on the cusp of scientific quantum advantage – solving certain scientific problems better than the world's best classical methods can," says Ashley Montanaro, a physicist at the University of Bristol who co-founded the quantum software company Phasecraft. "But we haven't yet got to the stage of practical quantum advantage, where quantum computers solve commercially important and practically relevant problems such as discovering the next lithium-ion battery." It's no longer if or how, but when that will happen.

Pick your platform

As the quantum-computing business is such an emerging area, today's devices use wildly different types of physical systems for their qubits, see the box on p38, "Comparing computing modalities: from qubits to architectures". There is still no clear sign as to which of these platforms, if any, will emerge as the winner.

The global quantum ecosystem

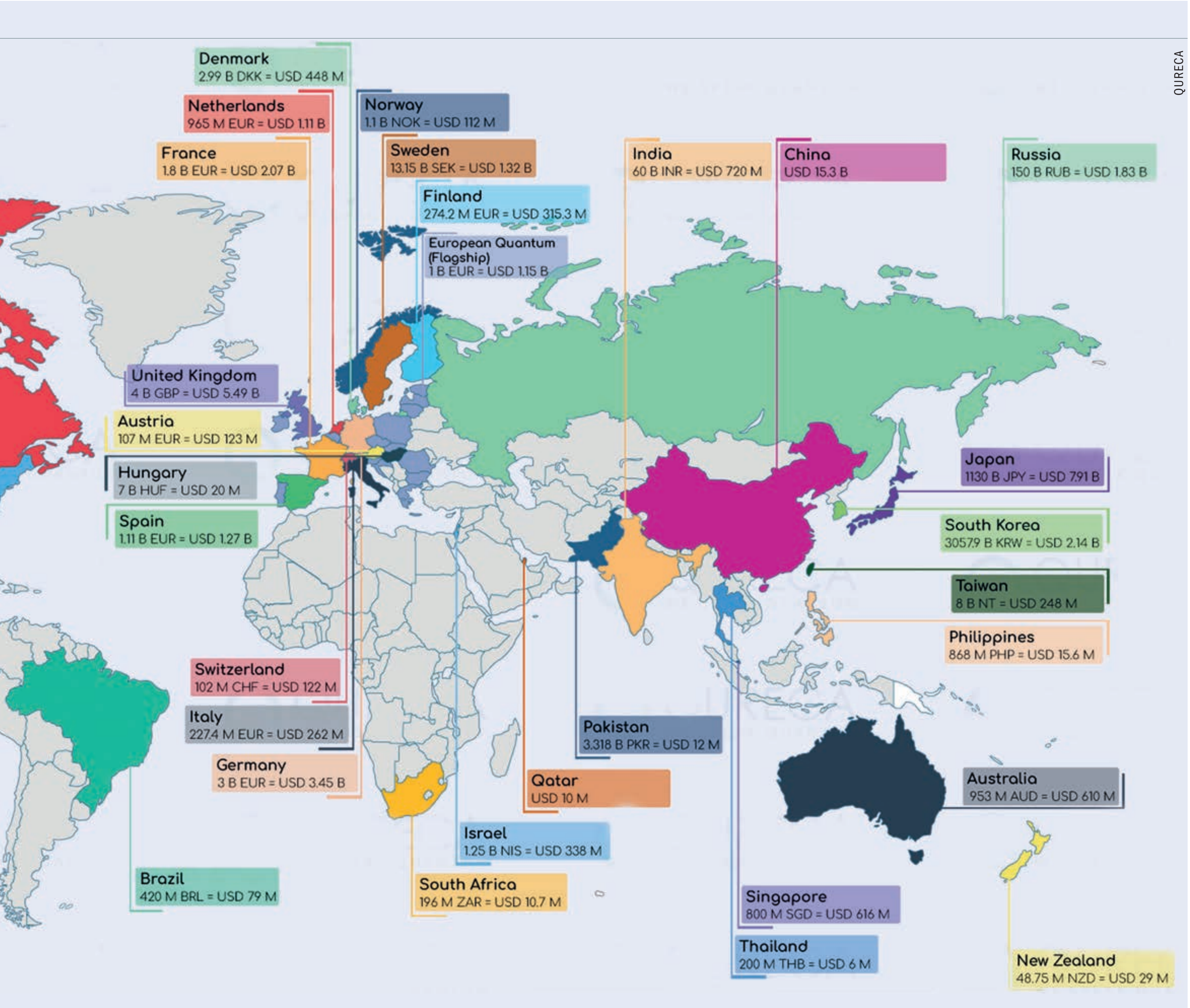
We are on the cusp of a second quantum revolution, with quantum science and technologies growing rapidly across the globe. This includes quantum computers; quantum sensing (ultra-high precision clocks, sensors for medical diagnostics); as well as quantum communications (a quantum internet). Indeed, according 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.

As of this year, worldwide investments in quantum tech – by governments and industry – exceed $55.7 billion, and the market is projected to reach $106 billion by 2040. With the multitude of ground-breaking capabilities that quantum technologies bring globally, it's unsurprising that governments all over the world are eager to invest in the industry.

With data from a number of international reports and studies, quantum education and skills firm QURECA has summarized key programmes and efforts around the world. These include total government funding spent through 2025, as well as future commitments spanning 2–10 year programmes, varying by country. These initiatives generally represent government agencies' funding announcements, related to their countries' advancements in quantum technologies, excluding any private investments and revenues.

Indeed many researchers believe that no single qubit type will ever dominate. The top-performing quantum computers, like those made by Google (with its 105-qubit Willow chip) and IBM (which has made the 121-qubit Condor), use qubits in which information is encoded in the wavefunction of a superconducting material. Until recently, the strongest competing platform seemed to be trapped ions, where the qubits are individual ions held in electromagnetic traps – a technology being developed into working devices by the US company IonQ, spun out from the University of Maryland, among others.

But over the past few years, neutral trapped atoms have emerged as a major contender, thanks to advances in controlling the positions and states of these qubits. Here the atoms are prepared in highly excited electronic states called Rydberg atoms, which can be entangled with one another over a few microns. A Harvard start-up called QuEra is developing this technology, as is the French start-up Pasqal. In September a team from



the California Institute of Technology announced a 6100-qubit array made from neutral atoms. "Ten years ago I would not have included [neutral-atom] methods if I were hedging bets on the future of quantum computing," says Deutsch's Oxford colleague, the quantum information theorist Andrew Steane. But like many, he thinks differently now.

Some researchers believe that optical quantum computing, using photons as qubits, will also be an important platform. One advantage here is that there is no need for complex conversion of photonic signals in existing telecommunications networks going to or from the processing units, which is also handy for photonic interconnections between chips. What's more, photonic circuits can work at room temperature, whereas trapped ions and superconducting qubits need to be cooled. Photonic quantum computing is being developed by firms like PsiQuantum, Orca and Xanadu.

Other efforts, for example at Intel and Silicon Quantum Computing in Australia, make qubits from either quantum dots (Intel) or precision-placed phosphorus atoms (SQC), both in good old silicon, which benefits from a very mature manufacturing base. "Small qubits based on ions and atoms yield the highest quality processors", says Michelle Simmons of the University of New South Wales, who is the founder and CEO of SQC. "But only atom-based systems in silicon combine this quality with manufacturability."

And it's not impossible that entirely new quantum computing platforms might yet arrive. At the start of 2025, researchers at Microsoft's laboratories in Washington State caused a stir when they announced that they had made topological qubits from semiconducting and superconducting devices, which are less error-prone than those currently in use. The announcement left some scientists disgruntled because it was not accompanied by a peer-reviewed paper providing the evidence for these long-sought entities. But in any event, most researchers think it would take a decade or more for topological quantum computing to catch up

Comparing computing modalities: from qubits to architectures

PatentVest

Modality	How it works	Key advantages	Key limitations	Representative companies
Superconducting qubits	Electrical circuits made from superconducting materials, operated at millikelvin temperatures, where current flows without resistance. Qubits are formed using Josephson junctions	Fast gate speeds, mature nanofabrication, strong ecosystem	Short coherence times, complex cryogenic wiring	IBM, Google, Rigetti, IQM
Trapped ions	Individual charged atoms suspended in electromagnetic traps, manipulated by lasers	Exceptional fidelity, long coherence, all-to-all connectivity	Slow operation, complex optical set-ups	IonQ, Quantinuum, Alpine
Neutral atoms	Neutral atoms held in optical tweezers and excited to Rydberg states for interaction	Naturally identical qubits, scalable arrays, parallel gates	Precision laser control needed, electronics scaling challenge	QuEra, Pasqal, Infleqtion
Photonic qubits	Single photons in optical circuits or fibres, encoded in polarization, time, or path	Room-temperature operation, easy networking	Photon loss, probabilistic entanglement	PsiQuantum, Xanadu, ORCA
Silicon spin qubits	Electron or nuclear spins in semiconductor quantum dots, controlled electrically or magnetically	CMOS-compatible fabrication, small footprint	Extreme cryogenics, coherence challenges	Diraq, Quantum Motion, Silicon Quantum Computing
Annealing	Superconducting flux qubits arranged to find low-energy solutions to optimization problems	Only modality with commercial revenue today (optimization)	Not universal computing	D-Wave

Much like classical computers, quantum computers have a core processor and a control stack – the difference being that the core depends on the type of qubit being used. Currently, quantum computing is not based on a single platform, but rather a set of competing hardware approaches, each with its own physical basis for creating and controlling qubits and keeping them stable.

The data above – taken from the August 2025 report *Quantum Computing at the Inflection Point: Who's Leading, What They Own, and Why IP Decides Quantum's Future* by US firm PatentVest – shows the key "quantum modalities", which refers to the different types of qubits and architectures used to build these quantum systems. Differing qubits each have their own pros and cons, with varying factors including the temperature at which they operate, coherence time, gate speed, and how easy they might be to scale up.

with the platforms already out there.

Each of these quantum technologies has its own strengths and weaknesses. "My personal view is that there will not be a single architecture that 'wins', certainly not in the foreseeable future," says Michael Cuthbert, founding director of the UK's National Quantum Computing Centre (NQCC), which aims to facilitate the transition of quantum computing from basic research to an industrial concern. Cuthbert thinks the best platform will differ for different types of computation: cold neutral atoms might be good for quantum simulations of molecules, materials and exotic quantum states, say, while superconducting and trapped-ion qubits might be best for problems involving machine learning or optimization.

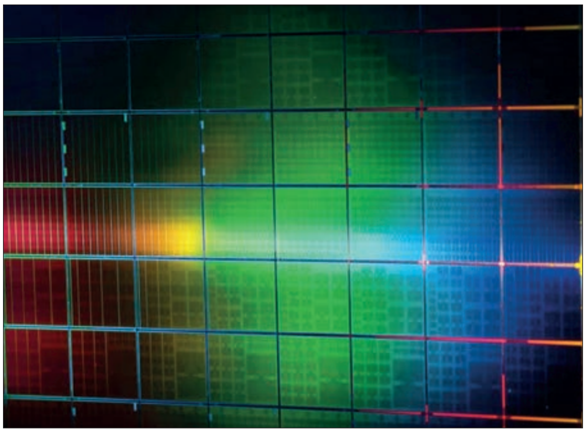
Measures and metrics

Given these pros and cons of different hardware platforms, one difficulty in assessing their merits is finding meaningful metrics for making comparisons. Should we be comparing error rates, coherence times (basically how long qubits remain entangled), gate speeds (how fast a single computational step can be conducted), circuit depth (how many steps a single computation can sustain), number of qubits in a processor, or what? "The metrics and measures that have been put forward so far tend to suit one or other platform more than others," says Cuthbert, "such that it becomes almost a marketing exercise rather than a scientific benchmarking exercise as to which quantum computer is better."

The NQCC evaluates the performance of devices using a factor known as the "quantum operation" (QuOp). This is simply the number of quantum operations that can be carried out in a single computation, before the qubits lose their coherence and the computation dissolves into noise. "If you want to run a computation, the number of coherent operations you can run consecutively is an objective measure," Cuthbert says. If we want to get beyond the NISQ era, he adds, "we need to progress to the point where we can do about a million coherent operations in a single computation. We're now at the level of maybe a few thousand. So we've got a long way to go before we can run large-scale computations."

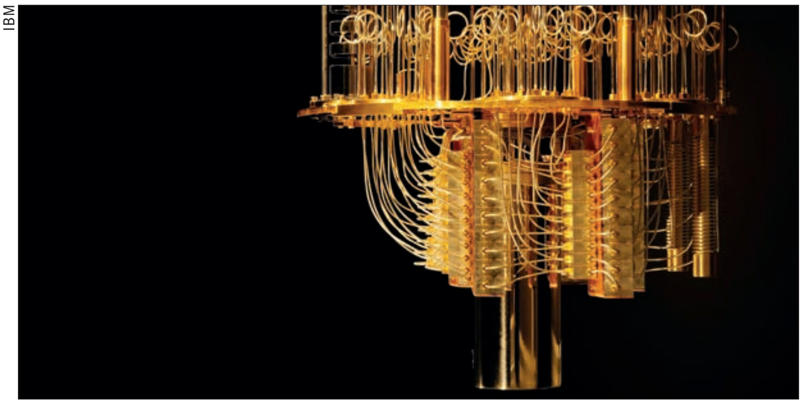
One important issue is how amenable the platforms are to making larger quantum circuits. Cuthbert contrasts the issue of scaling up – putting more qubits on a chip – with "scaling out", whereby chips of a given size are linked in modular fashion. Many researchers think it unlikely that individual quantum chips will have millions of qubits like the silicon chips of today's machines. Rather, they will be modular arrays of relatively small chips linked at their edges by quantum interconnects.

Intel Corporation



Spinning around Intel's silicon spin qubits are now being manufactured on an industrial scale.

IBM



Building up Quantum computing behemoth IBM says that by 2029, its fault-tolerant system should accurately run 100 million gates on 200 logical qubits, thereby truly achieving quantum advantage.

Qubit comparisons: evaluating key metrics

PatentVest

	Superconducting	Trapped-ion	Neutral atoms	Photonics	Silicon spin
Key players	Google, IBM, Rigetti, IQM	Quantinuum, IonQ, Oxford Ionics	QuEra, Atom Computing	PsiQuantum, Xanadu	Intel, Silicon Quantum Computing
Qubit count	100s to ~1000, multi-die	~35–56	~200s	~12	~12
Fidelity (2-qubit)	~99%-99.9%	~99.99%	99.5%	99%	99.9%
Coherence time	Microseconds to milliseconds	Seconds to minutes	Milliseconds	Extremely short	Tens of seconds
Gate speed	Fastest (50–100 ns)	Slow (300–500 µs)	Slow (300–500 µs)	N/A	Fast (0.8–100 ns)
Operating temperature	Cryogenic (~10 mK)	Room temp, but vacuum needed	Room temp	Room temp	Cryogenic (100 mk to 4 K)
Error correction overhead	High	Lower due to high fidelities	Moderate, still developing	Very high	Low due to high fidelities
Scalability	Cryogenic and fabrication complexity / industrial semi benefits	Photonic interconnects for 200+ qubit scaling	Error rates, atom placement, control electronics	Photon loss, error correction overhead	Industrial semi benefits, challenging fabrication

As different quantum computing firms pick their qubit of choice to build a universal fault-tolerant system, no single qubits-type or architecture platform has come out on top. Essentially, when it comes to some of the key metrics of success for quantum advantage, different qubits have varying pros and cons. These are closely dependent on specific domains and uses; such as optimization, quantum simulation, or error-corrected subroutines.

The table above – complied with data from the *Quantum Computing at the Inflection Point: Who's Leading, What They Own, and Why IP Decides Quantum's Future* by US firm PatentVest, and other sources – show how quickly performance gaps can widen once scale, noise and control align. The data show how no single modality has solved speed, fidelity and scalability at once.

Having made the Condor, IBM now plans to focus on modular architectures (scaling out) – a necessity anyway, since superconducting qubits are micron-sized, so a chip with millions of them would be "bigger than your dining room table", says Cuthbert. But superconducting qubits are not easy to scale out because microwave frequencies that control and read out the qubits have to be converted into optical frequencies for photonic interconnects. Cold atoms are easier to scale up, as the qubits are small, while photonic quantum computing is easiest to scale out because it already speaks the same language as the interconnects.

To be able to build up so called "fault tolerant" quantum computers, quantum platforms must solve the issue of error correction, which will enable more extensive computations without the results becoming degraded into mere noise.

In part two of this feature, we will explore how this is being achieved and meet the various firms developing quantum software. We will also look into the potential high-value commercial uses for robust quantum computers – once such devices exist. ■

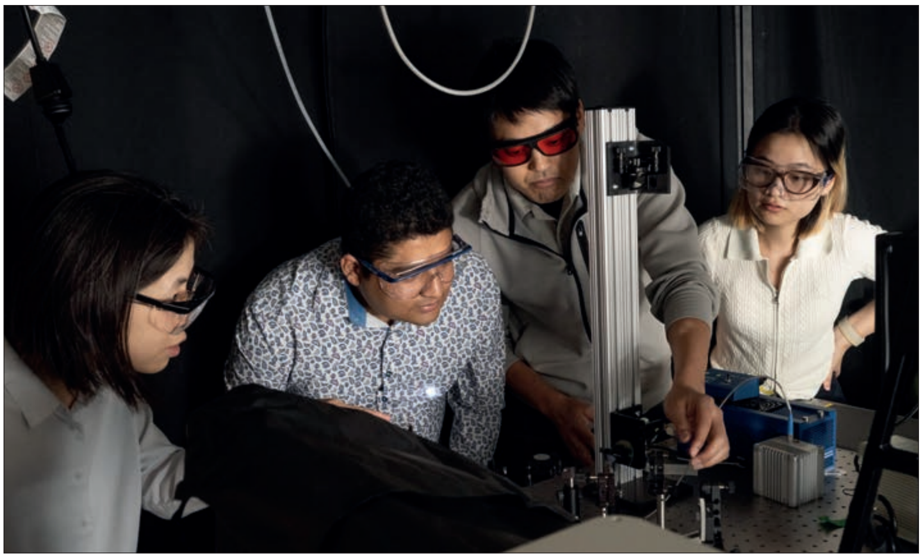
Shengxi Huang: how defects can boost 2D materials as single-photon emitters

Shengxi Huang explains why Picoquant's instruments are helping her to develop 2D materials that are highly efficient sources of single photons

Everyday life is three dimensional, with even a sheet of paper having a finite thickness. Shengxi Huang from Rice University in the US, however, is attracted by 2D materials, which are usually just one atomic layer thick. Graphene is perhaps the most famous example – a single layer of carbon atoms arranged in a hexagonal lattice. But since it was first created in 2004, all sorts of other 2D materials, notably boron nitride, have been createds.

An electrical engineer by training, Huang did a PhD at the Massachusetts Institute of Technology and postdoctoral research at Stanford University before spending five years as an assistant professor at the Pennsylvania State University. Huang has been at Rice since 2022, where she is now an associate professor in the Department of Electrical and Computer Engineering, the Department of Material Science and NanoEngineering, and the Department of Bioengineering.

Her group at Rice currently has 12 people, including eight graduate students and four postdocs. Some are physicists, some are engineers, while others have backgrounds in material science or chemistry. But they all share an interest in understanding the optical and electronic properties of quantum materials and seeing how they can be used, for example, as biochemical sensors. Lab equipment from Picoquant is vital in helping in that quest, as Huang explains in an interview with *Physics World*.



Jeff Fitlow

Hidden depths Shengxi Huang (left) with members of her lab at Rice University in the US, where she studies 2D materials as single-photon sources.

Why are you fascinated by 2D materials?

I'm an electrical engineer by training, which is a very broad field. Some electrical engineers focus on things like communication and computing, but others, like myself, are more interested in how we can use fundamental physics to build useful devices, such as semiconductor chips. I'm particularly interested in using 2D materials for optoelectronic devices and as single-photon emitters.

What kinds of 2D materials do you study?

The materials I am particularly interested in are transition metal dichalcogenides, which consist of a layer of transition-metal atoms sandwiched between two layers of chalcogen atoms – sulphur, selenium or tellurium. One of the most common examples is molybdenum disulphide, which in its monolayer form has a layer of sulphur on either side of a layer of molybdenum. In multi-layer molybdenum disulphide, the van der Waals forces between the tri-layers are relatively weak, meaning that the material is widely used as a lubricant – just like graphite, which is a many-layer version of graphene.

Why do you find transition metal dichalcogenides interesting?

Transition metal dichalcogenides have some very useful optoelectronic properties. In particular, they emit light whenever the electron and hole that make up an "exciton" recombine. Now because these dichalcogenides are so thin, most of the light they emit can be used. In a 3D material, in contrast, most light is generated deep in the bulk of the material and doesn't penetrate beyond the surface. Such 2D materials are therefore very efficient and, what's more, can be easily integrated onto chip-based devices such as waveguides and cavities.

Transition metal dichalcogenide materials also have promising electronic applications, particularly as the active material in transistors. Over the years, we've seen silicon-based transistors get smaller and smaller as we've followed Moore's law, but we're rapidly reaching a limit where we can't shrink them any further, partly because the electrons in very thin layers of silicon move so slowly. In 2D transition metal dichalcogenides, in contrast, the electron mobility can actually be higher than in silicon of the same thickness, making them a promising material for future transistor applications.

What can such sources of single photons be used for?

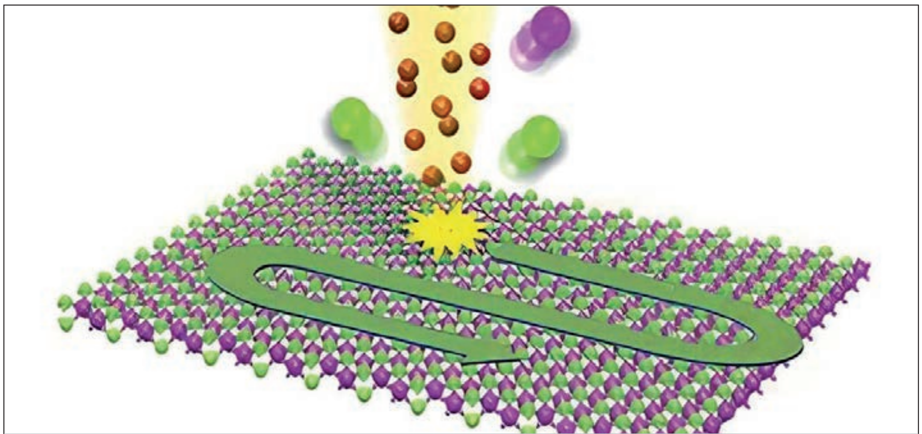
Single photons are useful for quantum communication and quantum cryptography. Carrying information as zero and one, they basically function as a qubit, providing a very secure communication channel. Single photons are also interesting for quantum sensing and even quantum computing. But it's vital that you have a highly pure source of photons. You don't want them mixed up with "classical photons", which – like those from the Sun – are emitted in bunches as otherwise the tasks you're trying to perform cannot be completed

What approaches are you taking to improve 2D materials as single-photon emitters?
What we do is introduce atomic defects into a 2D material to give it optical properties that are different to what you'd get in the bulk. There are several ways of doing this. One is to irradiate a sample with ions or electrons, which can bombard individual atoms out to generate "vacancy defects". Another option is to use plasmas, whereby atoms in the sample get replaced by atoms from the plasma.

So how do you study the samples?
Se can probe defect emission using a technique called photoluminescence, which basically involves shining a laser beam onto the material. The laser excites electrons from the ground state to an excited state, prompting them to emit light. As the laser beam is about 500-1000 nm in diameter, we can see single photon emission from an individual defect if the defect density is suitable.

What sort of experiments do you do in your lab?
We start by engineering our materials at the atomic level to introduce the correct type of defect. We also try to strain the material, which can increase how many single photons are emitted at a time. Once we've confirmed we've got the correct defects in the correct location, we check the material is emitting single photons by carrying out optical measurements, such as photoluminescence. Finally, we characterize the purity of our single photons – ideally, they shouldn't be mixed up with classical photons but in reality, you never have a 100% pure source. As single photons are emitted one at a time, they have different statistical characteristics to classical light. We also check the brightness and lifetime of the source, the efficiency, how stable it is, and if the photons are polarized. In fact, we have a feedback loop: what improvements can we do at the atomic level to get the properties we're after?

Is it difficult adding defects to a sample?
It's pretty challenging. You want to add just one defect to an area that might be just one micron square so you have to control the atomic structure very finely. It's made harder because 2D materials are atomically thin and very fragile. So if you don't do the engineering correctly, you may accidentally introduce other types of defects that you don't want, which will alter the defects' emission.



Click here to watch our webinar with Shengxi Huang

What techniques do you use to confirm the defects are in the right place?
Because the defect concentration is so low, we cannot use methods that are typically used to characterise materials, such as X-ray photo-emission spectroscopy or scanning electron microscopy. Instead, the best and most practical way is to see if the defects generate the correct type of optical emission predicted by theory. But even that is challenging because our calculations, which we work on with computational groups, might not be completely accurate.

How do your PicoQuant instruments help in that regard?
We have two main pieces of equipment – a MicroTime 100 photoluminescence microscope and a FluoTime 300 spectrometer. These have been customized to form a Hanbury Brown Twiss interferometer, which measures the purity of a single photon source. We also use the microscope and spectrometer to characterise photoluminescence spectrum and lifetime. Essentially, if the material emits light, we can then work out how long it takes before the emission dies down.

Did you buy the equipment off-the-shelf?
It's more of a customised instrument with different components – lasers, microscopes, detectors and so on – connected together so we can do multiple types of measurement. I put in a request to Picoquant, who discussed my requirements with me to work out how to meet my needs. The equipment has been very important for our studies as we can carry out high-throughput measurements over and over again. We've tailored it for our own research purposes basically.

So how good are your samples?
The best single-photon source that we currently work with is boron nitride, which has a single-photon purity of 98.5% at room temperature. In other words, for every 200 photons only three are classical. With transition-metal dichalcogenides, we get a purity of 98.3% at cryogenic temperatures.

What are your next steps?
There's still lots to explore in terms of making better single-photon emitters and learning how to control them at different wavelengths. We also want to see if these materials can be used as high-quality quantum sensors. In some cases, if we have the right types of atomic defects, we get a high-quality source of single photons, which we can then entangle with their spin. The emitters can therefore monitor the local magnetic environment with better performance than is possible with classical sensing methods.

More information about the author's work can be found in Sci. Adv. (**11** 2899), *Nano. Lett.* (**25** 10263), *ACS Nano* (**16** 7428) *and J. Phys. Chem. Lett.* (**14** 3274).

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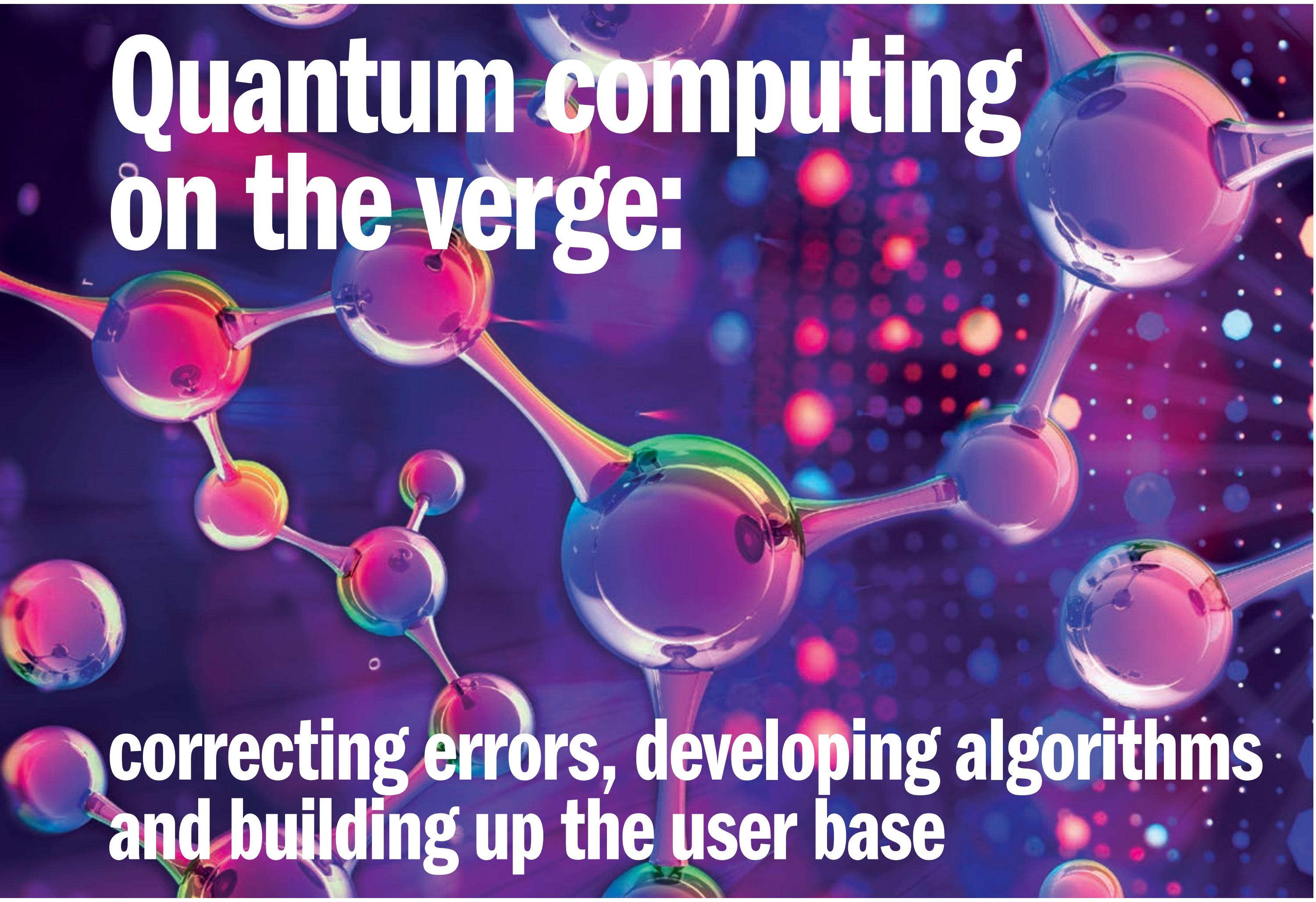
This article was written by *Physics World* on behalf of PicoQuant. Read more on *physicsworld.com*.

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



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

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

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

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

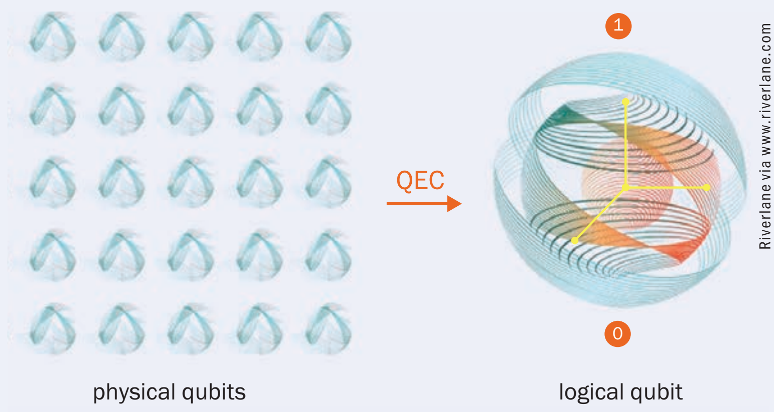
Protected states

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

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

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

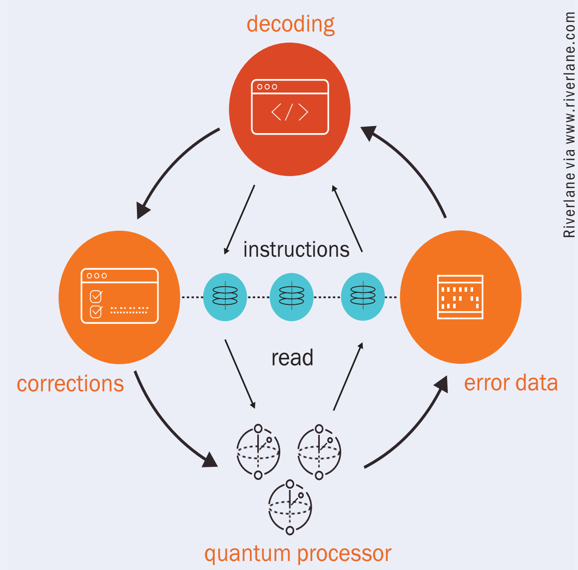
1 From many to few



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

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

2 Error correction in action



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

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

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

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

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

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

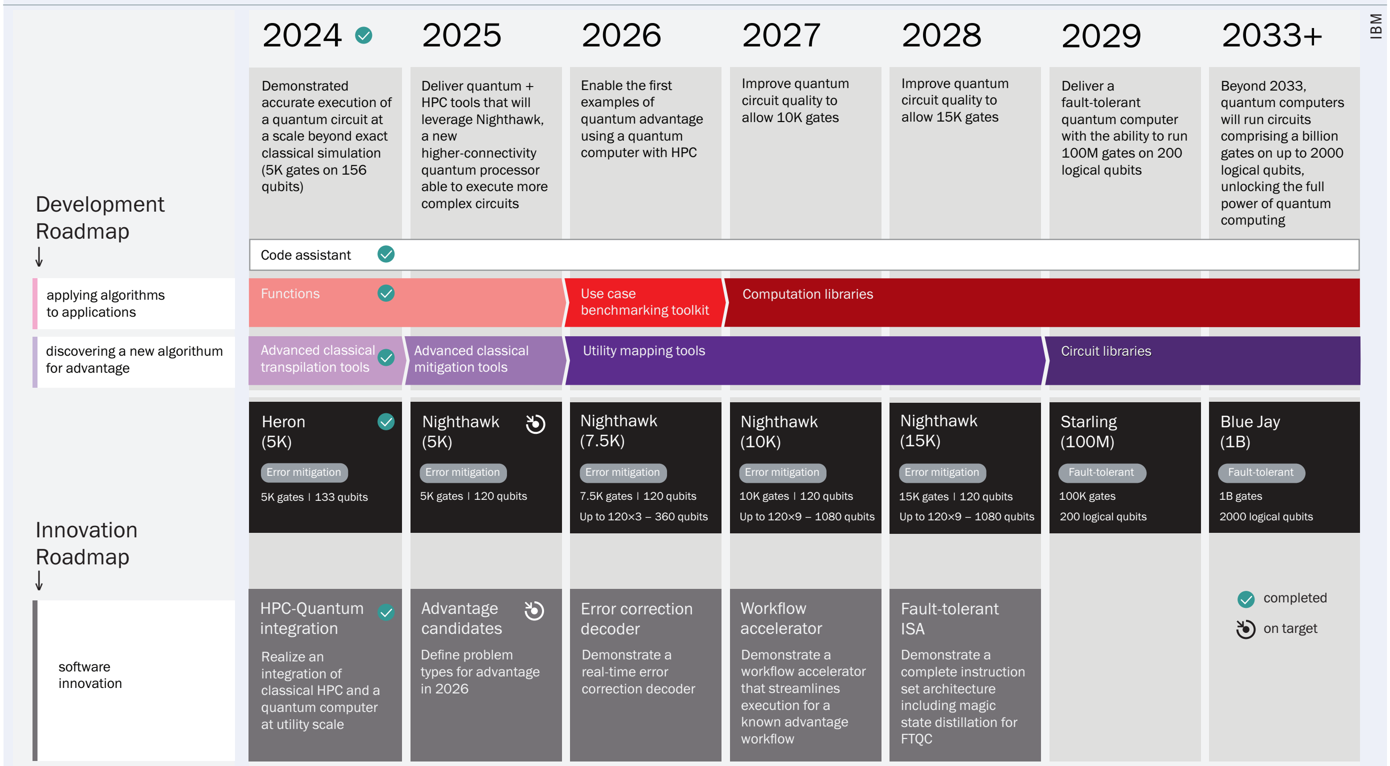
It sounds like a tall order, but Gambetta is confident that IBM will achieve these figures by 2029. By building on what has been achieved so far with error correction and mitigation, he feels "more confident than I ever did before that we can achieve a fault-tolerant computer." Jerry Chow, previous manager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

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

Platform independent

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

3 The road ahead for IBM



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

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

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

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

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

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

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

Early adopters?

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

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

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

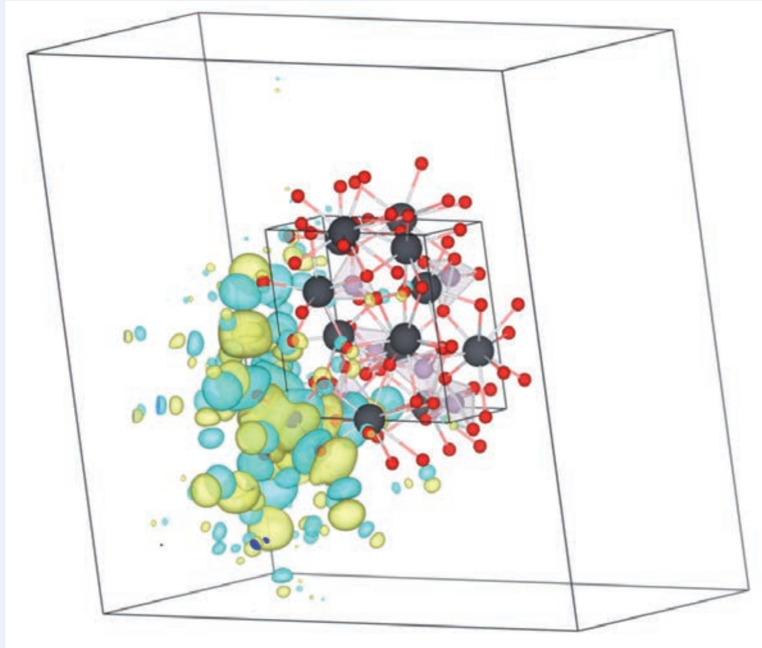
IBM

RIKEN

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

4 Structural insights

Phasecraft



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

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

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

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

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

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

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

Building the market

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

The fact that quantum computers, especially if used with HPC, are already unique scientific tools should establish their value in the immediate term, says Gambetta. "I think this is going to accelerate, and will keep the funding going." It is why IBM is focusing on utility-scale systems of around 100 qubits or so and more than

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

a thousand gate operations, he says, rather than simply trying to build ever bigger devices.

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

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

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

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

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

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

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

With the quantum sector quickly evolving, governments are getting scientific policies and regulations in place to ensure the new technology will benefit our society. During their PhDs, **Elizabeth Pasatembou** and **Dimitrie Cielecki** took part in policy engagement to understand the process and how scientists can get involved

When we started our PhDs in physics at Imperial College London, our paths seemed conventional: a lot of lab work, conferences and a bit of teaching on the side. What we did not expect was that within a couple of years we would be talking with MPs in the House of Commons, civil servants in Whitehall and business leaders in industry. We found ourselves contributing to policy reports and organizing roundtable discussions alongside policy-makers, scientists and investors; focusing on quantum technology and its impact on the economy and society.

Our journey into science policy engagement started almost by chance. Back in 2022 we received an e-mail from Imperial's Centre for Quantum Engineering Science and Technology (QuEST) advertising positions for PhD students to support evidence-based policy-making. Seeing it as an opportunity to contribute beyond the lab, we both took up the challenge. It became an integral part of our PhD experience. What started as a part-time role alongside our PhDs turned into something much more than that.

We joined QuEST and the Imperial Policy Forum – the university's policy engagement programme – in 2022 and were soon sitting at the table with leading voices in the nascent quantum technology field. We had many productive conversations with senior figures from most quantum technology start-ups in the UK. We also found ourselves talking to leaders of the National Quantum Technology Programme (including its chair, Sir Peter Knight); to civil servants from the Office for Quantum in the Department of Science, Innovation and Technology (DSIT); and to members of both the House of Commons and the House of Lords.

Elizabeth Pasatembou is a postdoctoral fellow in the Cyprus Quantum Communications Infrastructure group at Cyprus University of Technology. **Dimitrie Cielecki** is a researcher at the Institute for Deep Tech Entrepreneurship at Imperial College London

Elizabeth Pasatembou

Getting started Imperial College London encourages its researchers – established and early-career – to get involved in shaping policy. From left: Dimitrie Cielecki, Michael Ho, Louis Chen, Elizabeth Pasatembou.

Sometimes we would carry out tasks such as identifying the relevant stakeholders for an event or a roundtable discussion with policy implications. Other times we would do desk research and contribute to reports used in the policy-making process. For example, we responded to the House of Commons written evidence inquiry on *Commercialising Quantum Technologies* (2023) and provided analysis and insights for the Regulatory Horizons Council report *Regulating Quantum Technology Applications* (2024). We also moderated a day of roundtable discussions with quantum specialists for the Parliamentary Office of Science and Technology's briefing note *Quantum Computing, Sensing and Communications* (2025).

A two-way street

When studying science, we tend to think of it as a purely intellectual exercise, divorced from the real world. But we know that the field is applied to many areas of life, which is why countries, governments and institutions need policies to decide how science should be regulated, taught, governed and so on.

Science policy has two complimentary sides. First, it's about how governments and institutions support and shape the practice of science through, for example, how funding is allocated. Second, science policy looks at how scientific knowledge informs and guides policy decisions in society, which also links to the increasingly important area of evidence-informed policy-making. These two dimensions are of course linked – science policy connects the science and its applications to regulation, economics, strategy and public value.

Quantum policy specifically focuses on the frameworks, strategies and regulations that shape how governments, industries and research institutions develop and deploy quantum technologies. Many countries have published national quantum strategies, which include technology roadmaps tied to government investments. These outline the infrastructure needed to speed up the adoption of quantum technology – such as facilities, supply chains and a skilled workforce.

In the UK, the National Quantum Technology Programme (NQTP) – a government-led initiative that brings together industry, academia and government – has pioneered the idea of co-ordinated national efforts for the development of quantum technologies. Set up in 2014, the programme has influenced other countries to adopt a similar approach. The NQTP has been immensely successful in bringing together different groups from both the public and private sectors to create a productive environment that advances quantum science and technology. Co-operation and communication have been at the core of this programme, which has led to the UK's 10-year National Quantum Strategy. Launched in 2023, this details specific projects to help accelerate technological progress and make the country a leading quantum-enabled economy. But that won't happen unless we have mechanisms to help translate science into innovation, resilient supply chains, industry-led standardization, stable regulatory frameworks and a trained workforce.

Quantum technologies can bring benefits for national security, from advanced sensing to secure communications. But their dual-use nature also poses potential threats as the technology matures, particularly with the prospect of cryptographically relevant quantum computers – machines powerful enough to break encryption. To mitigate these risks in a complex geopolitical landscape, governments need tailored regulations, whether that's preparing for the transition to post-quantum cryptography (making communication safe from powerful code-cracking quantum computers) or controlling exports of sensitive products that could compromise security.

Like artificial intelligence (AI) and other emerging technologies, there are also ethical considerations to take into account when developing quantum technologies. In particular, we need policies to ensure transparency, inclusivity and equitable access. International organizations such as UNESCO and the World Economic Forum have already started integrating quantum into their policy agendas. But as quantum technology is such a rapidly evolving new field, we need to strike a balance between innovation and regulation. Too many rules can stifle innovation but, on the other hand, policy needs to keep up with innovation to avoid any future serious incidents.

Language barriers

Policy engagement involves collaborating with three sets of stakeholders – academia; industry and investors; and policy-makers. But as we started to work with these groups, we noticed each had a different way of communicating, creating a kind of language barrier. Scientists love throwing around equations, data and figures, often using highly technical terminology. Industry leaders and investors, on the other hand, talk in terms of how innovations could affect business performance and profitability, and what the risk for their investments could be. As for policy-makers, they focus more on how to distinguish between reality and hype, and look at budgets and regulations.

We found ourselves acting as cross-sector translators, seeking to bridge the gap between the three groups. We had to listen to each stakeholder's requirements and understand what they needed to know. We then had to reframe technical insights and communicate them in a relevant and useful way – without simplifying the science. Once we grasped everyone's needs and expectations, we offered relevant information, putting it into

Mixing PhDs and policy

Elizabeth Pasatembou

Elizabeth Pasatembou started her PhD in 2021, working with the particle-physics group and Centre for Cold Matter at Imperial College London. Her research focused on quantum sensing for fundamental physics as part of the Atom Interferometer Observatory and Network (AION) project. She is now a postdoctoral fellow working on quantum communications with the Cyprus Quantum Communications Infrastructure (CyQCI) team at the Cyprus University of Technology, which is part of the pan-European Quantum Communication Infrastructure (EuroQCI) project.

Her interest in science policy engagement started out of curiosity and the desire to make a more immediate impact during her PhD. "Research can feel slow," she says. "Taking up this role and getting involved in policy gave me the chance to use my expertise in a way that felt directly relevant, and develop new skills along the way. I also saw this as an opportunity to challenge myself and try something new."

Pasatembou also worked on a collaborative project between the Imperial Deep Tech Entrepreneurship and QuEST, conducting interviews with investors to inform the design of a tailored curriculum on quantum technologies for the investors community.

Dimitrie Cielecki

Dimitrie Cielecki joined Imperial's Complex Nanophotonics group as a PhD candidate in 2021. The opportunity to work in science policy came at a time when his research was evolving in new directions. "The first year of my PhD was not straightforward, with my project taking unexpected, yet exciting, turns in the realm of photonics, but shifting away from quantum," explains Cielecki, whose PhD topic was spatio-temporal light shaping for metamaterials.

Craig Whittall

Getting involved From left: Dimitrie Cielecki, Elizabeth Pasatembou and Michael Ho in the UK Houses of Parliament.

After seeing an advert for a quantum-related policy fellowship, he decided to jump in. "I didn't even know what supporting policy-making meant at that point," he says. "But I quickly became driven by the idea that my actions and opinions could have a quick impact in this field."

Cielecki is now a quantum innovation researcher at the Institute for Deep Tech Entrepreneurship in the Imperial Business School, where he is conducting research on the correlations between technical progress, investors' confidence and commercial success in the emerging quantum sector.

context for each group so everyone was on the same page.

To help us do this, we considered the stakeholders as "inventor", "funder", "innovator" or "regulator". As quantum technology is such a rapidly growing sector, the groupings of academia, industry and policy-makers are so entangled that the roles are often blurred. This alternative framework helped us to identify the needs and objectives of the people we were working with and to effectively communicate our science or evidence-backed messages.

Finding the right people

During our time as policy fellows, we were lucky to have mentors to teach us how to navigate this quantum landscape. In terms of policy, Craig Whittall from the Imperial Policy Forum was our guide on protocol and policy scoping. We worked closely with QuEST management – Peter Haynes and Jess Wade – to organize discussions, collect evidence from researchers, generate policy leads, and formulate insights or recommendations. We also had the pleasure of working with other PhD students, including Michael Ho, Louis Chen and Victor Lovic, who shared the same passion for bridging quantum research and policy.

Having access to world-leading scientists and a large pool of early-career researchers spread across all departments and faculties, facilitated by the network in QuEST, made it easier for us to respond to policy inquiries. Early on, we mapped out what quantum-related research is going on at Imperial and created a database of the researchers involved. This helped inform the university's strategy regarding quantum research, and let us identify who should contribute to the various calls for evidence by government or parliament offices.

PhD students are often treated as learners rather than contributors. But our experience showed that with the right support and guidance, early-career researchers (ECRs) such as ourselves can make real impact by offering fresh perspectives and expertise. We are the scientists, innovators or funders of the future so there is value in training people like us to understand the bigger picture as we embark on our careers.

To encourage young researchers to get involved in policy, QuEST and DSIT recently organized two policy workshops for ECR quantum tech specialists. Civil servants from the Office for Quantum explained their efforts and priorities, while we answered questions about our experience – the aim being to help ECRs to engage in policy-making, or choose it as a career option.

In April 2025 QuEST also launched an eight-week quantum primer for policy-makers. The course was modelled on a highly successful equivalent for AI, and looked to help policy-makers make more technically informed policy discussions. The first cohort welcomed civil servants from across government, and it was so highly reviewed a second course will be running from October 2025.

Our experience with QuEST has shown us the importance of scientists taking an active role in policy-making. With the quantum sector evolving at a formidable rate, it is vital that a framework is in place to take research from the lab to society. Scientists, industry, investors and policy-makers need to work together to create regulations and policies that will ensure the responsible use of quantum technologies that will benefit us all. ■

Quantum sensing for healthcare

Advances in quantum sensors could transform the worlds of medicine and healthcare. **Matt Jones** examines five of the most promising areas

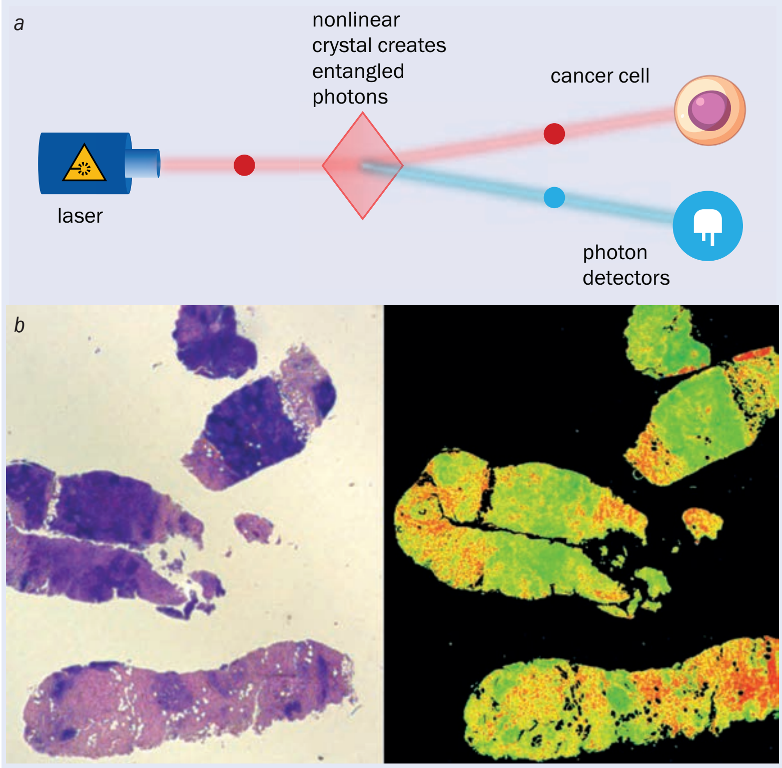
Matt Jones is doing a PhD in quantum physics within QET Labs at the University of Bristol, UK, and is part-time knowledge transfer manager at Innovate UK Business Connect. He wrote the Innovate UK report *Quantum for Life: How UK Life Sciences and Healthcare Can Benefit from Quantum Technologies*

As the world celebrates the 2025 International Year of Quantum Science and Technology, it's natural that we should focus on the exciting applications of quantum physics in computing, communication and cryptography. But quantum physics is also set to have a huge impact on medicine and healthcare. Quantum sensors, in particular, can help us to study the human body and improve medical diagnosis – in fact, several systems are close to being commercialized.

Quantum computers, meanwhile, could one day help us to discover new drugs by providing representations of atomic structures with greater accuracy and by speeding up calculations to identify potential drug reactions. But what other technologies and projects are out there? How can we forge new applications of quantum physics in healthcare and how can we help discover new potential use cases for the technology?

Those are the some of the questions tackled in a recent report, on which this *Physics World* article is based, published by Innovate UK in October 2024. Entitled *Quantum for Life*, the report aims to kickstart new collaborations by raising awareness of what quantum physics can do for the healthcare sector. While the report says quite a bit about quantum computing and quantum networking, this article will focus on quantum sensors, which are closer to being deployed.

1 Entangled thoughts



Adapted from Quantum for Life: How UK Life Sciences and Healthcare Can Benefit from Quantum Technologies by IOP Publishing

Digistain

a One way in which quantum physics is benefiting healthcare is through entangled photons created by passing laser light through a nonlinear crystal (left). Each laser photon gets converted into two lower-energy photons – one visible, one infrared – in a process called spontaneous parametric down conversion. In technology pioneered by the UK company Digistain, the infrared photon can be sent through a sample, with the visible photon picked up by a detector. As the photons are entangled, the visible photon gives information about the infrared photon and the presence of, say, cancer cells.

b On the left are cells seen with traditional stained biopsy and on the right are cells imaged using Digistain's method.

Sense about sensors

The importance of quantum science to healthcare isn't new. In fact, when a group of academics and government representatives gathered at Chicheley Hall back in 2013 to hatch plans for the UK's National Quantum Technologies Programme, healthcare was one of the main applications they identified. The resulting £1bn programme, which co-ordinated the UK's quantum-research efforts, was recently renewed for another decade and – once again – healthcare is a key part of the remit.

As it happens, most major hospitals already use quantum sensors in the form of magnetic resonance imaging (MRI) machines. Pioneered in the 1970s, these devices manipulate the quantum spin states of hydrogen atoms using magnetic fields and radio waves. By measuring how long those states take to relax, MRI can image soft tissues, such as the brain, and is now a vital part of the modern medicine toolkit.

While an MRI machine measures the quantum properties of atoms, the sensor itself is classical, essentially consisting of electromagnetic coils that detect the magnetic flux produced when atomic spins change direction. More recently, though, we've seen a new generation of nanoscale quantum sensors that are sensitive enough to detect magnetic fields emitted by a target biological system. Others, meanwhile, consist of just a single atom and can monitor small changes in the environment.

As the *Quantum for Life* report shows, there are lots of different quantum-based companies and institutions working in the healthcare sector. There are also many promising types of quantum sensors, which use photons, electrons or spin defects within a material, typically diamond. But ultimately what matters is what quantum sensors can achieve in a medical environment.

Quantum diagnosis

While compiling the report, it became clear that quantum-sensor technologies for healthcare come in five broad categories. The first is what the report labels "lab diagnostics", in which trained staff use quantum sensors to observe what is going on inside the human body. By monitoring everything from our internal temperature to the composition of cells, the sensors can help to identify diseases such as cancer.

Currently, the only way to definitively diagnose cancer is to take a sample of cells – a biopsy – and examine them under a microscope in a laboratory. Biopsies are often done with visual light but that can damage a sample, making diagnosis tricky. Another option is to use infrared radiation. By monitoring the specific wavelengths the cells absorb, the compounds in a sample can be identified, allowing molecular changes linked with cancer to be tracked.

Unfortunately, it can be hard to differentiate these signals from background noise. What's more, infrared cameras are much more expensive than those operating in the visible region. One possible solution is being explored by Digistain, a company that was spun out of Imperial College, London, in 2019. It is developing a product called EntangleCam that uses two entangled photons – one infrared and one visible (figure 1).

If the infrared photon is absorbed by, say, a breast cancer cell, that immediately affects the visible photon with which it is entangled. So by measuring the visible light, which can be done with a cheap, efficient detector, you can get information about the infrared photon – and hence the presence of a potential cancer cell (*Phys. Rev.* **108** 032613). The technique could therefore allow cancer to be quickly diagnosed before a tumour has built up, although an oncologist would still be needed to identify the area for the technique to be applied.

Point of care

The second promising application of quantum sensors lies in "point-of-care" diagnostics. We all became familiar with the concept during the COVID-19 pandemic when lateral-flow tests proved to be a vital part of the worldwide response to the virus. The tests could be taken anywhere and were quick, simple, reliable and relatively cheap. Something that had originally been designed to be used in a lab was now available to most people at home.

Quantum technology could let us miniaturize such tests further and make them more accurate, such that they could be used at hospitals, doctor's surgeries or even at home. At the moment, biological indicators of disease tend to be measured by tagging molecules with fluorescent markers and measuring where, when and how much light they emit. But because some molecules are naturally fluorescent, those measurements have to be processed to eliminate the background noise.

One emerging quantum-based alternative is to characterize biological samples by measuring their tiny magnetic fields. This can be done, for example, using diamond specially engineered with nitrogen-vacancy (NV) defects. Each is made by removing two carbon atoms from the lattice and implanting a nitrogen atom in one of the gaps, leaving a vacancy in the other. Behaving like an atom with discrete energy levels, each defect's spin state is influenced by the local magnetic field and can be "read out" from the way it fluoresces.

One UK company working in this area is Element Six. It has joined forces with the US-based firm QDTI to make a single-crystal diamond-based device that can quickly identify biomarkers in blood plasma, cerebrospinal fluid and other samples extracted from the body. The device detects magnetic fields produced by specific proteins, which can help identify diseases in their early stages, including various cancers and neurodegenerative conditions like Alzheimer's. Another firm using single-crystal diamond to detect cancer cells is Germany-based Quantum Total Analysis Systems (QTAS).

Matthew Markham, a physicist who is head of quantum technologies at Element Six, thinks that healthcare has been "a real turning point" for the company. "A few years ago, this work was mostly focused on academic problems," he says. "But now we are seeing this technology being applied to real-world use cases and that it is transitioning into industry with devices being tested in the field."

An alternative approach involves using tiny nanometre-sized diamond particles with NV centres, which have the advantage of being highly biocompatible. QT Sense of the Netherlands, for example, is using these nanodiamonds to build nano-MRI scanners that can measure the concentration of molecules that have an intrinsic magnetic field. This equipment has already been used by biomedical researchers to investigate single cells (figure 2).

Australian firm FeBI Technologies, meanwhile, is developing a device that uses nanodiamonds to measure the magnetic properties of ferritin – a protein that stores iron in the body. The company claims its technology is nine orders of magnitude more sensitive than traditional MRI and will allow patients to monitor the amount of iron in their blood using a device that is accurate and cheap.

Wearable healthcare

The third area in which quantum technologies are benefiting healthcare is what's billed in the *Quantum for Life* report as "consumer medical monitoring and wearable healthcare". In other words, we're talking about devices that allow people to monitor their health in daily life on an ongoing basis. Such technologies are particularly useful for people who have a diagnosed medical condition, such as diabetes or high blood pressure.

NIQS Tech, for example, was spun off from the University of Leeds in 2022 and is developing a highly accurate, non-invasive sensor for measuring glucose levels. Traditional glucose-monitoring devices are painful and invasive because they basically involve sticking a needle in the body. While newer devices use light-based spectroscopic measurements, they tend to be less effective for patients with darker skin tones.

The sensor from NIQS Tech instead uses a doped silica platform, which enables quantum interference effects. When placed in contact with the skin and illuminated with laser light, the device fluoresces, with the lifetime of the fluorescence depending on the amount of glucose in the user's blood, regardless of skin tone. NIQS has already demonstrated proof of concept with lab-based testing and now wants to shrink the technology to create a wearable device that monitors glucose levels continuously.

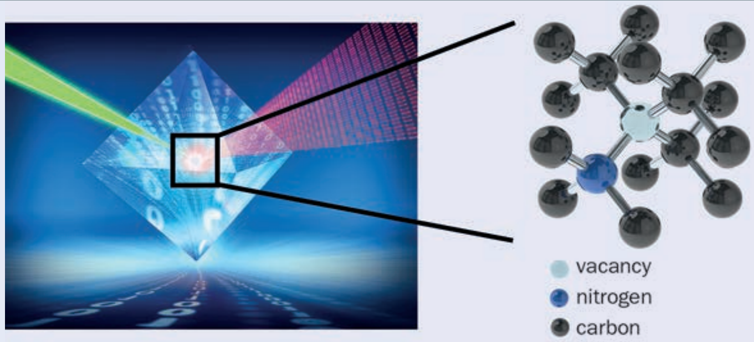
Body imaging

The fourth application of quantum tech lies in body scanning, which allows patients to be diagnosed without needing a biopsy. One company leading in this area is Cerca Magnetics, which was spun off from the University of Nottingham. In 2023 it won the inaugural qBIG prize for quantum innovation from the Institute of Physics, which publishes *Physics World*, for developing wearable optically pumped magnetometers for magnetoencephalography (MEG), which measure magnetic fields generated by neuronal firings in the brain. Its devices can be used to scan patients' brains in a comfortable seated position and even while they are moving.

Quantum-based scanning techniques could also help diagnose breast cancer, which is usually done by exposing a patient's breast tissue to low doses of X-rays. The trouble with such mammograms is that all breasts contain a mix of low-density fatty and other, higher-density tissue. The latter creates a "white blizzard" effect against the dark background, making it challenging to differentiate between healthy tissue and potential malignancies.

That's a particular problem for the roughly 40% of women who have a higher concentration of higher-density tissue. One alternative is to use molecular breast imaging (MBI), which involves imaging the distribution of a radioactive tracer that has been intravenously injected into a patient. This tracer, however, exposes patients to a higher (albeit still safe) dose of radiation than with a mammogram, which means that patients

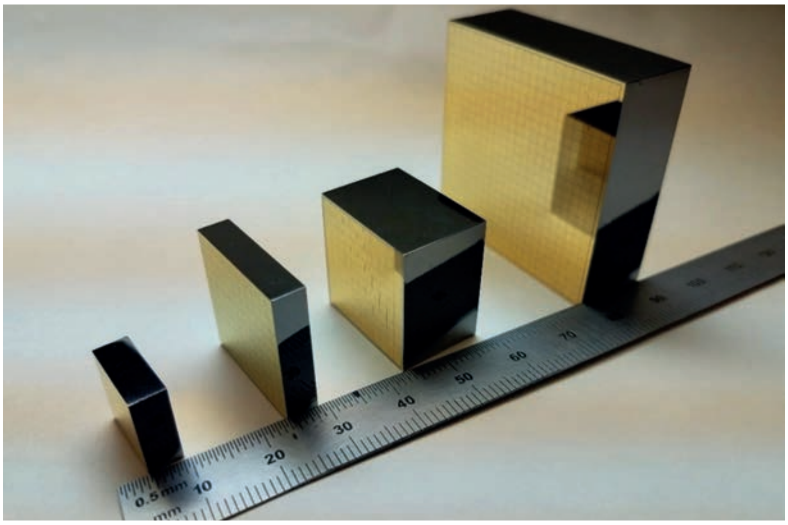
2 Centre of attention



Element Six

A nitrogen-vacancy defect in diamond – known as an NV centre – is made by removing two carbon atoms from the lattice and implanting a nitrogen atom in one of the gaps, leaving a vacancy in the other. Using a pulse of green laser light, NV centres can be sent from their ground state to an excited state. If the laser is switched off, the defects return to their ground state, emitting a visible photon that can be detected. However, the rate at which the fluorescent light drops while the laser is off depends on the local magnetic field. As companies like Element Six and QTSense are discovering, NV centres in diamond are great way of measuring magnetic fields in the human body especially as the surrounding lattice of carbon atoms shields the NV centre from noise.

Kromek



Faster and better Breast cancer is often detected with X-rays using mammography but it can be tricky to spot tumours in areas where the breast tissue is dense. One alternative is molecular breast imaging (MBI), which uses a radioactive tracer to "light up" areas of cancer in the breast and works even in dense breast tissue. However, MBI currently exposes patients to more radiation than with mammography, which is where cadmium zinc telluride (CZT) semiconductors, developed by the UK firm Kromek, could help. They produce a measurable voltage pulse from just a single gamma-ray photon, opening the door for "ultralow-dose MBI" – where much clearer images are created with barely one-eighth of the radiation.

> Quantum technologies can help us break the technological limits of microscopy

have to be imaged for a long time to get enough signal.

A solution could lie with the UK-based firm Kromek, which is using cadmium zinc telluride (CZT) semiconductors that produce a measurable voltage pulse from just a single gamma-ray photon. As well as being very efficient over a broad range of X-ray and gamma-ray photon energies, CZTs can be integrated onto small chips operating at room temperature. Preliminary results with Kromek's ultralow-dose and ultrafast detectors show they work with barely one-eighth of the amount of tracer as traditional MBI techniques.

"Our prototypes have shown promising results," says Alexander Cherlin, who is principal physicist at Kromek. The company is now designing and building a full-size prototype of the camera as part of Innovate UK's £2.5m "ultralow-dose" MBI project, which runs until the end of 2025. It involves Kromek working with hospitals in Newcastle along with researchers at University College London and the University of Newcastle.

Microscopy matters

The final application of quantum sensors to medicine lies in microscopy, which these days no longer just means visible light but everything from Raman and two-photon microscopy to fluorescence lifetime imaging and multiphoton microscopy. These techniques allow samples to be imaged at different scales and speeds, but they are all reaching various technological limits.

Quantum technologies can help us break those limits. Researchers at the University of Glasgow, for example, are among those to have used pairs of entangled photons to enhance microscopy through "ghost imaging". One photon in each pair interacts with a sample, with the image built up by detecting the effect on its entangled counterpart. The technique avoids the noise created when imaging with low levels of light (*Sci. Adv.* **6** eaay2652).

Researchers at the University of Strathclyde, meanwhile, have used nanodiamonds to get around the problem that dyes added to biological samples eventually stop fluorescing. Known as photobleaching, the effect prevents samples from being studied after a certain time (*Roy. Soc. Op. Sci.* **6** 190589). In the work, samples could be continually imaged and viewed using two-photon excitation microscopy with a 10-fold increase in resolution.

Looking to the future

But despite the great potential of quantum sensors in medicine, there are still big challenges before the technology can be deployed in real, clinical settings. Scalability – making devices reliably, cheaply and in sufficient numbers – is a particular problem. Fortunately, things are moving fast. Even since the *Quantum for Life* report came out late in 2024, we've seen new companies being founded to address these problems.

One such firm is Bristol-based RobQuant, which is developing solid-state semiconductor quantum sensors for non-invasive magnetic scanning of the brain. Such sensors, which can be built with the standard processing techniques used in consumer electronics, allow for scans on different parts of the body. RobQuant claims its sensors are robust and operate at ambient temperatures without requiring any heating or cooling.

Agnethe Seim Olsen, the company's co-founder and chief technologist, believes that making quantum sensors robust and scalable is vital if they are to be widely adopted in healthcare. She thinks the UK is leading the way in the commercialization of such sensors and will benefit from the latest phase of the country's quantum hubs. Bringing academia and businesses together, they include the £24m Q-BIOMED biomedical-sensing hub led by University College London and the £27.5m QuSIT hub in imaging and timing led by the University of Birmingham.

Q-BIOMED is, for example, planning to use both single-crystal diamond and nanodiamonds to develop and commercialize sensors that can diagnose and treat diseases such as cancer and Alzheimer's at much earlier stages of their development. "These healthcare ambitions are not restricted to academia, with many start-ups around the globe developing diamond-based quantum technology," says Markham at Element Six.

As with the previous phases of the hubs, allowing for further research encourages start-ups – researchers from the forerunner of the QuSIT hub, for example, set up Cerca Magnetics. The growing maturity of some of these quantum sensors will undoubtedly attract existing medical-technology companies. The next five years will be a busy and exciting time for the burgeoning use of quantum sensors in healthcare. ■

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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. Select a box to read or listen to more.

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.

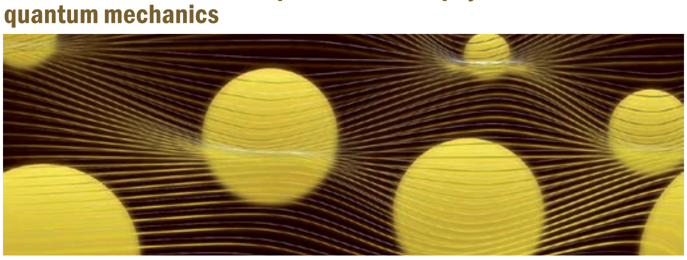
Can we use quantum computers to make music?

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.

How the STFC Hartree Centre is helping UK industry de-risk quantum computing investment

Stefano Mensa, group lead for advanced computing and emerging technologies at the STFC Hartree Centre in the UK which has more than 160 staff,, tells Joe McEntee how industry can utilize quantum computing to unlock new opportunities for commercial and regional growth.

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 **Tracy Northup** of the University of Vienna, **Michelle Simmons** from the University of New South Wales and **Peter Zoller** from the University of Innsbruck. All three experts were interviewed while attending the Helgoland 2025 in June.

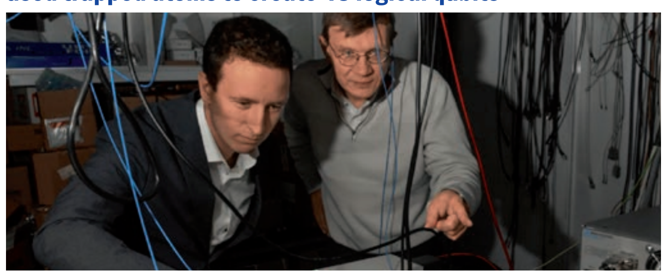
IYQ: our celebrations begin with a look at quantum networks and sensors

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

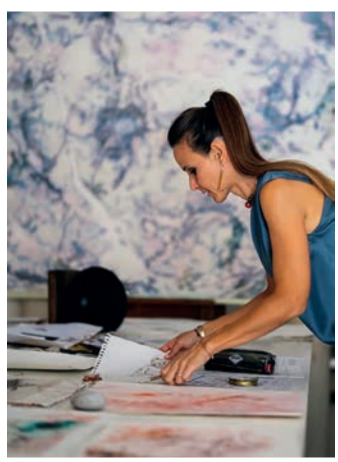


Mikhail Lukin and **Dolev Bluvstein** from Harvard University in the US explain the crucial role that error correction is playing in the development of practical quantum computers. They also describe how atoms are moved around their quantum processor and why this coordinated motion let them make logical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

Entangled expressions: where quantum science and art come together



What happens when you put a visual artist into a quantum physics lab? Find out more from **Serena Scapagnini**, current artist-in-residence at the Yale Quantum Institute in the US, and **Florian Carle**, a former rocket scientist who's managing director of the institute and co-ordinator of the residency. He believes art-science collaborations open new possibilities for engaging with quantum ideas.