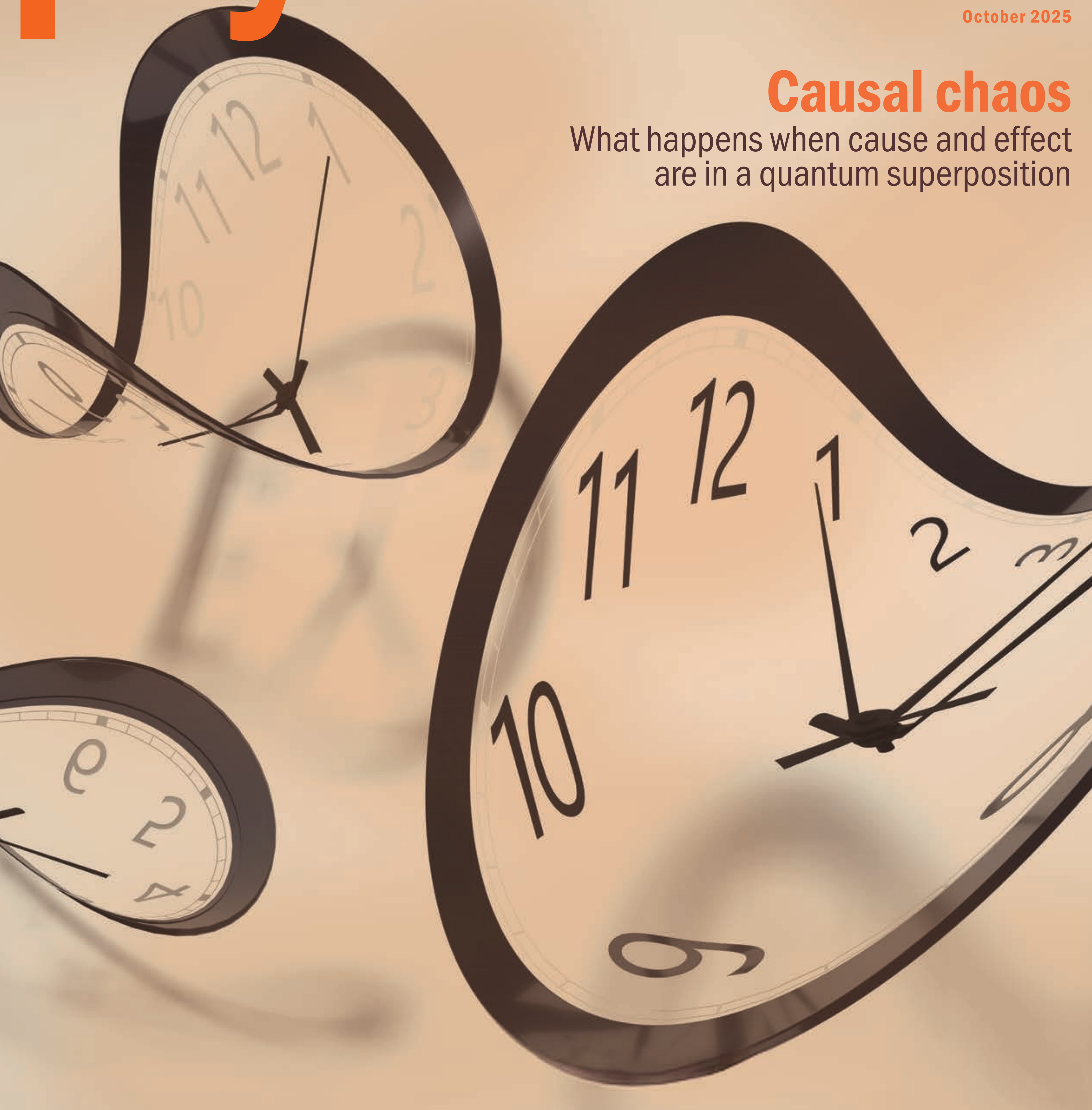
physicsworld

October 2025



Causal chaos

What happens when cause and effect are in a quantum superposition

Applied impact The link between quantum tech and fundamentals

Deliciously weird Nobel laureate Bill Phillips on the joys of quantum physics

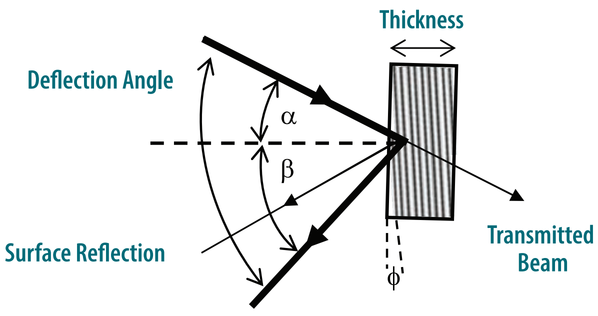
Working at GCHQ Building a career in cyber security and intelligence

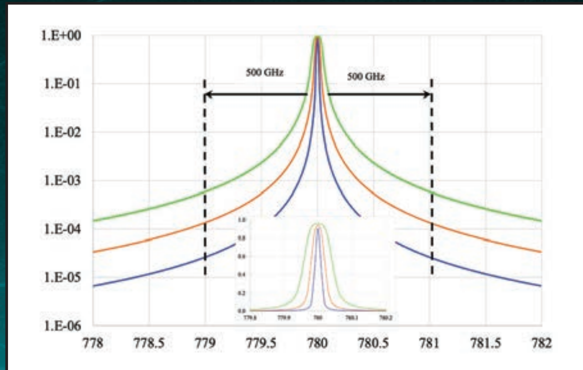
Volume Bragg Gratings (VBGs) for

Quantum Optics

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

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





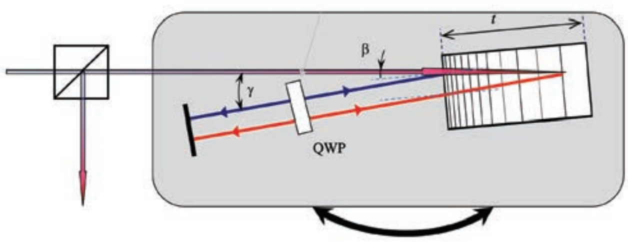
Spectral Shape of Reflecting VBG Filters with Bandwidth: 10 GHz; 25 GHz and 50 GHz

Chirped Bragg Gratings (CBGs) for

Qubit Control

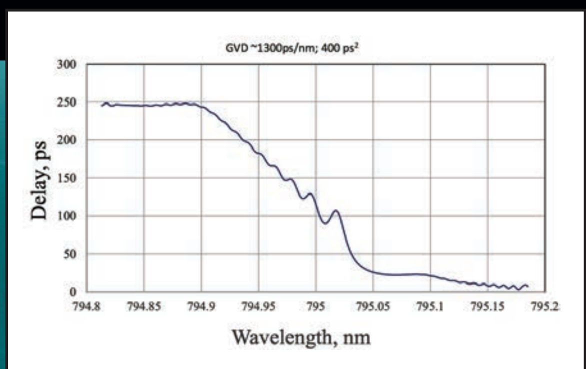
Extremely Large Dispersion 800 ps^2 enables effective and fast amplitude modulation

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



Schematic Diagram of CBG deployment for Qubit Filtering and Control

Group delay dispersion of Chirped Bragg grating (CBG)



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

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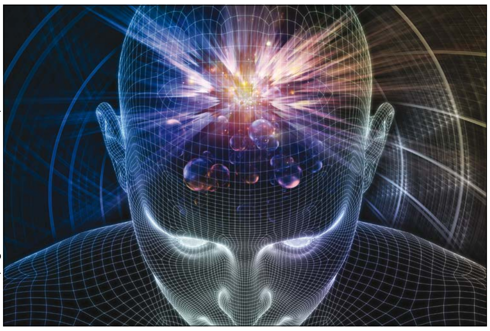

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AUDIO *Physics World* editors discuss their highlights of the October issue

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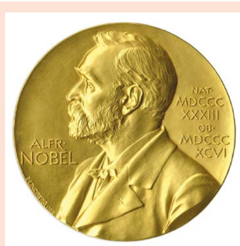

Nobel Prize for Physics

For all the latest coverage of the Nobel Prize for Physics 2025, check out our special collection.

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News & Analysis

Exam errors hit physics students

Students applying to do physics at UK universities this year could have been affected by errors in A-level physics papers. **Michael Banks** investigates

Errors in some of this year's A-level physics exam papers could leave students without good enough grades to study physics at university. The mistakes have forced Tom Grinyer, chief executive of the Institute of Physics (IOP), to write to all heads of physics at UK universities, calling on them to "take these exceptional circumstances into account during the final admissions process". The IOP is particularly concerned about students whose grades are lower than expected or are "a significant outlier" compared to other subjects.

The mistakes in question appeared in the physics (A) exam papers 1 and 2 set by the OCR exam board. Erratum notices had been issued to students at the start of the exam in June, but a further error in paper 2 was only spotted after the exam had taken place, causing some students to get stuck. Physics paper 2 from the rival AQA exam board was also seen to contain complex phrasing that hindered students' ability to answer the question and led to time pressures.

A small survey of physics teachers carried out after the exam by the IOP reveals that 41% were dissatisfied with the OCR physics exam papers and more than half (58%) felt that students had a negative experience. Two-thirds of teachers, meanwhile, reported that students had a negative experience during the AQA exam.

Grinyer says that the IOP is engaging in "regular, open dialogue with exam boards" to ensure that the assessment process supports and encourages students, while maintaining the rigour and integrity of the qualification. "Our immediate concern," Grinyer warns, "is that the usual standardization processes and adjustments to grade boundaries – particularly for the OCR paper with errors – may fail to compensate fully for the negative effect on exam performance for some individuals."

Shutterstock/monkey business images

Pressure points A-level entries are the highest in 25 years, but the Institute of Physics says that recent errors in some papers could leave students without the grades to do physics at university or put them off the subject altogether.

> The added challenge of inaccessible or error-prone exam papers risks compounding disadvantage and may not reflect the true potential of these students

An OCR spokesperson told *Physics World* that the exam board is "sorry to the physics students and teachers affected by errors in A-level physics this year". The board says that it "evaluated student performance across all physics papers, and took all necessary steps to mitigate the impact of these errors". The OCR claims that the 13 000 students who sat OCR A-level physics A this year "can be confident" in their A-level physics.

"We have taken immediate steps to review and strengthen our quality assurance processes to prevent such issues from occurring in the future," the OCR adds. "We appreciated the opportunity to meet with the Institute of Physics to discuss these issues, and also to discuss our shared interest in encouraging the growth of this vital subject."

Almost 23 500 students sat AQA A-level physics this year and an AQA spokesperson told *Physics World* that the exam board "listened to feedback and took steps to make A-level physics more accessible" to students and that there "is no need for universities to make an exception for AQA physics outcomes when it comes to admissions criteria".

"These exam papers were error-free, as teachers and students would expect, and we know that students found the papers this year to be more accessible than last year," the AQA says. "We'll continue to engage with any feedback that we receive, including feedback from the Institute of Physics, to explore how we can enhance our A-level physics assessments and give students the best possible experience when they sit exams."

Students 'in tears'

The IOP now wants A-level physics students to be given a "fair opportunity" when it comes to university admissions. "These issues are particularly concerning for students on widening participation pathways, many of whom already face structural barriers to high-stakes assessment," the IOP letter states. "The added challenge of inaccessible or error-prone exam papers risks compounding disadvantage and may not reflect the true potential of these students."

The IOP also contacted AQA last year over inaccessible contexts and language used in previous physics exams. But despite AQA's assurances that the problems would be addressed, some of the same issues have now recurred. Helen Sinclair, head of physics at the all-girls Wimbledon High School, believes that the "variable quality" of recent A-level papers have had "far-reaching consequences" on young people thinking of going into physics at university.

"Our students have exceptionally high standards for themselves and the opaque nature of many questions affects them deeply, no matter what grades they ultimately achieve. This has even led some to choose to apply for other subjects at university," she told *Physics World*. "This is not to say that papers should not be challenging; however, better scaffolding within some questions would help students anchor themselves in what is an already stressful environment, and would ultimately enable them to better demonstrate their full potential within an exam."

Those concerns are echoed by Abbie Hope, head of physics at Stokesley School near Middlesbrough. She says the errors in this year's exam papers are "not acceptable" and believes that OCR has "failed their students". Hope says that AQA physics papers in recent years have been "very challenging" and have resulted in students feeling like they cannot do physics. She also says some have emerged from exam halls in tears.

"Students come out of the exams feeling disheartened and share their perceptions with younger students," she says. "I would rather students sat a more accessible paper, with higher grade boundaries so they feel more successful, rather than convinced they have underachieved and then getting a surprise on results day." Hope fears the mistakes will undermine efforts to encourage uptake and participation in physics.

A 'growing unease'

Rachael Houchin, head of physics at Royal Grammar School Newcastle, says this year's errors have added to her "growing unease" about the state of physics education in the UK. "Such incidents – particularly when they are public and recurring – do little to improve the perception of the subject or encourage its uptake," she says. "Everyone involved in physics education – at any level – has a duty to get it right. If we fail, we risk physics drifting into the category of subjects taught predominantly in selective or independent schools, and increasingly absent from the mainstream."

Hari Rentala, associate director of education and workforce at the IOP, is concerned that the errors unfairly "perpetuate the myth" that physics is a difficult subject. "OCR appear to have managed the situation as best they can, but this is not much consolation for how students will have felt during the exam and over the ensuing weeks," says Rentala. "Once again AQA set some questions that were overly challenging. We can only hope that the majority of students who had a negative experience as a result of these issues at least receive a fair grade – as grade boundaries have been adjusted down."

Michael Banks is news editor of *Physics World*

Mixed news for UK school pupils

Despite the problems with some specific papers (see main text), almost 45 000 students took A-level physics in the UK this year – a rise of 4.3% on last year – to reach the highest level for 25 years. Physics is now the sixth most popular subject at A-level, up from ninth last year, with girls representing a quarter of all candidates. In Scotland the number of entries in both National 5 and Higher physics was 13 680 and 8560, respectively, up from 13 355 and 8065 last year.

"We are delighted so many young people, and increasing numbers of girls, are hearing the message that physics can open up a lifetime of opportunities," says Institute of Physics chief executive Tom Grinyer. "If we can build on this momentum there is a real opportunity to finally close the gap between boys and girls in physics at A-level. To do that we need to continue to challenge the stereotypes that still put too many young people off physics and ensure every young person knows that physics – and a career in science and innovation – could be for them."

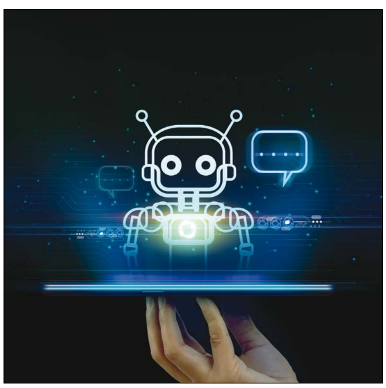
However, there is less good news for younger pupils, with a new IOP report finding that more than half a million GCSE students are expected to start the new school year without a physics teacher. It reveals that a quarter of English state schools have no specialist physics teachers at all and the IOP fears that more than 12 000 students could miss out on taking A-level physics because of this. The IOP wants the UK government to invest £120m over the next 10 years to address the shortage by retaining, recruiting and retraining a new generation of physics teachers.

Publishing

Artificial intelligence could help detect 'predatory' journals

Artificial intelligence (AI) could help sniff out questionable open-access publications that are more interested in profit than scientific integrity. That is according to an analysis of 15 000 scientific journals by an international team of computer scientists. They find that dubious journals tend to publish an unusually high number of articles and feature authors who have many affiliations and frequently self-cite (*Sci. Adv.* 11 eadt2792).

Open access removes the requirement for traditional subscriptions. Articles are instead made immediately and freely available for anyone to read, with publication costs covered by authors by paying an article-processing charge. But as the popularity of open-access journals has risen, there has been a growth in "predatory" journals that exploit the open-access model by making scientists pay publication fees without a proper peer-review process in place.



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Quality control Researchers say that a new AI tool could help to pre-screen large numbers of journals.

To build an AI-based method for distinguishing legitimate from questionable journals, Daniel Acuña, a computer scientist at the University of Colorado Boulder, and colleagues used the Directory of Open Access Journals (DOAJ) – an online, community-curated index of open-access journals. The researchers trained their machine-learning model on 12 869 journals indexed on the DOAJ and 2536 journals that have been removed from the DOAJ due to questionable practices that violate the community's listing criteria. The team then tested the tool on 15 191 journals listed by Unpaywall, an online directory of free research articles.

The AI-model flagged 1437 journals as questionable, with the researchers concluding that 1092 were genuinely questionable while 345 were false positives. They also identified around 1780 problematic journals that the AI screening failed to flag. According to the study authors, their analysis shows that problematic publishing practices leave detectable patterns in citation behaviour such as the last authors having a low h-index together with a high rate of self-citation.

Michael Allen

Taking the risk out of quantum computing

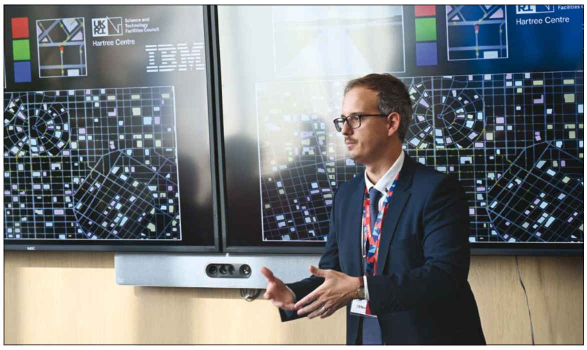
Stefano Mensa, group lead for advanced computing and emerging technologies at the STFC Hartree Centre, tells Joe McEntee how industry can utilize quantum computing to unlock new opportunities for commercial and regional growth

What role does the Hartree Centre play in quantum computing?
The Hartree Centre gives industry fast-track access to next-generation supercomputing, AI and digital capabilities. We are a "connector" when it comes to quantum computing, helping UK businesses and public-sector organizations to de-risk the early-stage adoption of a technology that is not yet ready to buy off-the-shelf. Our remit spans quantum software, theoretical studies and, ultimately, the integration of quantum computing into existing high-performance computing (HPC) infrastructure and workflows.

What does industry need when it comes to quantum computing?
It's evident that industry wants to understand the commercial upsides of quantum computing, but doesn't yet have the necessary domain knowledge and skill sets to take full advantage of the opportunities. By working with the STFC Hartree Centre, businesses can help their computing and R&D teams to bridge that quantum knowledge gap.

How does the interaction with industry partners work?
The Hartree Centre's quantum computing effort is built around a cross-disciplinary team of scientists and a mix of expertise spanning physics, chemistry, mathematics, computer science and quantum information science. We offer specialist quantum consultancy to clients across industries as diverse as energy, pharmaceuticals and food manufacturing.

How does that work in practice?
We begin by doing the due diligence on the client's computing challenge, understanding the computational bottlenecks and, where appropriate, translating the research problem so that it can be executed, in whole or in part, on a quantum computer or a mixture of hybrid and quantum computing resources.



STFC

Growth opportunities The Hartree Centre's Stefano Mensa is helping UK industry to understand the commercial upsides of quantum computing.

What are the operational priorities for the Hartree Centre in quantum computing?
Integrating classical HPC and quantum computing is a complex challenge along three main pathways: infrastructure – bridging fundamentally different hardware architectures; software – workflow management, resource scheduling and organization; and finally applications – adapting and optimizing computing workflows across quantum and classical domains. All of these competencies are mandatory for successful exploitation of quantum computing systems.

So it's likely these pathways will converge?
Correct. Ultimately, the task is how do we distribute a workload to run on an HPC platform, also on a quantum computer, when many of the algorithms and data streams must loop back and forth between the two systems.

How do you link up classical computing and quantum resources?
We have been addressing this problem with our quantum technology partners – IBM and Pasqal – and a team at Rensselaer Polytechnic in New York. Together, we have introduced a Quantum Resource Management Interface – an open-source tool that supports unified job submission for quantum and classical computing tasks and that's scalable to cloud computing environments. It's the "black-box" solution industry has been looking for to bridge the established HPC and emerging quantum domains.

The Hartree Centre has a flagship collaboration with IBM in quantum computing. Can you tell us more?
The Hartree National Centre for Digital Innovation (HNCDI) is a £210m public–private partnership with IBM to create innovative digital technologies spanning HPC, AI, data analytics and quantum computing. HNCDI is the cornerstone of IBM's quantum technology strategy in the UK and, over the past four years, the collaboration has clocked up more than 30 joint projects with industry. In each of these projects, HNCDI is using quantum computers to tackle problems that are out of reach for classical computers.

Do you have any examples of early wins for HNCDI in quantum?
One is streamlining drug discovery and development. As part of a joint effort with the pharmaceutical firm AstraZeneca and quantum-software developer Algorithmiq, we have improved the accuracy of molecular modelling with the help of quantum computing and, by extension, developed a better understanding of the molecular interactions and processes involved in drug synthesis. Another eye-catching development is Qiskit Machine Learning (ML), an open-source library for quantum machine-learning tasks on quantum hardware and classical simulators. While Qiskit ML started as a proof-of-concept library from IBM, our team at the Hartree Centre has, over the past couple of years, developed it into a modular tool for non-specialist users as well as quantum computational scientists and developers.

So quantum computing could play a big role in healthcare?
Healthcare has yielded productive lines of enquiry, including a proof-of-concept study to demonstrate

the potential of quantum machine-learning in cancer diagnostics. Working with Royal Brompton and Harefield Hospitals and Imperial College London, we have evaluated histopathology datasets to categorize different types of breast-cancer cells through AI workflows. It's research that could eventually lead to better predictions regarding the onset and progression of disease.

And what about other sectors?
We have been collaborating with the German power utility E.ON to study the complex challenges that quantum computing may be able to address in the energy sector – such as strategic infrastructure development, effective energy demand management and streamlined integration of renewable energy sources.

What does the next decade look like for the Hartree Centre's quantum computing programme?
Longer term, the goal is to enable our industry partners to become at-scale end-users of quantum computing, delivering economic and societal impact along the way. As for our own development roadmap at the Hartree Centre, we are evaluating options for the implementation of a large-scale quantum computing platform to further diversify our existing portfolio of HPC, AI, data science and visual computing technologies.

STFC Hartree Centre: helping UK industry deliver societal impact

The Hartree Centre is part of the Science and Technology Facilities Council (STFC), one of the main UK research councils supporting fundamental and applied initiatives in astronomy, physics, computational science and space science.

Based at the Daresbury Laboratory, part of the Sci-Tech Daresbury research and innovation campus in north-west England, the Hartree Centre has more than 160 scientists and technologists specializing in supercomputing, applied scientific computing, data science, AI, cloud and quantum computing.

"Our goal is to help UK industry generate economic growth and societal impact by exploiting advanced HPC capabilities and digital technologies," explains Vassil Alexandrov, chief science officer at STFC Hartree Centre.

One of the core priorities for Alexandrov and his team is the interface between "exascale" computing and scalable AI. It's a combination of technologies that's being lined up to tackle "grand challenges" like the climate crisis and the transition from fossil fuels to clean energy.

A case in point is the Climate Resilience Demonstrator, which uses "digital twins" to simulate how essential infrastructure like electricity grids and telecoms networks might respond to extreme weather events. "These kinds of insights are critical to protect communities, maintain service delivery and build more resilient public infrastructure," says Alexandrov.

Elsewhere, as part of the Fusion Computing Lab, the Hartree Centre is collaborating with the UK Atomic Energy Authority on sustainable energy generation from nuclear fusion. "We have a joint team of around 60 scientists and engineers working on this initiative to iterate and optimize the building blocks for a fusion power plant," notes Alexandrov. "The end-game is to deliver net power safely and affordably to the grid from magnetically confined fusion."

Exascale computing and AI also underpin the Research Computing and Innovation Centre, a collaboration with AWE, the organization that runs research, development and support for the UK's nuclear-weapons stockpile.

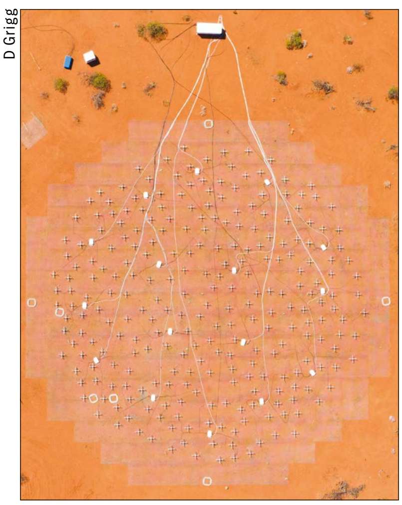
Joe McEntee is a consultant editor based in South Gloucestershire, UK

Space

Starlink emissions impact radio astronomy

The largest ever survey of low-frequency radio emissions from satellites has detected signals from the Starlink satellite "mega-constellation" across scientifically important low-frequency bands, including some that are protected for radio astronomy by international regulations. These emissions, which come from onboard electronics and are not intentional transmissions, could mask the weak radio-wave signals that astronomers seek to detect. As well as being damaging for radio astronomy, the findings highlight the need for new regulations that cover unintended transmissions, not just deliberate ones (*A&A* 699 A307).

The main purpose of Starlink and other mega-constellations is to provide Internet coverage around the world. While the effects of mega-constellations on optical astronomy have been widely studied, Dylan Grigg, a PhD student at the Curtin Institute of Radio Astronomy in Australia, who is lead author of the survey, says that researchers are just beginning to realize the extent to which they are also adversely affecting radio astronomy. Grigg and colleagues turned to a radio telescope called the Engineering Development Array 2 (EDA2). This is a prototype station for the low-frequency half of the Square Kilometre Array (SKA-Low). Using the EDA2, the researchers imaged the sky every two seconds at the frequencies that SKA-Low will cover.



D Grigg

Listening in A new survey has detected more than 112 000 radio emissions from over 1800 Starlink satellites in just four months.

During the survey period, the researchers detected more than 112 000 radio emissions from over 1800 Starlink satellites. At some frequencies, up to 30% of all survey images contained at least one Starlink detection. "While Starlink is not the only satellite network, it is the most immediate and frequent source of potential interference for radio astronomy," Grigg says. "Indeed, it launched 477 satellites during this study's four-month data collection period alone and has the most satellites in orbit – more than 7000 during the time of this study."

But it is not only the sheer number of satellites that poses a challenge for astronomers. So, too, does the strength and frequency of their emissions. From a regulatory perspective, the widespread detection of unintended emissions, including within protected frequency bands, shows the need for international regulation and limits on unintended emissions, says Grigg.
Isabelle Dumé

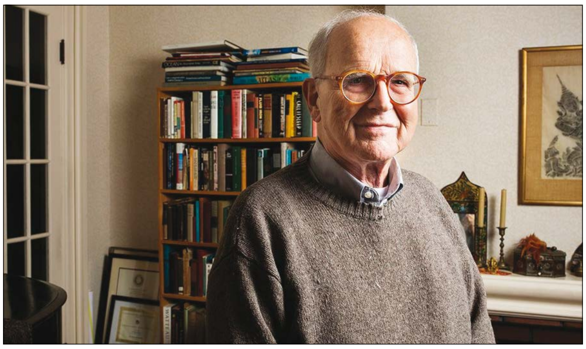
People

Rainer Weiss: gravitational-wave pioneer dies aged 92

Rainer Weiss, who shared the Nobel Prize for Physics in 2017 for the discovery of gravitational waves, died on 25 August at the age of 92. Weiss came up with the idea of detecting gravitational waves by measuring changes in distance as tiny as 10^{-18} m via an interferometer several kilometres long. His proposal eventually led to the formation of the twin Laser Interferometer Gravitational-Wave Observatory (LIGO), which first detected such waves in 2015.

Weiss was born in Berlin, Germany, on 29 September 1932 shortly before the Nazis rose to power. With a father who was Jewish and an ardent communist, Weiss and his family were forced to flee the country – first to Czechoslovakia and then to the US in 1939. Weiss was raised in New York, finishing his school days at the private Columbia Grammar School thanks to a scholarship from a refugee relief organization.

In 1950 Weiss began studying electrical engineering at Massachusetts Institute of Technology (MIT) before switching to physics, eventually earning a PhD in 1962. He then worked at Tufts University before moving to Princeton University, where he was a research associate with the astronomer and physicist Robert Dicke. In 1964 Weiss returned to MIT, where he began developing his idea of using a large interferometer to measure gravitational waves. Teaming up with Kip Thorne at the California Institute of Technology (Caltech), Weiss drew up a feasibility study for a kilometre-scale laser interferometer. In 1979 the National Science Foundation funded Caltech and MIT to develop the proposal to build LIGO.


M Scott Brauer

Creating waves Rainer Weiss pioneered the idea that a laser interferometer could be used to detect gravitational waves.

Construction of two LIGO detectors – one in Hanford, Washington and the other at Livingston, Louisiana – began in 1990, with the facilities opening in 2002. On 14 September 2015 – during the first observation run of a subsequent upgrade to LIGO known as Advanced LIGO, or aLIGO – the interferometer detected gravitational waves from two merging black holes. The discovery was announced by those working on aLIGO in February 2016.

The following year, Weiss was awarded one half of the 2017 Nobel Prize for Physics "for decisive contributions to the LIGO detector and the observation of gravitational waves". The other half was shared by Thorne and fellow Caltech physicist Barry Barish, who was LIGO project director.

MIT's dean of science Nergis Mavalvala, who worked with Weiss to build an early prototype of a gravitational-wave detector as part of her PhD, says that every gravitational-wave event that is observed "will be a reminder of his legacy". "[Weiss] leaves an indelible mark on science and a gaping hole in our lives," says Mavalvala. "I am heartbroken, but also so grateful for having him in my life, and for the incredible gifts he has given us."

Michael Banks

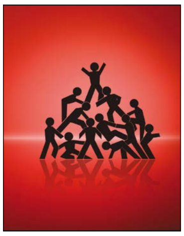
Publishing

Scientists in the US slow down after tenure, finds study

Researchers in the US who receive tenure produce more novel but less impactful work, according to an analysis of the output of more than 12 000 academics across 15 disciplines. The study also finds that publication rates rise steeply and steadily during tenure-track, typically peaking the year before a scientist receives a permanent position. After tenure, their average publication rate settles near the peak value (*Proc. Natl Acad. Sci.* **122** e2500322122).

Carried out by data scientists led by Giorgio Tripodi from Northwestern University in Illinois, the study examined the publication history of academics five years before tenure and five years after. The researchers say that the observed pattern – a rise before tenure, followed by a peak and then a steady level – is highly reproducible. "Tenure in the US academic system is a very peculiar contract," explains Tripodi. "It [features] a relatively long probation period followed by a permanent appointment [which is] a strong incentive to maximize research output and avoid projects that are more likely to fail during the tenure track."

The study reveals that academics in non-lab-based disciplines, such as mathematics, business and economics, exhibit a fall in research output after tenure. But for those in the other 10 disciplines, including physics, publication rates are sustained around the pre-tenure peak. "In lab-based fields, collaborative teams and sustained funding streams may help maintain high productivity post-tenure," says Tripodi. "In contrast, in more individual-centred disciplines, the post-tenure slowdown appears to be more pronounced."


iStock

Keeping on track A study has found that researchers publish more high-impact papers before tenure – a pattern that is replicated across 15 research disciplines.

The team also looked at the proportion of high-impact papers – defined as those in the top 5% of a field – and found that researchers in all 15 disciplines publish more high-impact papers before tenure than after. As for "novelty" – defined as atypical combinations of work – this increases with time, but the most novel papers tend to appear after tenure. According to Tripodi, once tenure and job security has been secured, the pressure to publish shifts towards other objectives – a move that explains the plateau or decline seen in publications. "Our results show that tenure allows scientists to take more risks, explore novel research, and reorganize their portfolio," he adds.

Michael Allen

Research updates

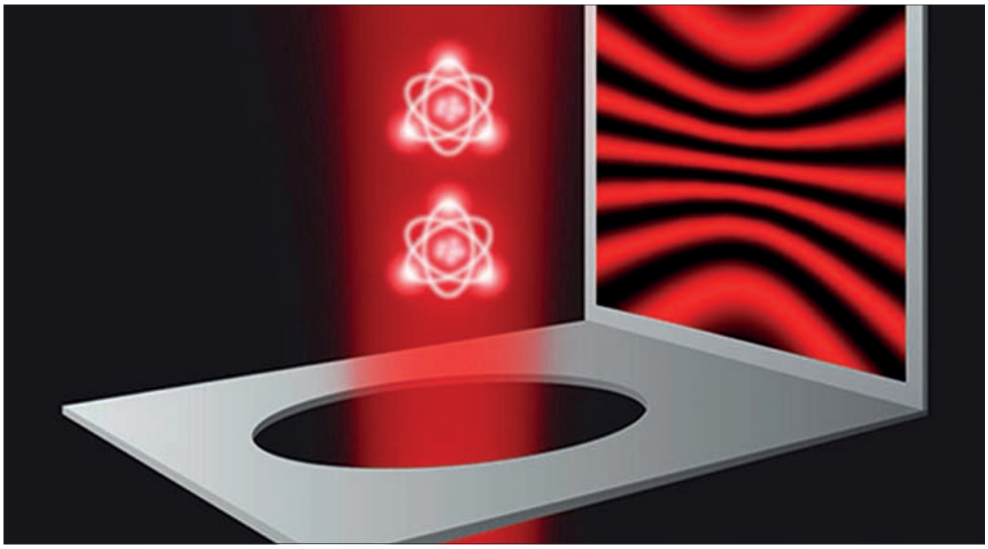
Double slit passes single-atom test

A new result emphasizes the fundamental nature of wave–particle duality by using single ultracold atoms as slits. **Ananya Palivela** reports

Scientists at the Massachusetts Institute of Technology (MIT) in the US have achieved the cleanest demonstration yet of the famous double-slit experiment. Using two single atoms as the slits, they inferred the photon's path by measuring subtle changes in the atoms' properties after photon scattering. Their results matched the predictions of quantum theory: interference fringes when no path was observed, two bright spots when it was (*Phys. Rev. Lett.* **135** 043601).

First performed in the 1800s by Thomas Young, the double-slit experiment has been revisited many times. Its set-up is simple: send light towards a pair of slits in a screen and watch what happens. Its outcome, however, is anything but. If the light passes through the slits unobserved, as it did in Young's original experiment, an interference pattern of bright and dark fringes appears, like ripples overlapping in a pond. But if you observe which slit the light goes through, as Albert Einstein proposed in a 1920s "thought experiment" and as other physicists have since demonstrated in the lab, the fringes vanish in favour of two bright spots. Hence, whether light acts as a wave (fringes) or a particle (spots) depends on whether anyone observes it – reality itself seems to shift with the act of looking.

Einstein disliked the implications of this and stated that the observation only has an effect because it introduces noise. If the slits were mounted on springs, he suggested, their recoil would reveal the photon's path without destroying the fringes. Niels Bohr countered that measuring the photon's recoil precisely enough to reveal its path would blur the slits' positions and erase interference. For him, this was not a flaw of technology but a law of nature – namely, his own principle of complementarity, which states that quantum systems can show wave-like or particle-like behaviour, but never both at once.



Wolfgang Ketterle, Vitaly Fedoseev, Hanzhen Lin, Yu-Kun Lu, Yoo Kyung Lee and Jiahao Lyu

Mind the gap The team at Massachusetts Institute of Technology used two single atoms as slits in Thomas Young's famous double-slit experiment.

Physicists have performed numerous versions of the experiment since, and each time the results have sided with Bohr. Yet the unavoidable noise in real set-ups left room for doubt that this counterintuitive rule was truly fundamental. To celebrate the International Year of Quantum Science and Technology, physicists in Wolfgang Ketterle's group at MIT performed Einstein's thought experiment directly. They began by cooling more than 10 000 rubidium atoms to near absolute zero and trapping them in a laser-made lattice such that each one acts as an individual scatterer of light. If a faint beam of light is sent through this lattice, a single photon could scatter off an atom.

Since the beam was so faint, the team could collect very little information per experimental cycle. "This was the most difficult part," says MIT team member Hanzhen Lin. "We had to repeat the experiment thousands of times to collect enough data." In every such experiment, the key was to control how much photon path information the atoms provided. The team did this by adjusting the laser traps to tune the "fuzziness" of the atoms' position. Tightly trapped atoms had well-defined positions and so, according to Heisenberg's uncertainty principle, they could not reveal much about the photon's path. In these experiments, fringes appeared. Loosely trapped atoms, in contrast, had more position uncertainty and were able to move, meaning an atom struck by a photon could carry a trace of that interaction. This faint record was enough to collapse the interference fringes, leaving only spots. Once again, Bohr was right.

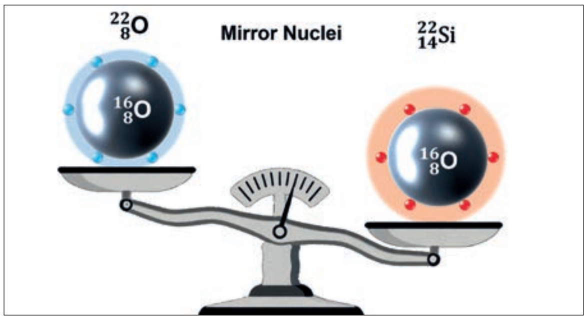
While Lin acknowledges that this is not the first experiment to measure scattered light from trapped atoms, he says it is the first to repeat the measurements after the traps were removed, while the atoms floated freely. This went further than Einstein's spring-mounted slit idea, and (since the results did not change) eliminated the possibility that the traps were interfering with the observation. The MIT team now want to observe what happens when there are two atoms per site in the lattice instead of one. "The interactions between the atoms at each site may give us interesting results," Lin says.

Nuclear physics

Physicists discover a new proton magic number

The first precise mass measurements of an extremely short-lived and proton-rich nucleus, silicon-22, have revealed the "magic" nature of nuclei containing 14 protons. As well as shedding light on nuclear structure, the discovery could improve our understanding of the strong nuclear force and the mechanisms by which elements form (*Phys. Rev. Lett.* **135** 012501).

At the lighter end of the periodic table, stable nuclei tend to contain similar numbers of neutrons and protons. As the number of protons increases, additional neutrons are needed to balance out the mutual repulsion of the positively-charged protons. As a rule, therefore, an isotope of a given element will be unstable if it contains either too few neutrons or too many. In 1949, Maria Goeppert Mayer and J Hans D Jensen proposed an explanation for this rule. According to their nuclear shell model, nuclei that contain certain "magic" numbers of nucleons (neutrons and/or protons) are more bound because they have just the right number of nucleons to fully fill their shells. Nuclei that contain magic numbers of both protons and neutrons are even more bound and are said to be "doubly magic". Subsequent studies showed that for neutrons, these magic numbers are 2, 8, 20, 28, 50, 82 and 126.



IMP

Weighty matters Mass measurements of silicon-22 reveal that it possesses a double-magic structure similar to that of its mirror nucleus, oxygen-22.

While the magic numbers for stable and long-lived nuclei are now well-established, those for exotic, short-lived ones with unusual proton-neutron ratios are comparatively little understood. After measurements on oxygen-22 (14 neutrons, 8 protons) showed that 14 is a magic number of neutrons for this neutron-rich isotope, the hunt was on for a proton-rich counterpart. "Of all the new neutron-rich doubly-magic nuclei discovered, only one loosely bound mirror nucleus for oxygen-22 exists," says Yuhu Zhang, a physicist at the Institute for Modern Physics (IMP) of the Chinese Academy of Sciences. "This is silicon-22."

The problem is that silicon-22 (14 protons, 8 neutrons) has a short half-life and is hard to produce in quantities large enough to study. To overcome this, the researchers used an improved version of a technique known as Bρ-defined isochronous mass spectroscopy. Working at the Cooler-Storage Ring of the Heavy Ion Research Facility in Lanzhou, China, the researchers accelerated a primary beam of stable $^{36}Ar^{15+}$ ions onto a 15 mm-thick beryllium target, causing some of the ^{36}Ar ions to fragment into silicon-22 nuclei. After injecting these nuclei into the storage ring, the researchers could measure their velocity and the time it took them to circle the ring. From this, they could determine their mass with the measurements confirming that the proton number 14 is indeed magic in silicon-22.

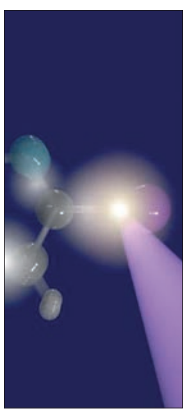
Isabelle Dumé

Materials

Zero-point motion of atoms measured directly for the first time

Physicists in Germany have measured the correlated behaviour of atoms in molecules prepared in their lowest quantum energy state for the first time. Using a technique known as Coulomb explosion imaging, they showed that the atoms do not simply vibrate individually. Instead, they move in a coupled fashion that displays fixed patterns (*Science* 389 650).

According to classical physics, molecules with no thermal energy – for example, those held at absolute zero – should not move. However, according to quantum theory, the atoms making up these molecules are never completely "frozen", so they should exhibit some motion even at this chilly temperature. This motion comes from the atoms' zero-point energy, which is the minimum energy allowed by quantum mechanics for atoms in their ground state at absolute zero, and is known as zero-point motion.



Till Jahnke / Goethe University Frankfurt

All together now The researchers found that atoms do not simply vibrate individually, but do so in correlated, coordinated patterns.

To study this movement, a team led by Till Jahnke from the Institute for Nuclear Physics at Goethe University Frankfurt used the European XFEL near Hamburg to bombard their sample – an iodopyridine molecule consisting of 11 atoms – with ultrashort, high-intensity X-ray pulses. These high-intensity pulses violently eject electrons out of the iodopyridine, causing its constituent atoms to become positively charged (and thus to repel each other) so rapidly that the molecule essentially explodes.

To image the molecular fragments generated by the explosion, the researchers used a customized version of a COLTRIMS reaction microscope. This approach allowed them to reconstruct the molecule's original structure. From this reconstruction, the researchers were able to show that the atoms do not simply vibrate individually, but that they do so in correlated, coordinated patterns. "This is known, of course, from quantum chemistry, but it had so far not been measured in a molecule consisting of so many atoms," Jahnke explains.

Since the technique provides detailed information that is hidden to other imaging approaches, such as crystallography, the researchers are now using it to perform further time-resolved studies – for example, of photochemical reactions. For theoretical condensed-matter physicist Asaad Sakhel at Balqa Applied University in Jordan, who was not involved in this study, the new work is "an outstanding achievement". "Being able to actually 'see' zero-point motion allows us to delve deeper into the mysteries of quantum mechanics in our quest to a further understanding of its foundations," he says.

Isabelle Dumé

Materials

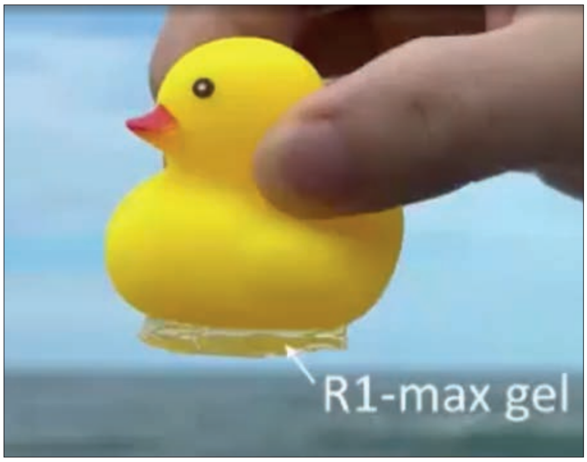
New super sticky underwater hydrogels created thanks to AI

Researchers at Hokkaido University in Japan have combined artificial intelligence (AI) with data mining methods to develop an ultra-sticky hydrogel suitable for wet environments. The materials could have applications from biomedical engineering to deep-sea exploration and marine farming (*Nature* 644 89).

Hydrogels are a permeable soft material composed of interlinked polymer networks with water held within the network. Hydrogels are highly versatile, with properties controlled by altering the chemical makeup and structure of the material. Designing hydrogels computationally to perform a specific function is difficult, however, because the polymers used to build the hydrogel network can contain a plethora of chemical functional groups, complicating the discovery of suitable polymers and the structural makeup of the hydrogel.

There are further challenges for adhesive hydrogels in wet environments, as hydrogels swell in the presence of water, which needs to be factored into the material design.

To develop a hydrogel with a strong and lasting underwater adhesion, the researchers mined data from the National Center for Biotechnology Information (NCBI) protein database. This database contains the amino acid sequences responsible for adhesion in underwater biological systems – such as those found in bacteria, viruses, archaea and eukaryotes. The protein sequences were synthetically mimicked and adapted for the polymer strands in hydrogels. The researchers then used information from the database to initially design and synthesize 180 bioinspired hydrogels, each with a unique polymer network and all of which showed adhesive properties beyond other hydrogels.



WPI-ICReDD, Hokkaido University

Like a duck to water A rubber duck glued to a seaside rock using the hydrogel withstood repeated tides and wave impacts.

The team used machine learning to create hydrogels that demonstrated the strongest underwater adhesive properties to date, with instant and repeatable adhesive strengths exceeding 1 MPa – an order-of-magnitude improvement over previous materials. In addition, the AI-designed hydrogels were found to be functional across many different surfaces in both fresh and saline water.

The researchers took the three best performing hydrogels and tested them in different wet environments. One hydrogel was used to stick a rubber duck to a rock by the sea, which remained in place despite continuous wave impacts over many tide cycles. A second hydrogel was used to patch a 20 mm hole on a pipe filled with water, instantly stopping a high-pressure leak and remained in place for five months without issue. A third hydrogel was placed under the skin of mice to demonstrate biocompatibility. The team now wants to study the molecular mechanisms behind these adhesives in more depth, and to "expand this data-driven design strategy to other soft materials, such as self-healing and biomedical hydrogels".

Liam Critchley

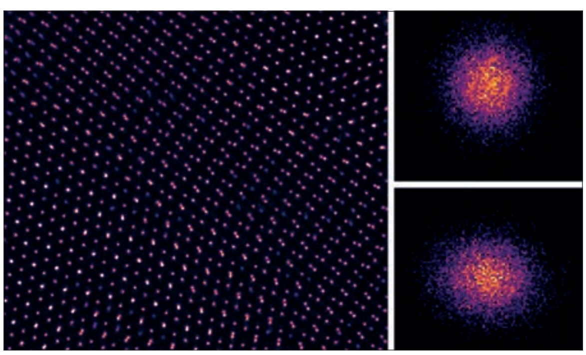
Optics

High-resolution images of a single atom reveal new kind of vibrations

Researchers in the US have directly imaged a class of extremely low-energy atomic vibrations called moiré phasons for the first time. In doing so, they proved that these vibrations are not just a theoretical concept, but are in fact the main way that atoms vibrate in certain twisted 2D materials. Such vibrations may play a critical role in heat and charge transport and how quantum phases behave in these systems (*Science* **389** 423).

When two sheets of a 2D material are placed on top of each other and slightly twisted, their atoms form a moiré pattern, or superlattice. This superlattice contains quasi-periodic regions of rotationally aligned regions (denoted AA or AB) separated by a network of stacking faults called solitons. Materials of this type are also known to possess distinctive vibrational modes known as moiré phonons, which arise from vibrations of the material's crystal lattice.

In addition to moiré phonons, 2D moiré materials are also predicted to host a second class of vibrational mode known as phasons, which have never been directly observed experimentally. In the new work, the researchers used a powerful microscopy technique called electron ptychography that enabled them to image samples with spatial resolutions of 15 picometres (15×10^{-12} m). At this precision, subtle changes in thermally driven atomic vibrations can be detected by analysing the shape and size of individual atoms.



The Grainger College of Engineering at the University of Illinois Urbana-Champaign

Good vibrations The team says that imaging moiré phasons opens up the possibility to understand and control how vibrations behave in complex 2D systems.

"What we found was striking: the vibrations weren't uniform – atoms showed larger amplitudes in AA-stacked regions and highly anisotropic behaviour at soliton boundaries. These patterns align precisely with theoretical predictions for moiré phasons," says Yichao Zhang of the University of Maryland.

Zhang says the work opens new possibilities for understanding and eventually controlling how vibrations behave in complex 2D systems.

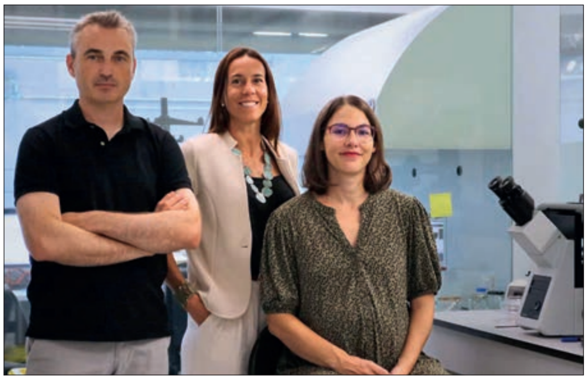
Isabelle Dumé

Biophysics

First real-time visualization of human embryo implantation

A team at the Institute for Bioengineering of Catalonia (IBEC) have visualized human embryo implantation in the laboratory for the first time. The researchers hope that quantifying the dynamics of implantation could improve fertility rates and aid assisted reproductive technologies (*Sci. Adv.* **11** eadr5199).

At its very earliest stage, an embryo comprises a small ball of cells called a blastocyst. About six days after fertilization, this blastocyst starts to embed itself into the walls of the uterus and failing to do so is one of the main causes of miscarriage. To study this implantation process in real time, the IBEC team created an *ex vivo* platform that simulates the outer layers of the uterus. Unlike previous studies that mostly focused on the biochemical and genetic aspects of implantation, the new technique enables study of the mechanical forces exerted by the embryo to penetrate the uterus.



Institute for Bioengineering of Catalonia

Team effort An *ex-vivo* platform to simulate embryo implantation has been created by (from left to right) Samuel Ojosnegros, Anna Seriola and Amélie Godeau from the Institute for Bioengineering of Catalonia.

The implantation platform incorporates a collagen gel to mimic the extracellular matrix encountered *in vivo*, as well as globulin-rich proteins that are required for embryo development. The researchers designed two configurations: a 2D platform, in which blastocysts settle on top of a flat gel; and a 3D version where the blastocysts are placed directly inside collagen drops.

To capture the dynamics of blastocyst implantation, the researchers recorded time-lapse movies using fluorescence imaging and traction-force microscopy. They imaged the matrix fibres and their deformations using light scattering and visualized autofluorescence from the embryo under multiphoton illumination. To quantify matrix deformation, they used the fibres as markers for real-time tracking and derived maps showing the direction and amplitude of fibre displacements – revealing the regions where the embryo applied force and invaded the matrix.

In the 2D platform, 72% of human blastocysts attached to and then integrated into the collagen matrix, reaching a depth of up to 200 μm in the gel. The embryos increased in size over time and stayed spherical without spreading on the surface. Implantation in the 3D platform, in which the embryo is embedded directly inside the matrix, led to 80% survival and invasion rate.

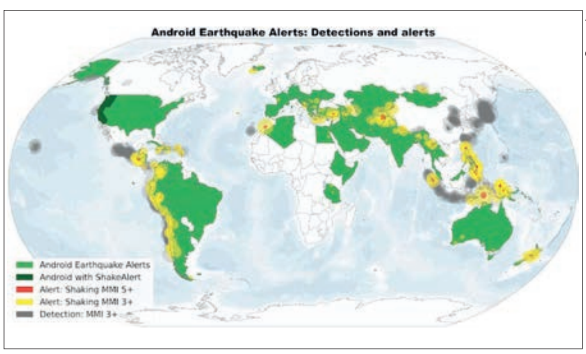
The researchers also monitored the traction forces that the embryos exerted on the collagen matrix, moving and reorganizing it with a displacement that increased over time. They note that the displacement was not perfectly uniform and that the pulling varied over time suggesting that this pulsatile behaviour may help the embryos to continuously sense the environment. The team now plans to develop a theoretical framework to better understand the physical processes underlying implantation.

Tami Freeman

Environment

Android phone network provides early warning system for earthquakes

The global network of Android smartphones makes a useful earthquake early warning system, giving many users precious seconds to act before the shaking starts. These findings, which come from researchers at Android's parent organization Google, are based on a three-year study involving millions of phones in 98 countries. According to the researchers, the network's capabilities could be especially useful in areas that lack established early warning systems (*Science* 389 254).



Google

On shaky ground The Android Earthquake Alert system detected an average of 312 earthquakes a month between 2021 and 2024, with magnitudes ranging from 1.9 to 7.8.

Traditional earthquake early warning systems use networks of seismic sensors that rapidly detect earthquakes in areas close to the epicentre and issue warnings across the affected region. Even a few seconds of warning can be useful because it enables people to take protective actions. Building such seismic networks, however, is expensive, and many earthquake-prone regions do not have them. With that in mind, scientists have been testing the use of smartphones to detect earthquakes. "Although the accelerometers in these phones are less sensitive than the permanent instruments used in traditional seismic networks, they can still detect tremors during strong earthquakes," says study co-leader Richard Allen, who directs the Berkeley Seismological Laboratory at the University of California.

Working with Marc Stogaitis, a software engineer at Android, Allen and colleagues tested the Android Earthquake Alert (AEA) system between 2021 and 2024. During this period, the app detected an average of 312 earthquakes a month, with magnitudes ranging from 1.9 to 7.8, corresponding to events in Japan and Türkiye, respectively. For earthquakes of magnitude 4.5 or higher, the system sent "TakeAction" alerts to users. The system sent alerts of this type on average 60 times per month during the study period, for an average of 18 million individual alerts per month. The system also delivered lesser "BeAware" alerts to regions expected to experience a shaking intensity of 3 or 4.

Isabelle Dumé

Opinion

physicsworld

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IOP Publishing

A quantum celebration

Join us as the IOP commemorates the past, present and future of quantum physics

Regular readers of *Physics World* will know that the UN chose 2025 to be the International Year of Quantum Science and Technology (IYQ). With a global diary of events, conferences, talks, workshops and more, its aim is to raise awareness of the impact of quantum physics and its myriad future applications, from healthcare and energy to infrastructure and optimization.

With the Institute of Physics (IOP) being one of the IYQ's six founding members, we have already seen a packed agenda – including the UK's opening meeting hosted by the Royal Society in February; a week-long parliamentary exhibition on quantum run by the IOP in June; plus numerous hackathons and careers events. It has been a very busy year.

INTERNATIONAL YEAR OF
Quantum Science
and Technology

As the IYQ comes to a close, the UK is giving it a worthy send-off with an entire Quantum Week on 3–7 November. The IOP and the National Physical Laboratory will host conferences and public events, including a talk on "A new quantum world: 'spooky' physics to tech revolution" by quantum scientist and TV presenter Jim Al-Khalili.

The highlight of the week for quantum physicists based in the UK will be the IOP's two-day conference – Quantum Science and Technology: The First 100 Years; Our Quantum Future – at the Royal Institution in London. Day one, organized by the IOP's History of Physics group, will look back on the first 100 years of quantum mechanics. Speakers will revisit foundational breakthroughs, while charting the evolution of quantum theory, from its early abstract framework to the main pillar it forms in modern physics. Day two – led by the IOP's quantum Business Innovation and Growth group – will look to the future of quantum tech and its expanding role in society, as quantum computing, sensing and communications become a part of our world.

Despite us celebrating a century of quantum advances, it's interesting to note that most physicists are still undecided on some of the very foundational aspects of quantum theory. Even 100 years on, we cannot agree on which interpretation of quantum mechanics holds strong; whether the wavefunction is merely a mathematical tool or a true representation of reality; or the effects of an observer on a quantum state. Indeed, some of the biggest open questions in physics – where exactly is the boundary between the quantum and the classical world; and how do we reconcile gravity and quantum mechanics – lie at the very heart of these conundrums. As we all gather at the IOP's conference, to look back and ahead, perhaps some answers to these puzzles will become apparent. Be sure to register for the event by 20 October at iop.eventsair.com/qst2025 so that you are in the room as we perhaps crack the quantum code to our universe.

Tushna Commissariat, features editor, *Physics World*

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.

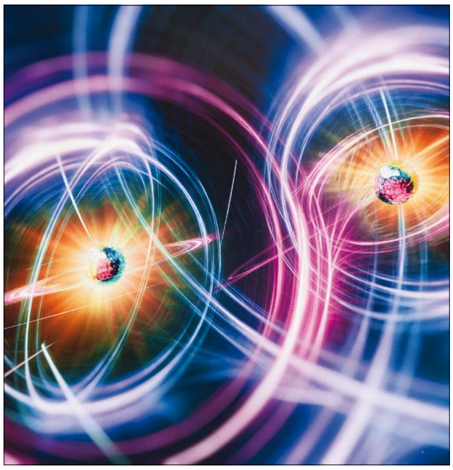
Yet as we celebrate these achievements, we should still reflect on what quantum mechanics reveals about the world itself. What, for example, does this formalism actually tell us about the nature of reality? Do quantum systems have definite properties before we measure them? Do our observations create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



iStock/koto feja

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.


Ana María Cetto and **Luis de la Peña** are at the Institute of Physics, National Autonomous University of Mexico, e-mail ana@fisica.unam.mx

Critical Point Physics for presidents

What would you tell the US president if you had the chance? Robert P Crease catches up with Berkeley physicist Richard Muller, whose 2008 book tries to do just that


Shutterstock/Alexzel

Talking points Richard Muller's book *Physics for Future Presidents* assumes that politicians should value scientific advice – a premise that might now be misplaced.

Richard Muller, a physicist at the University of California, Berkeley, was in his office when someone called Liz showed up who'd once taken one of his classes. She said her family had invited a physicist over for dinner, who touted controlled nuclear fusion as a future energy source. When Liz suggested solar power was a better option, the guest grew patronizing. "If you wanted to power California," he told her, "you'd have to plaster the entire state with solar cells."

Fortunately, Liz remembered what she'd learned on Muller's course, entitled "Physics for Future Presidents", and explained why the dinner guest was wrong. "There's a kilowatt in a square metre of sunlight," she told him, "which means a gigawatt in a square kilometre – only about the space of a nuclear power plant." Stunned, the physicist grew silent. "Your numbers don't sound wrong," he finally said. "Of course, today's solar cells are only 15% efficient. But I'll take a look again."

It's a wonderful story that Muller told me when I visited him a few months ago to ask about his 2008 book *Physics for Future Presidents: the Science Behind the Headlines*. Based on the course that Liz took, the book tries to explain physics concepts underpinning key issues including energy and climate change. "She hadn't just memorized facts," Muller said. "She knew enough to shut up an expert who hadn't done his homework. That's what presidents should be able to do." A president, Muller believes, should know enough science to have a sense for the value of expert advice.

Dissenting minds

Muller's book was published shortly before Barack Obama's two terms as US president. Obama was highly pro-science, appointing the Nobel-prize-winning physicist Steven Chu as his science adviser. With Donald Trump in the White House, I had come to ask Muller what advice – if any – he would change in the book. But it wasn't easy for me to keep Muller on topic, as he derails easily with anecdotes of fascinating situations and extraordinary people that he's encountered in his remarkable life.

Born in New York City, Muller, 81, attended Bronx High School of Science and Columbia University, joining the University of California, Berkeley as a graduate student in the autumn of 1964. A few weeks after entering, he joined the Free Speech Movement to protest against the university's ban on campus political activities. During a sit-in, Muller was arrested and dragged down the steps of Sproul Hall, Berkeley's administration building.

As a graduate student, Muller worked with Berkeley physicist Luis Alvarez – who would later win the 1968 Nobel Prize for Physics – to send a balloon with a payload of cosmic-ray detectors over the Pacific. Known as the High Altitude Particle Physics Experiment (HAPPE), the apparatus crashed in the ocean. Or so Muller thought.

As Muller explained in a 2023 article in the *Wall Street Journal*, US intelligence recovered a Chinese surveillance device, shot down over Georgia by the US military, with a name that translated as "HAPI". Muller found enough other similarities to conclude that the Chinese had recovered the device and copied it as a model for their balloons. But by then Muller had switched to studying negative kaon particles using bubble chambers. After his PhD, he stayed at Berkeley as a postdoc, eventually becoming a professor in 1980.

Muller is a prominent contrarian, publishing an article advancing the controversial – though some now argue that it's plausible – view that the COVID-19 virus originated in a Chinese lab. For a long time he was a global-warming sceptic, but in 2012, after three years of careful analysis, he publicly changed his mind via an article in the *New York Times*. Former US President Bill Clinton cited Muller as "one of my heroes because he changed his mind on global warming".

Muller loved that remark, but told me: "I'm not a hero. I'm just a scientist."

Muller was once shadowed by a sociology student for a week for a course project. "She was like [the anthropologist] Diane Fosse and I was a gorilla," Muller recalls. She was astonished. "I thought physicists spent all their time thinking and experimenting," the student told him. "You spend most of your time talking." Muller wasn't surprised. "You don't want to spend your time rediscovering something somebody already knows," he said. "So physicists talk a lot."

Recommended recommendations

I tried again to steer Muller back to the book. He said it was based on a physics course at Berkeley known originally as "Qualitative physics" and informally as physics for poets or dummies. One of the first people to teach it had been the theorist and "father of the fusion bomb" Edward Teller. "Teller was exceedingly popular," Muller told me, "possibly because he gave everyone in class an A and no exams."

After Teller, fewer and fewer students attended the course until enrolment dropped to 20. So when Muller took over in 1999 he retitled it "Physics for future presidents", he refocused it on contemporary issues, and rebuilt the enrolment until it typically filled a large auditorium with about 500 students. He retired in 2010 after a decade of teaching the course.

Making a final effort, I handed Muller a copy of his book, turned to the last page where he listed a dozen or so specific recommendations for future presidents, and asked him to say whether he had changed his mind in the intervening 17 years.

Fund strong programmes in energy efficiency and conservation? "Yup!"

Raise the miles-per-gallon of autos substantially? "Yup."

Support efforts at sequestering carbon dioxide? "I'm not much in favour anymore because the developing world can't afford it."

Encourage the development of nuclear power? "Yeah. Particularly fission; fusion's too far in the future. Also, I'd tell the president to make clear that nuclear waste storage is a solved problem, and make sure that Yucca mountain is quickly approved."

See that China and India are given substantial carbon credits for building coal-fired power stations and nuclear plants? "Nuclear power plants yes, carbon credits no. Over a million and a half people in China die from coal pollution each year."

Encourage solar and wind technologies? "Yes." Cancel subsidies on corn ethanol? "Yes". Encourage developments in efficient lighting? "Yes." Insulation is better than heating? "Yes." Cool roofs save more energy than air conditioners and often better than solar cells? "Yes."

The critical point

Muller's final piece of advice to the future president was that the "emphasis must be on technologies that the developing world can afford". He was adamant. "If what you are doing is buying expensive electric automobiles that will never sell in the developing world, it's just virtue signalling in luxury."

I kept trying to find some new physics Muller would tell the president, but it wasn't much. "Physics mostly stays the same," Muller concluded, "so the advice mainly does, too." But not everything remains unvarying. "What changes the most", he conceded, "is how the president listens". Or even whether the president is listening at all.

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

Transactions AI needs good data

Honor Powrie welcomes the use of AI in everyday life, but warns us to proceed with caution

Artificial intelligence (AI) is fast becoming the new "Marmite". Like the salty spread that polarizes taste buds, you either love AI or you hate it. To some, AI is miraculous, to others it's threatening or scary. But one thing is for sure – AI is here to stay, so we had better get used to it.

In many respects, AI is very similar to other data-analytics solutions in that how it works depends on two things. One is the quality of the input data. The other is the integrity of the user to ensure that the outputs are fit for purpose.

Previously a niche tool for specialists, AI is now widely available for general-purpose use, in particular through Generative AI (GenAI) tools. Also known as Large Language Models (LLMs), they're now widely available through, for example, OpenAI's ChatGPT, Microsoft Co-pilot, Anthropic's Claude, Adobe Firefly or Google Gemini.

GenAI has become possible thanks to the availability of vast quantities of digitized data and significant advances in computing power. Based on neural networks, this size of model would in fact have been impossible without these two fundamental ingredients.

GenAI is incredibly powerful when it comes to searching and summarizing large volumes of unstructured text. It exploits unfathomable amounts of data and is getting better all the time, offering users significant benefits in terms of efficiency and labour saving.

Many people now use it routinely for writing meeting minutes, composing letters and e-mails, and summarizing the content of multiple documents. AI can also tackle complex problems that would be difficult for humans to solve, such as climate modelling, drug discovery and protein-structure prediction.

I'd also like to give a shout out to tools such as Microsoft Live Captions and Google Translate, which help people from different locations and cultures to communicate. But like all shiny new things, AI comes with caveats, which we should bear in mind when using such tools.

LLMs, by their very nature, have been trained on historical data. They can't therefore tell you exactly what may happen in the future, or indeed what may have happened since the model was originally trained. Models can also be constrained in their answers.

iStock/Adam Webb

Amber alert Artificial intelligence has its uses, but we must move carefully when working with it.

Take the Chinese AI app DeepSeek. When the BBC asked it what had happened at Tiananmen Square in Beijing on 4 June 1989 – when Chinese troops cracked down on protestors – the Chatbot's answer was suppressed. Now, this is a very obvious piece of information control, but subtler instances of censorship will be harder to spot.

We also need to be conscious of model bias. At least some of the training data will probably come from social media and public chat forums such as X, Facebook and Reddit. Trouble is, we can't know all the nuances of the data that models have been trained on – or the inherent biases that may arise from this.

One example of unfair gender bias was when Amazon developed an AI recruiting tool. Based on 10 years' worth of CVs – mostly from men – the tool was found to favour men. Thankfully, Amazon ditched it. But then there was Apple's gender-biased credit-card algorithm that led to men being given higher credit limits than women of similar ratings.

Another problem with AI is that it sometimes acts as a black box, making it hard for us to understand how, why or on what grounds it arrived at a certain decision. Think about those Captcha tests we have to take to when accessing online accounts. They often present us with a street scene and ask us to select those parts of the image containing a traffic light.

The tests are designed to distinguish between humans and computers or bots – the expectation being that AI can't consistently recognize traffic lights. However, AI-based advanced driver assist systems (ADAS) presumably perform this function seamlessly on our roads. If not, surely drivers are being put at risk?

A colleague of mine, who drives an electric car that happens to share its name with a well-known physicist, confided that the ADAS in his car becomes unresponsive, especially when at traffic lights with filter arrows or multiple sets of traffic lights. So what exactly is going on with ADAS? Does anyone know?

Caution needed

My message when it comes to AI is simple: be careful what you ask for. Many GenAI applications will store user prompts and conversation histories and will likely use this data for training future models. Once you enter your data, there's no guarantee it'll ever be deleted. So think carefully before sharing any personal data, such medical or financial information. It also pays to keep prompts non-specific (avoiding using your name or date of birth) so that they cannot be traced directly to you.

Democratization of AI is a great enabler and it's easy for people to apply it without an in-depth understanding of what's going on under the hood. But we should be checking AI-generated output before we use it to make important decisions and we should be careful of the personal information we divulge.

It's easy to become complacent when we are not doing all the legwork. We are reminded under the terms of use that "AI can make mistakes", but I wonder what will happen if models start consuming AI-generated erroneous data. Just as with other data-analytics problems, AI suffers from the old adage of "garbage in, garbage out".

But sometimes I fear it's even worse than that. We'll need a collective vigilance to avoid AI being turned into "garbage in, garbage squared".

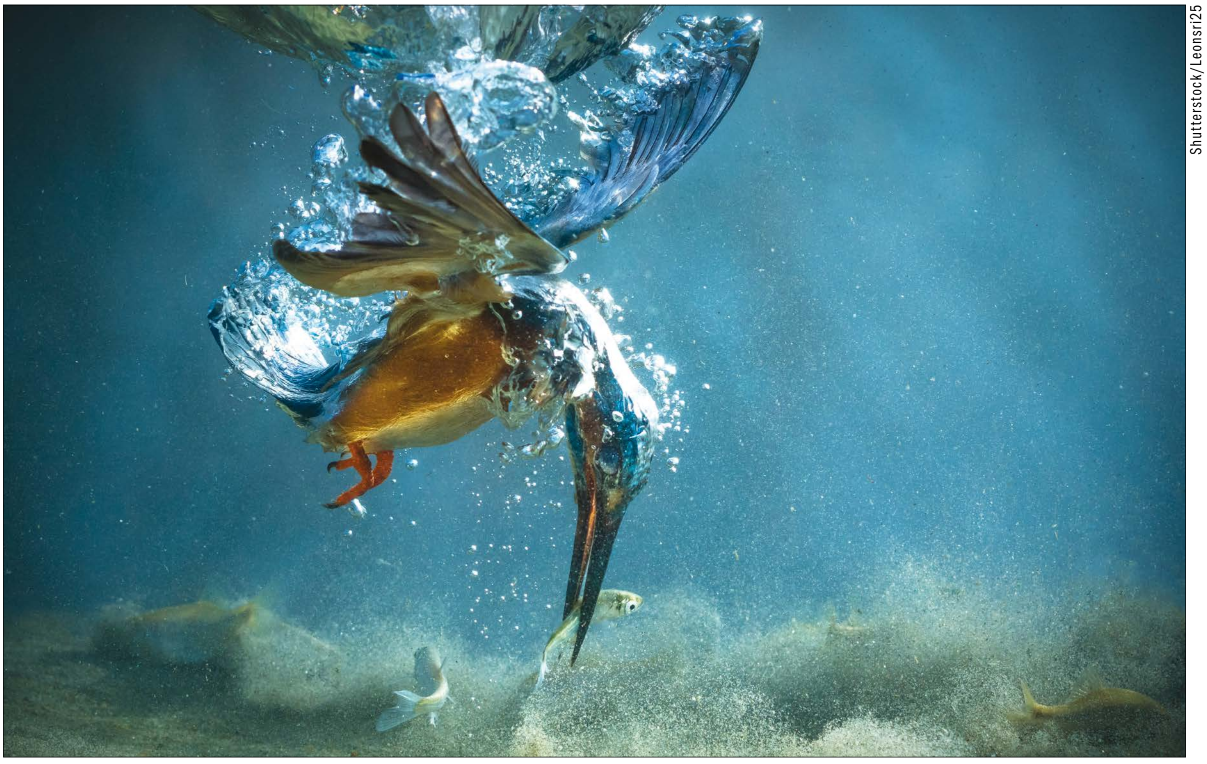
Honor Powrie is an engineer who is now senior director for data science and analytics at GE in Southampton, UK. She is writing here in a personal capacity

Reviews

More physics than birds

David Norman reviews *The Physics of Birds and Birding: the Sounds, Colors and Movements of Birds, and Our Tools for Watching Them* by Michael Hurben

The Physics of Birds and Birding: the Sounds, Colors and Movements of Birds, and Our Tools for Watching Them
Michael Hurben
2025 Pelagic Publishing 240pp
£30 pb; £30 ebook



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The physics of (king)fishing When kingfishers dive for fish, they compensate for the change of refractive index at the surface of the water.

Lots of people like birds. In Britain alone, 17 million households collectively spend £250m annually on 150 000 tonnes of bird food, while 1.2 million people are paying members of the Royal Society for the Protection of Birds (RSPB), Europe's largest conservation charity. But what is the Venn diagram overlap between those who like birds and those who like physics?

The 11 000 or more species of birds in the world have evolved to occupy separate ecological niches, with many remarkable abilities that, while beyond human capabilities, can be explained by physics. Owls, for example, detect their prey by hearing with asymmetric ears then fly almost silently to catch it. Kingfishers and ospreys, meanwhile, dive for fish in freshwater or sea, compensating for the change of refractive index at the surface. Kestrels and hummingbirds, on the other hand, can hover through clever use of aerodynamics.

Many birds choose when to migrate by detecting subtle changes in barometric pressure. They are often colourful and can even be blue – a pigment that is scarce in nature – due to the structure of their feathers, which can make them appear kaleidoscopic depending on the viewing angle. Many species can even see into the ultraviolet; the blue tits in our gardens look very different in each other's eyes than they do to ours.

Those of us with inquisitive minds cannot help but wonder how they do these things. Now, *The Physics of Birds and Birding: the Sounds, Colors and Movements of Birds, and Our Tools for Watching Them* by retired physicist Michael Hurben covers all of these wonders and more.

Where are the birds?

In each chapter Hurben introduces a new physics-related subject, often with an unexpected connection to birds. The more abstruse topics include fractals, gravity, electrostatics, osmosis and Fourier transforms. You might not think quarks would be mentioned in a book on birds, but they are. Some of these complicated subjects, however, take the author several pages to explain, and it can then be a disappointment to discover just a short paragraph mentioning a bird. It is also only in the final chapter that the author explains flight, the attribute unique among vertebrates to birds (and bats).

The antepenultimate chapter justifies the second part of the book's title – birding. It describes the principles underlying some of the optical instruments used by humans to detect and identify birds, such as binoculars, telescopes and cameras. The physics is simpler, so the answers here might be more familiar to non-scientist birders. Indeed, focal

There are no images of birds whatsoever – and without them the book appears like an old fashioned black-and-white textbook

lengths, refractive indices, shape of lenses and anti-reflection coatings, for example, are often covered in school physics and known to anyone wearing spectacles.

Unfortunately, Hurben has not heeded the warning given to Stephen Hawking by his editor of *A Brief History of Time*, which is that each equation would halve the book's readership. That masterpiece includes only the single equation, which any physicist could predict. But *The Physics of Birds and Birding* sets the scene with seven equations in its first chapter, and many more throughout. While understanding is helped by over 100 small diagrams, if you're expecting beautiful photos and illustrations of birds, you'll be disappointed. In fact, there are no images of birds whatsoever – and without them the book appears like an old fashioned black-and-white textbook.

Physicist or birder?

The author's interest in birds appears to be in travelling to see them, and he has a "life-list" of over 5000 species. But not much attention in this book is paid to those of us who are more interested in studying birds for conservation. For example, there is no mention of thermal imaging instruments or drones – technology that depends a lot on physics – which are increasingly being used to avoid field-workers having to search through sensitive vegetation or climb trees to find birds or their nests. Nowadays, there are more interactions between humans and birds using devices such as smartphones, GPS or digital cameras, or indeed the trackers attached to birds by skilled and licensed scientists, but none of these is covered in *The Physics of Birds and Birding*.

Although I am a Fellow of the Institute of Physics and the Royal Society of Biology who has spent more than 50 years as an amateur birder and published many papers on both topics, it is not clear who is the intended target audience for this volume. It seems to me that it would be of more interest to some physicists who enjoy seeing physics being applied to the natural world, than for birders who want to understand how birds work. Either way, the book is definitely for only a select part of the birder-physicist Venn diagram.

David Norman is a chartered physicist and ornithologist

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.

NIST

"Deliciously weird" How William Phillips views quantum physics.

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.

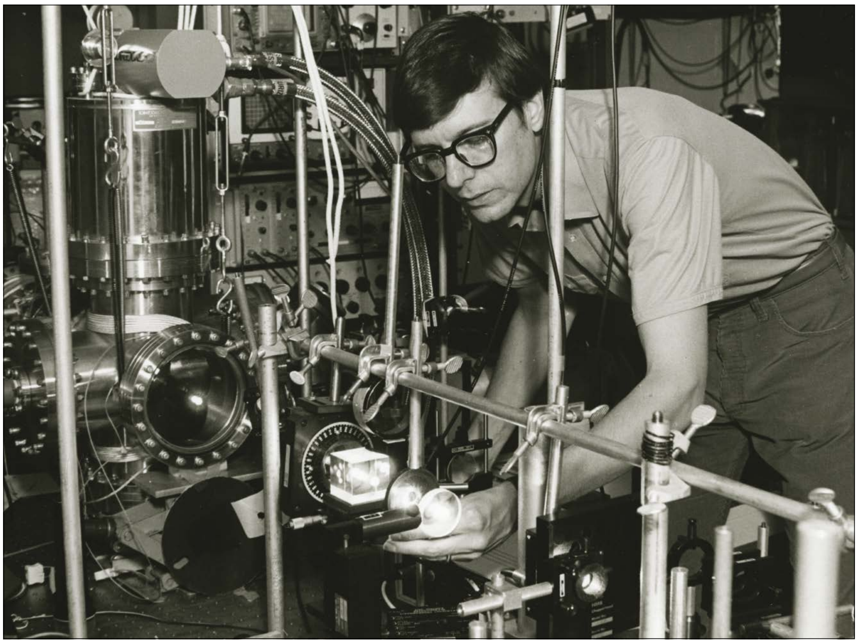
Is entanglement the most challenging concept in quantum mechanics?

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

NIST



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

called the National Bureau of Standards, the very best clock 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

AUDIO Listen to the full version of our interview with Bill Phillips

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.

AIP Emilio Segrè Visual Archives

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

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 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.

Margaret Harris is an online editor of *Physics World*

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

INTERNATIONAL YEAR OF Quantum Science and Technology

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 the paradox of Schrödinger's cat – a thought experiment in which a cat hidden in a box is simultaneously dead and

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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

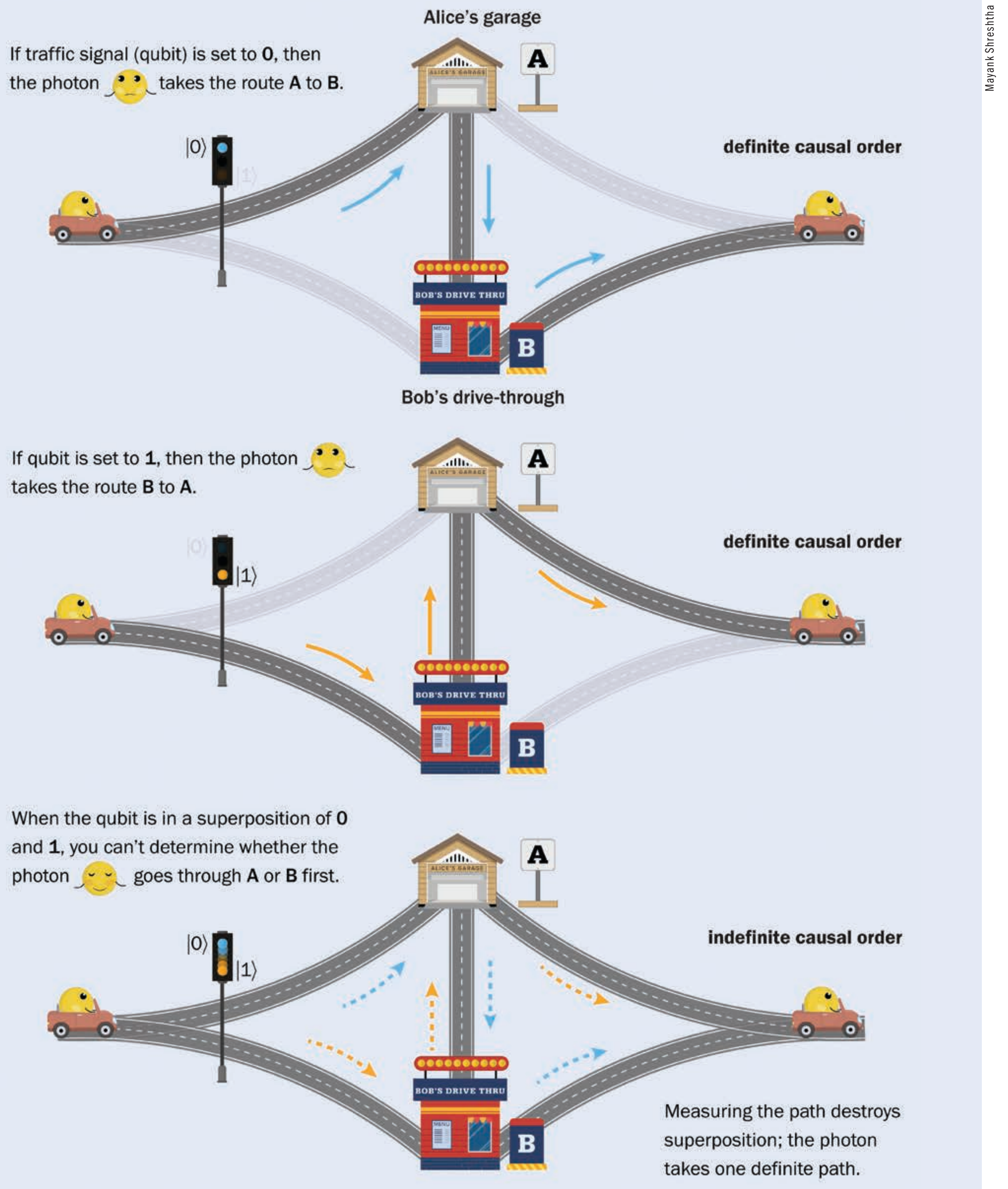
It turns out that different causal processes can also exist in a superposition. One example is a thought experiment called the "gravitational quantum switch", which was proposed in 2019 by Magdalena Zych of the University of Queensland and colleagues (*Nat. Comms* **10** 3772). This features our favourite 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 seems to be a trivial example. But it becomes more inter-

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.

esting 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.

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.

While other applications could be possible, it is often difficult to work out whether ICO offers the best solution to a specific problem

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. ■

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

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.

Hamish Johnston is an online editor of *Physics World*

INTERNATIONAL YEAR OF Quantum Science and Technology

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

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

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.

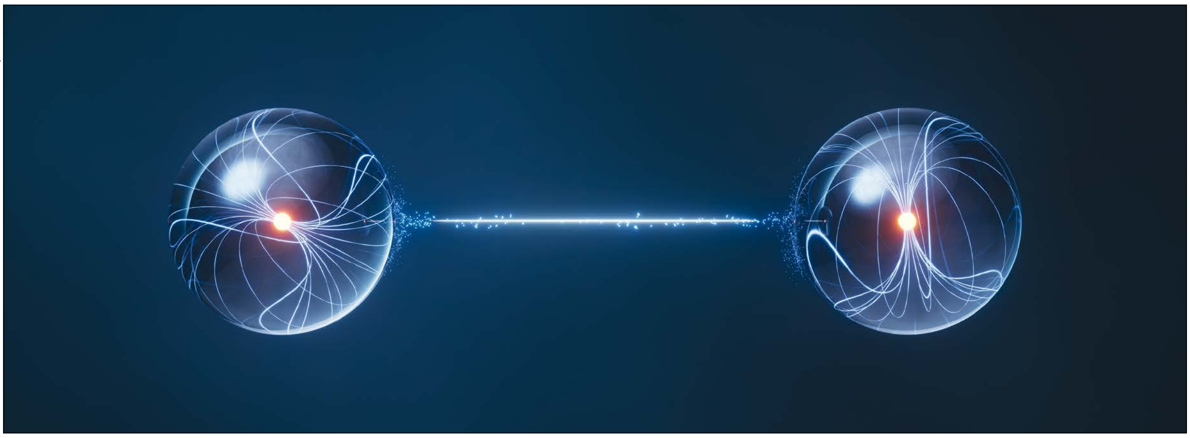
> We're learning so much at a fundamental level because of technological advances
> Stephanie Simmons

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 iStock/Jian Fen



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

wasn't around when Aspect did his first experiments, but 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.

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.

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

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

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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?

agenda. Failing to build a quantum computer would be a success for science: it would let us learn something 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?

> 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

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.

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 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.

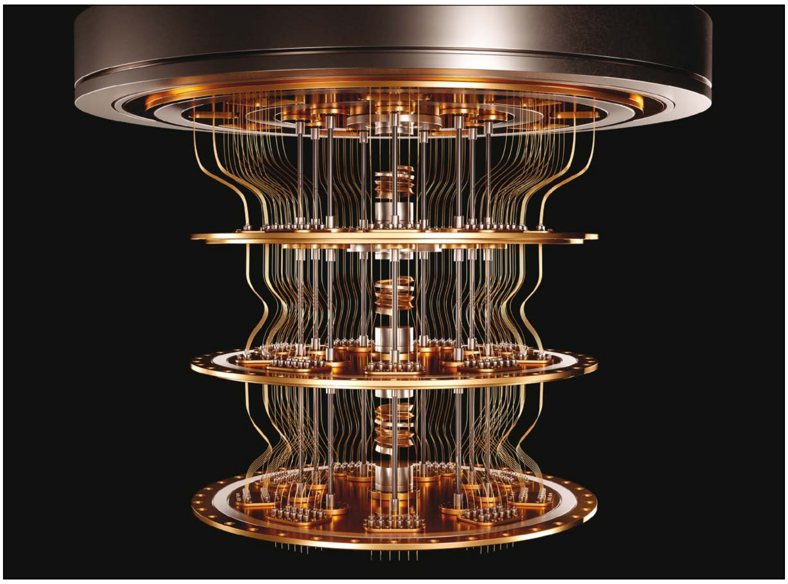
What technological or theoretical breakthrough do you most hope to see that make the biggest difference?

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



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

> 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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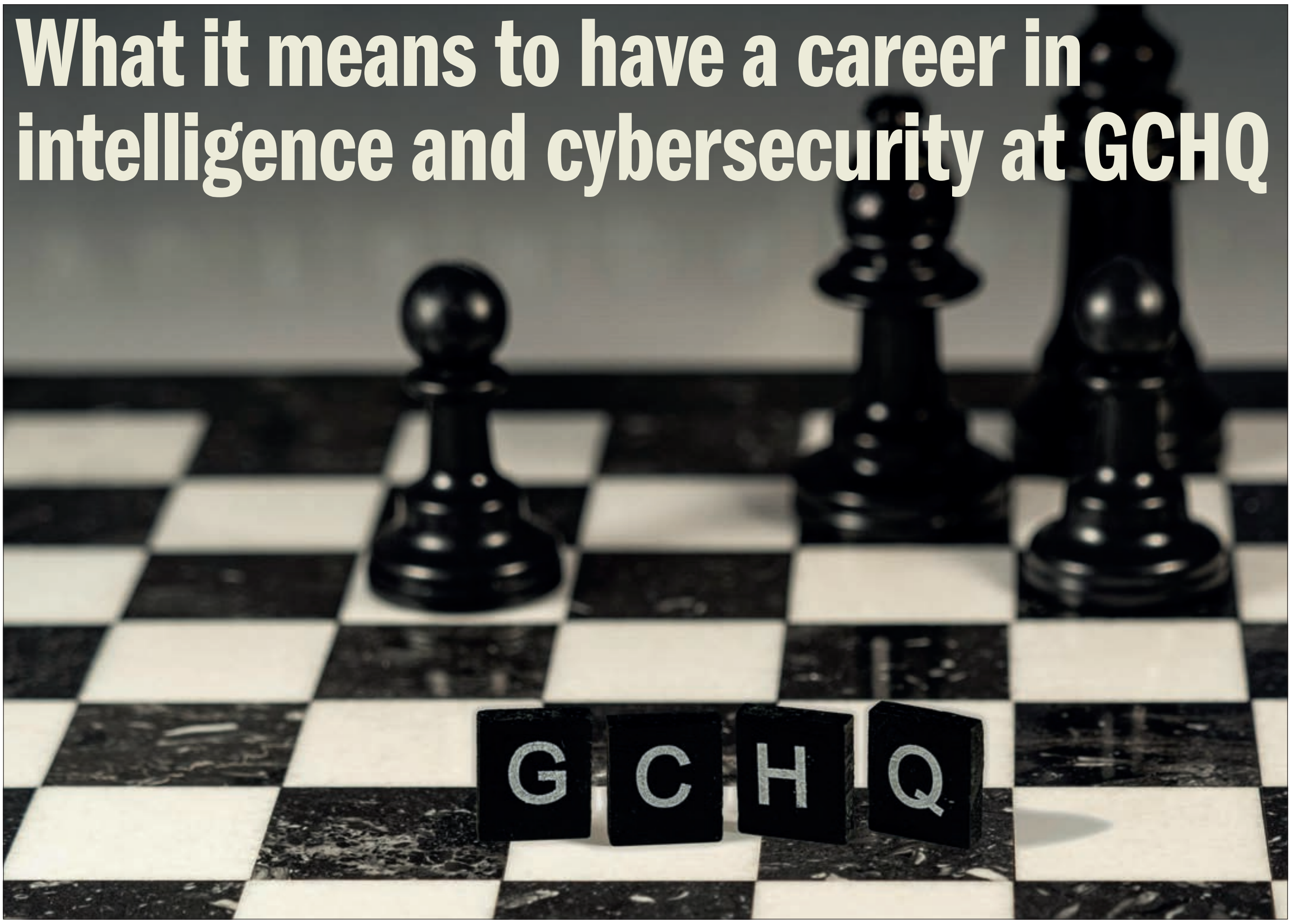
What it means to have a career in intelligence and cybersecurity at GCHQ



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Future proof Curiosity, problem-solving and resilience are the key qualities for a career in intelligence.

Two leaders from GCHQ – the UK's intelligence, security and cyber agency – talk to **Tushna Commissariat** about their unique careers, as well as their advice on how to join them

As a physics graduate or an early career researcher looking for a job, you might not think of the UK's primary intelligence and security agency – Government Communications Headquarters (GCHQ) – as somewhere you might consider. But GCHQ, which covers counter-terrorism, cybersecurity, organized crime and defence support for the UK, hires a vast number of physicists. Indeed, to celebrate the 2025 International Year of Quantum Science and Technology, the agency has hosted many internal talks, informational campaigns and more.

GCHQ works with the Secret Intelligence Service (MI6), MI5, as well as the armed forces, a number of international partners, and firms in the private sector and academia. To find out more about a career at GCHQ – working with cutting-edge technology to identify, analyse and disrupt threats to the UK – *Physics World* speaks to two people with academic backgrounds who have a long career at the organization. They tell us about the benefits, the difficulties and the complexity of working at an intelligence agency.

Nia is the deputy director for science at GCHQ, where she has worked for the past 15 years. After studying physics at university, she joined GCHQ as a graduate and has since contributed to a wide range of scientific and technological initiatives in support of national security. She is a Fellow of both the Institute of Physics (IOP), which publishes *Physics World*, and the Institution of Engineering and Technology (IET).

Cheryl leads GCHQ's adoption of quantum technologies. Following a degree in engineering, her career began as an apprentice at an avionics company. Since then, she has had many roles across research and development at GCHQ and across broader UK government departments, with a focus on understanding and implementing emerging technology. Cheryl is a Fellow of the IET and a Member of the IOP.

When did your interest in science first develop?

Nia My fascination with science was nurtured from a young age, largely inspired by my parents. My mum was a physics teacher, and my dad is a passionate historian with an insatiable curiosity about the world. Growing up in an environment rich with books, experiments and discussions about how things work – whether exploring astrophysics, geology or ancient Egypt – instilled in me a lifelong desire to understand our universe. My mum's electronics, mechanics

I've had some amazing and unique opportunities and experiences Cheryl, GCHQ

and physics lessons meant there were always breadboards, crocodile clips and even a Van de Graaff generator in the house, transforming learning into an exciting tangible experience.

Cheryl As a child I was always interested in nature and in how things work. I used to build bug farms in the garden and still have my old *Observer's* books with the butterflies, etc, ticked off when spotted. Leaning towards my practical side of constantly making things (and foolishly believing my careers teacher that a physics degree would only lead to teaching), I took physics, chemistry and maths A-levels and a degree in engineering.

Could you tell us a bit about your educational background and your career path that led to you work at GCHQ?

Nia I was born and grew up in South Wales and attended a Welsh-language school where I studied physics, maths and chemistry at A-level. I then studied physics at Durham University for four years, before I started working at GCHQ as a graduate. My first role was in an area that is now the National Cyber Security Centre (NCSC). As the cyber security arm of GCHQ, it researches the reliability of semiconductors in national security applications and uses that research to shape policy and security standards. This was great for me as my final year in university was focused on material science and condensed matter physics which came in very useful.

Cheryl My engineering degree apprenticeship was through an aerospace company in Cheltenham, and I worked there afterwards designing test kits for the RAF. It was almost natural that I should at least try a few years at GCHQ as a local employer and I had plans to then move to other R&D labs.

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Safety net Maintaining secure communication and anticipating new threats are key to the work carried out at GCHQ.

What's it like to work here – what are some of the stresses of working in this kind of an environment and not being able to discuss your job with friends and family? What are some of the best aspects of working at GCHQ?

Nia Working at GCHQ is rewarding and exciting especially as we look at the most exciting developments in emerging technologies. It can also be challenging especially when navigating the complexities of global security challenges amid an unpredictable geopolitical landscape. There are days when media reports or international events feel overwhelming, but knowing that my work contributes towards safeguarding the UK's interests today and into the future offers a strong sense of purpose.

The most rewarding aspect, by far, is the people. We have some of the brightest, most dedicated experts – mentors, colleagues, friends – whose commitment inspires me daily. Their support and collaboration make even the most demanding days manageable.

Cheryl At GCHQ I found that I have been able to enjoy several very different "careers" within the organization, including opportunities to travel and to develop diverse skills. This, together with a flexibility to change working patterns to suit stages of family life, has meant I have stayed for most of my career.

I've had some amazing and unique opportunities and experiences. In the Cheltenham area it's accepted that so many people work here and is widely respected that we cannot talk about the detail of what we do.

What role does physics and especially quantum science play in what you do? And what role does physics play when it comes to the national security of the UK?

Nia As deputy director of science at GCHQ, my role involves collaborating with experts to understand how emerging technologies, including quantum science, impact national security. Quantum offers extraordinary potential for secure communication and advanced sensing – but it equally threatens to upend existing security protocols if adversaries harness it maliciously. A deep understanding of physics is crucial – not only to spot opportunities but also to anticipate and counter threats.

Quantum science is just one example of how a fundamental understanding of physics and maths gives you the foundations to understand the broad waterfront of emerging technologies coming our way. We work closely with government departments, academia, industry and start-ups to ensure the UK remains at the forefront of this field, shaping a resilient and innovative security ecosystem.

Cheryl I first came across quantum science, technologies and quantum computing around 15 years ago through an emerging technology analysis role in R&D; and I watched and learned keenly as I could see that these would be game changing. Little did I know at the time that I would later be leading our adoption of quantum and just how significant these emerging technologies for sensing, timing and computing would grow to be.

Maintaining a hunger to learn and adapt is what will set you apart

Nia, GCHQ

The UK national ecosystem developing around quantum technologies is a great mix of minds from academia, industry and government departments and is one of the most collegiate, inspiring and well-motivated communities that I have interacted with.

For today's physics graduates who might be interested in a career at GCHQ, what are some of the key skills they require?

Nia Many people will have heard of historic tales of the tap on the shoulder for people to work in intelligence agencies, but as with all other jobs the reality is that people can find out about careers at GCHQ in much the same way they would with any other kind of job.

I would emphasize qualities like curiosity, problem-solving and resilience as being key. The willingness to roll up your sleeves, a genuine care for collaborative work, and empathy are equally important – particularly because much of what we do is sensitive and demands trust and discretion. Maintaining a hunger to learn and adapt is what will set you apart.

Cheryl We have roles where you will be helping to solve complex problems – doing work you simply won't find anywhere else. It's key to have curiosity, an open mind and don't be put off by the fact you can't ask too many questions in advance!

What sort of equality, diversity and inclusion initiatives do you have at GCHQ and how are you looking to get more women and minorities working there?

Nia Diversity and inclusion are mission-critical for us at GCHQ, gathering the right mix of minds to find innovative solutions to the toughest of problems. We're committed to building on our work to better represent the communities we serve, including increasing the number of people from ethnic minority backgrounds and the number of women in senior roles.

Cheryl We are committed to having a workforce that reflects the communities we serve. Our locations in the north-west, in both Manchester and now Lancashire, are part of the mission to find the right mix of minds

What is your advice to today's physics grads? What is it that you know today that you wish you knew at the start of your career?

Nia One key lesson is that career paths are rarely linear. When starting out, uncertainty can feel daunting, but it's an opportunity for growth. Embrace challenges and seize opportunities that excite you – whether they seem narrowly related to your studies or not. Every experience contributes to your development. Additionally, don't underestimate the importance of work–life balance. GCHQ offers a supportive environment – remember, careers are marathons, not sprints. Patience and curiosity will serve you well.

Cheryl It takes multidisciplinary teams to deliver game-changers and new ecosystems. Your initial "career choices" are just a stepping stone from which you can forge your own path and follow your instincts.

Tushna Commissariat is features editor of *Physics World.*

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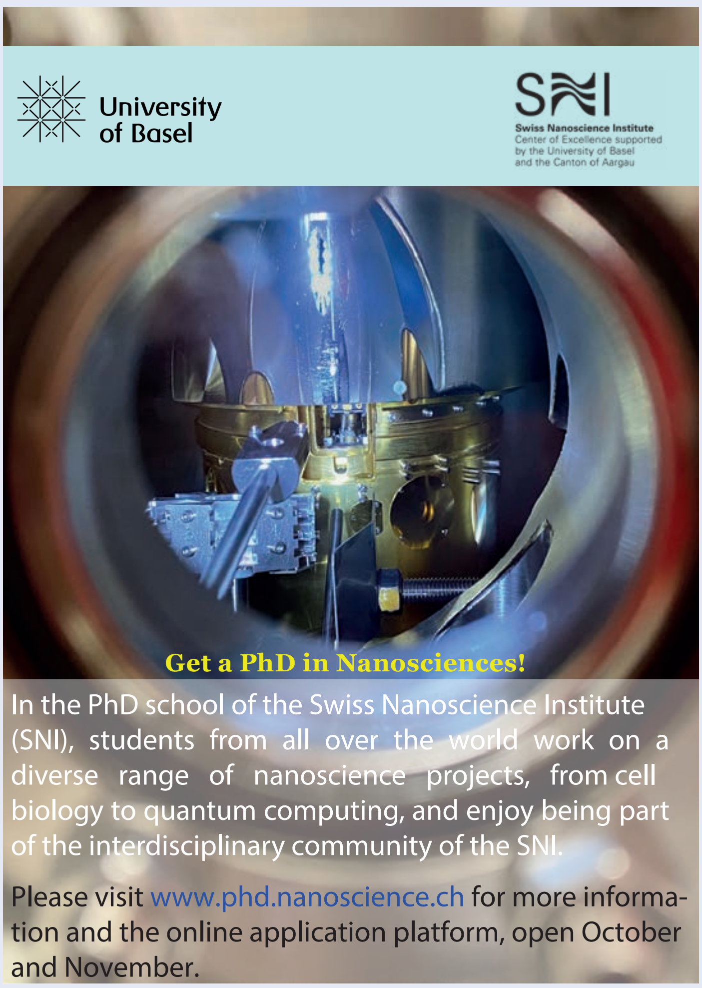
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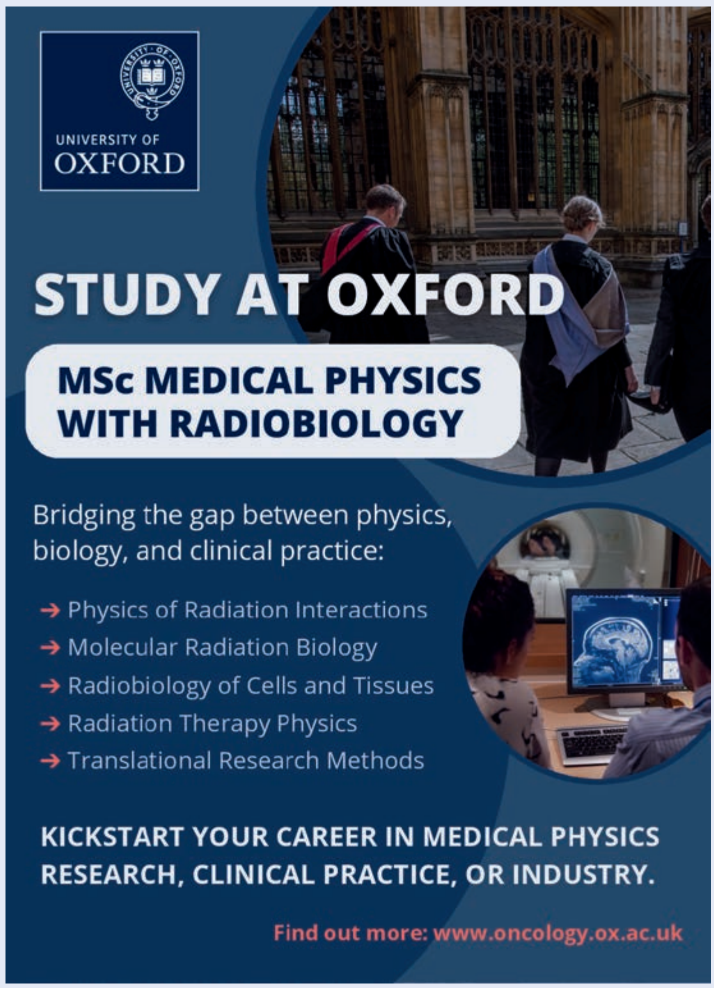
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Frothy beer, big data and glowing plants

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

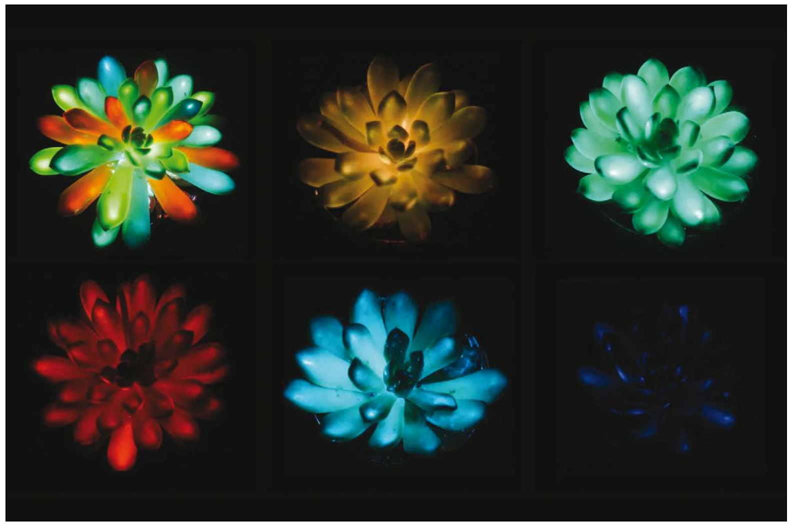
A clear sign of a good brew is a big head of foam at the top of a poured glass. Beer foam is made of many small bubbles of air, separated from each other by thin films of liquid. These thin films must remain stable, or the bubbles will pop, and the foam will collapse. What holds these thin films together is not completely understood and is likely conglomerates of proteins, surface viscosity or the presence of surfactants – molecules that can reduce surface tension and are found in soaps and detergents. To find out more, researchers from ETH Zurich and Eindhoven University of Technology investigated beer-foam stability for different types of beers at varying stages of the fermentation process (*Physics of Fluids* **37** 082139). They found that for single-fermentation beers, the foams are mostly held together with the surface viscosity of the beer. This is mostly influenced by the proteins in the beer – the more they contain, the more viscous the film and more stable the foam will be. However, for double-fermented beers, the proteins in the beer are slightly denatured by the yeast cells and come together to form a two-dimensional membrane that keeps the foam intact longer. The head was found to be even more stable for triple-fermented beers, which include Trappist beers. The team says that the work could be used to identify ways to increase or decrease the amount of foam so that everyone can pour a perfect glass of beer every time. Cheers!

Big data promotion

An astrophysics PhD student from County Armagh in Northern Ireland has combined his passion for science with Gaelic football to help his club achieve a historic promotion. Eamon McGleenan plays for his local team – O'Connell's GAC Tullysaran – and is a PhD student at Queen's University Belfast, where he is a member of the Predictive Sports Analytics (PSA) research team. McGleenan and his PhD supervisor David Jess teamed up with GAC Tullysaran to investigate whether data analysis and statistical techniques could improve their training and results. Over five months, the Queen's University researchers took over 550 million individual measurements from the squad, which included information such as player running speed, accelerations and heart rates. "We applied mathematical models to the big data we obtained from the athletes," notes McGleenan. "This allowed us to examine how the athletes evolved over time and we then provided key insights for the coaching staff, who then generated bespoke training routines and match tactics." The efforts immediately paid off as in July GAC Tullysaran won its league by two points and was promoted for the first time in 135 years to the top-flight Senior Football League, which they will start in March.

Glowing succulents

"Picture the world of *Avatar*, where glowing plants light up an entire ecosystem," describes Shuting Liu of South China Agricultural University in Guangzhou. Well, that vision is now a step closer thanks to researchers in China who have created glow-in-the-dark succulents that recharge in sunlight (*Matter* 10.1016/j.matt.2025.102370). Instead of coaxing cells to glow through genetic modification, the team instead used afterglow phosphor particles – materials similar to those found in glow-in-the-dark toys – that absorb light and release it slowly over time. The researchers then injected the particles into succulents, finding that they produced a strong glow, thanks to the narrow, uniform and evenly distributed channels within the leaf that helped to disperse the particles. After a couple of minutes of exposure to sunlight or indoor LED light, the modified plants glowed for up to two hours. By using different types of phosphors, the researchers created plants that shine in various colours, including green, red and blue. The team even built a glowing plant wall with 56 succulents, which was bright enough to illuminate nearby objects. "I just find it incredible that an entirely human-made, micro-scale material can come together so seamlessly with the natural structure of a plant," notes Liu. "The way they integrate is almost magical. It creates a special kind of functionality."



Liu *et al.*, *Matter*

Glow and behold Succulents glow in shades of red, green, blue, and more after being infused with afterglow phosphor particles that absorb and slowly release light.

People get all excited about science fiction films when they come out. You know, *Star Wars* or *Star Trek*. This is the real thing

Christian Sallaberger is president and chief executive officer of the Canadian firm Canadensys, which is developing the first Canadian-built rover for exploring the Moon, expected to launch in 2029 at the earliest. (Source: BBC)

There are trillion-dollar companies that say they're in this business, but the power button hasn't been depressed

Niccolo de Masi, head of the quantum-computing firm IonQ, was commenting on the fierce competition by firms, including tech titans, to report advances in building quantum computers. (Source: *Times*)

Michael Banks is news editor of *Physics World*

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