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February 2025

Structural impact

Metamaterials hit the market

Troubled birth The obscure paper that triggered the quantum revolution

Confronting reality What if physics metaphors were put to the test?

Outreach guide Using your scientific skills to engage and inspire others

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Volume 38 No 2

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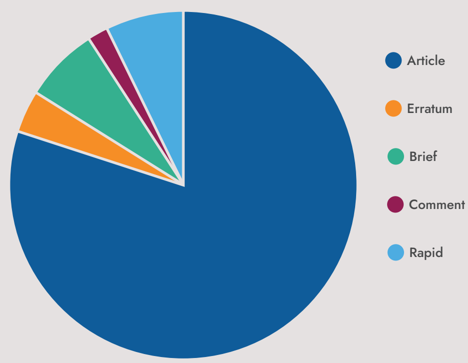

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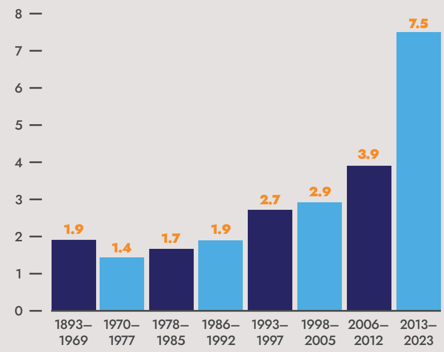

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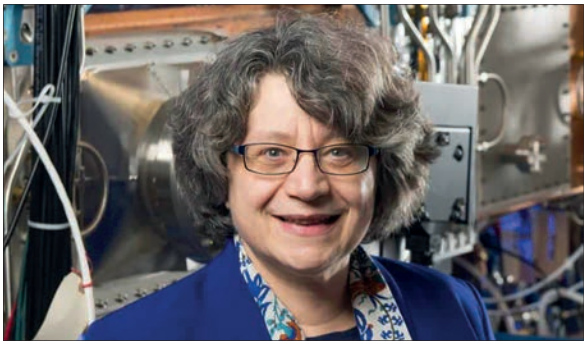
News & Analysis

Fermilab boss Lia Merminga resigns

Lia Merminga has resigned as director of Fermilab – the US's premier particle-physics lab. She stepped down last month after a turbulent year that saw staff layoffs, a change in the lab's management contractor and accusations of a toxic atmosphere. Merminga is being replaced by Young-Kee Kim from the University of Chicago, who will serve as interim director until a permanent successor is found. Kim was previously Fermilab's deputy director between 2006 and 2013.

Tracy Marc, a spokesperson for Fermilab, says that the search for Merminga's successor has already begun, although without a specific schedule. "Input from Fermilab employees is highly valued and we expect to have Fermilab employee representatives as advisory members on the search committee, just as has been done in the past," Marc told *Physics World*. "The search committee will keep the Fermilab community informed about the progress of this search."

The departure of Merminga, who became Fermilab director in August 2022, was announced by Paul Alivisatos, president of the University of Chicago. The university jointly manages the lab with Universities Research Association (URA), a consortium of research universities, as well as the industrial firms Amentum Environment & Energy, Inc. and Longenecker & Associates.


Reidar Hahn, Fermilab

Stepping down Lia Merminga has quit as Fermilab director after a turbulent few years at the lab.

"Her dedication and passion for high-energy physics and Fermilab's mission have been deeply appreciated," Alivisatos said in a statement. "This leadership change will bring fresh perspectives and expertise to the Fermilab leadership team."

The reasons for Merminga's resignation are unclear but Fermilab has experienced a difficult last two years with questions raised about its internal management and external oversight. Last August, a group of anonymous self-styled whistleblowers published a 113-page "white paper" on the arXiv preprint server, asserting that the lab was "doomed without a management overhaul".

The document highlighted issues such as management cover ups of dangerous behaviour including guns being brought onto Fermilab's campus and a male employee's attack on a female colleague. In addition, key experiments such as the Deep Underground Neutrino Experiment suffered notable delays. Cost overruns also led to a "limited operations period" with most staff on leave in late August.

In October, the US Department of Energy, which oversees Fermilab, announced a new organization – Fermi Forward Discovery Group – to manage the lab. Yet that decision came under scrutiny given it is dominated by the University of Chicago and URA, which had already been part of the management since 2007. Then a month later, almost 2.5% of Fermilab's employees were laid off, adding to portray an institution in crisis.

The whistleblowers, who told *Physics World* that they still stand by their analysis of the lab's issues, say that the layoffs "undermined Fermilab's scientific mission" and sidelined "some of its most accomplished" researchers at the lab. "Meanwhile, executive managers, insulated by high salaries and direct oversight responsibilities, remained unaffected," they allege.

Peter Gwynne
Boston, MA

Space

NASA's Nancy Grace Roman Space Telescope nears completion

Engineers have successfully integrated key parts of NASA's $4bn Nancy Grace Roman Space Telescope – marking a significant step towards completion. The mission's payload, which includes the telescope, two instruments and the instrument carrier, has been combined with the spacecraft that will deliver the observatory to its place in space at Lagrangian point L2.

The Roman telescope, which was previously named the Wide-Field Infrared Survey Telescope, was given top priority among large space-based missions in the 2010 US National Academy of Science Decadal Survey. Since then, however, the telescope has had a difficult existence. In Donald Trump's first term as US president it was twice given zero funding only for US Congress to reinstate its budget. Roman will be the most stable large telescope ever built, at least 10 times more so than NASA's James Webb Space Telescope.

The telescope's primary instrument is the Wide Field Instrument, a 300-megapixel infrared camera that will give it a deep, panoramic view of the universe. This will be used to study exoplanets, stars, galaxies and black holes with Roman able to image large areas of the sky 1000 times faster than Hubble with the same sharp, sensitive image quality. The next steps for the telescope involve installing its solar panels, aperture cover – that shields the telescope from unwanted light – as well as an "outer barrel assembly" that serves as the telescope's exoskeleton. The Roman mission should be complete next year with a launch before May 2027.


NASA/Jolearra Tshiteya

Progress update NASA's Nancy Grace Roman Space Telescope is expected to be launched before May 2027.

Michael Banks

Policy

Trump nominates AI experts for key science positions

US President Donald Trump has selected Silicon Valley executive Michael Kratsios as director of the Office of Science and Technology Policy (OSTP). Kratsios will also serve as Trump's science advisor, a position that, unlike the OSTP directorship, does not require approval by the US Senate. Meanwhile, computer scientist Lynne Parker from the University of Tennessee, Knoxville, has been appointed to a new position – executive director of the President's Council on Advisors on Science and Technology. Parker, who is a former member of OSTP, will also act as counsellor to the OSTP director.

Kratsios, with a BA in politics from Princeton University, was previously chief of staff to Silicon Valley venture capitalist Peter Thiel before becoming the White House's chief technology officer in 2017 at the start of Trump's first stint as US president. In addition to his technology remit, Kratsios was effectively Trump's science advisor until meteorologist Kelvin Droegemeier took that position in January 2019. Kratsios then became the Department of Defense's acting undersecretary of research and engineering. After the 2020 presidential election, Kratsios left government to run the San Francisco-based company Scale AI.

The White House and the University of Tennessee

Taking the helm Michael Kratsios will become Donald Trump's science advisor while Lynne Parker has been nominated to a new position as executive director of the President's Council on Advisors on Science and Technology.

Parker has a master's from the University of Tennessee and a PhD from Massachusetts Institute of Technology, both in computer science. She was founding director of the University of Tennessee's AI Tennessee Initiative before spending four years as a member of OSTP, bridging the first Trump and Biden administrations. There, she served as deputy chief technology officer and was the inaugural director of OSTP's National Artificial Intelligence Initiative Office.

Unlike some other Trump nominations, the appointments have been positively received by the science community. "APLU is enthusiastic that Trump has selected two individuals who recognize the importance of science to national competitiveness, health, and economic growth," noted the Association of Public & Land Universities – a membership organization of public research universities – in a statement. Analysts expect the nominations to reflect the returning president's interest in pursuing AI, which could indicate a move towards technology over scientific research in the coming four years.

• Bill Nelson – NASA's departing administrator – has handed over a decision to potential successor Jared Isaacman about when to retrieve samples collected by the Mars rover Perseverance. NASA had said last year that it would develop a fresh plan for the "Mars Sample Return" mission, which has been hit by cost increases and delays. Nelson now says the agency has two lower-cost plans in mind – but that a choice will not be made until mid-2026. Each option could cost up to $7.5bn – much less than the rejected plan's $11bn.

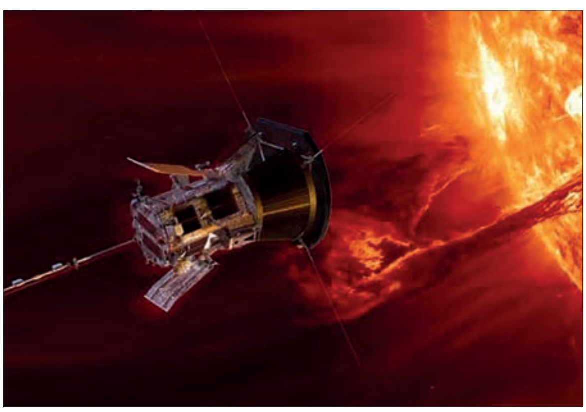
Peter Gwynne
Boston, MA

Space

NASA's Parker Solar Probe survives its first close-up solar encounter

NASA has confirmed that its Parker Solar Probe has survived its record-breaking closest approach to the solar surface. The incident occurred on 24 December where it flew some 6.1 million kilometres above the surface of the Sun – well within the orbit of Mercury. A "beacon tone" that was received on 26 December – along with further telemetry taken on 1 January – confirmed that the spacecraft not only survived but also executed the commands that had been pre-programmed into its flight computers before the flyby.

The Parker Solar Probe – named after physicist Eugene Parker who explained why the Sun's corona is hotter than its surface – was launched in 2018 from NASA's Kennedy Space Center in Florida. The mission carries four instruments including magnetometers, an imager and two dedicated particle analysers. To withstand the intense temperatures, which can reach almost 1400 °C, the spacecraft and instruments are protected by a 11.4 cm carbon-composite shield.



NASA/APL

Hot times NASA's Parker Solar Probe will perform 24 orbits around the Sun with the next close solar pass on 22 March.

During the mission's seven-year lifespan, it will perform 24 orbits around the Sun with the next close solar passes occurring on 22 March and 19 June. Data transmission from the first pass in December will begin later this month when the spacecraft and its most powerful onboard antenna are in better alignment with Earth to transmit at higher data rates. "Flying this close to the Sun is a historic moment in humanity's first mission to a star," notes British physicist Nicky Fox, who heads the Science Mission Directorate at NASA headquarters in Washington. "By studying the Sun up close, we can better understand its impacts throughout our solar system, including on the technology we use daily on Earth and in space, as well as learn about the workings of stars across the universe to aid in our search for habitable worlds beyond our home planet."

Michael Banks

Environment

Megaproject in Chile threatens world's darkest skies, astronomers warn

The darkest, clearest skies anywhere in the world could suffer "irreparable damage" by a proposed industrial megaproject. That is the warning from the European Southern Observatory (ESO) in response to plans by AES Andes, a subsidiary of the US power company AES Corporation, to develop a green hydrogen project just a few kilometres from ESO's flagship Paranal Observatory in Chile's Atacama Desert.

The Atacama Desert is considered one of the most important astronomical research sites in the world due to its stable atmosphere and lack of light pollution. Sitting 2635 m above sea level, on Cerro Paranal, the Paranal Observatory is home to key facilities such as the Very Large Telescope. The Extremely Large Telescope (ELT) – the largest visible and infrared light telescope in the world – is also being constructed at the observatory on Cerro Armazones with first light expected in 2028.

AES Chile submitted an Environmental Impact Assessment in Chile for an industrial-scale green hydrogen project at the end of December. The complex is expected to cover more than 3000 hectares – similar in size to 1200 football pitches. According to AES, the project is in the early stages of development, but could include green hydrogen and ammonia production plants, solar and wind farms as well as battery storage facilities.

G. Hüdepohl/ESO

Under threat A power project could endanger the Paranal Observatory in Chile's Atacama Desert, which is home to the Very Large Telescope.

ESO now wants the development to be relocated to preserve "one of Earth's last truly pristine dark skies" and "safeguard the future" of astronomy. "The proximity of the AES Andes industrial megaproject to Paranal poses a critical risk to the most pristine night skies on the planet," says ESO director general Xavier Barcons. "Dust emissions during construction, increased atmospheric turbulence, and especially light pollution will irreparably impact the capabilities for astronomical observation."

In a statement sent to *Physics World*, an AES spokesperson says they are aware of ESO's concerns but adds that the project would be in an area "designated for renewable energy development". They also claim that the company is "dedicated to complying with all regulatory guidelines and rules" and "supporting local economic development while maintaining the highest environmental and safety standards". According to the statement, the proposal "incorporates the highest standards in lighting" to comply with Chilean regulatory requirements designed "to prevent light pollution, and protect the astronomical quality of the night skies".

Yet Romano Corradi, director of the Gran Telescopio Canarias, which is located at the Roque de los Muchachos Observatory, La Palma, Spain, notes it is "obvious" that the light pollution from such a large complex will negatively affect observations.

Michael Allen

Materials

UK launches first-ever industrial materials strategy

Increased collaboration between different areas of materials research and development will be needed if the UK is to remain a leader in the field. That is according to the National Materials Innovation Strategy, which claims to be the first document aimed at boosting materials-based innovation in the UK. Failing to adopt a "clear, national strategy" for materials will hamper the UK's ability to meet its net-zero and other sustainability goals, the strategy says.

Led by the Henry Royce Institute – the UK's national institute for advanced materials – the strategy included the input of over 2000 experts in materials science, engineering, innovation, policy and industry. It says that some 52 000 people in the UK work or contribute to the materials industry, adding about £4.4bn to the UK economy each year. Of the 2700 companies in materials innovation in the UK, 70% are registered outside of London and the South East, with 90% being small and medium-sized enterprises.

According to the 160-page strategy, materials innovation touches "almost every strategically important sector in the UK" and points to "six areas of opportunity" where materials can have an impact. They are: energy; healthcare; structural innovations; surface technologies; electronics, telecommunications and sensors; and consumer products, packaging and specialist polymers.

The strategy, which is the first phase of an effort to speed up materials development in the UK, calls for a more collaborative effort between different fields to help spur materials innovation that has "traditionally been siloed across sectors". It claims that every materials-related job results in 12 additional jobs within "materials innovation business", adding that "a commitment to materials innovation" by the UK could double the number of materials-specific roles by 2035.

Shutterstock/Inozemtsev-Konstantin

Materials world Advanced materials are used in energy efficient supercomputers, implantable electrotherapy devices to treat brain cancer and carbon neutral steel.

"Advanced materials hold the key to finding and delivering solutions to some of the most pressing national and global challenges of today and directly contribute billions to our national economy," says materials engineer David Knowles, who is chief executive of the Henry Royce Institute. "But to unlock the full value of materials we must break down traditional long-standing silos within the industry. This strategy has kickstarted that process."

Michael Banks

NMR helps to clear a mine field

Field trials of a prototype landmine detector based on nuclear magnetic resonance could reduce the regular occurrence of false positives that hamper conventional technology, reports **Tereza Pultarova**

Novel landmine detectors based on nuclear magnetic resonance (NMR) have passed their first field-trial tests. Built by the Sydney-based company mRead, the devices could speed up the removal of explosives in former war zones. The company tested its prototype detectors in Angola late last year, finding that they could reliably sense explosives buried up to 15 cm underground — the typical depth of a deployed landmine.

Landmines are a problem in many countries recovering from armed conflict. According to NATO, some 110 million landmines are located in 70 countries worldwide. Ukraine is currently the world's most mine-infested country, making vast swathes of its agricultural land potentially unusable for decades.

According to the *Landmine and Cluster Munition Monitor*, nearly 2000 people died from landmine incidents in 2023 – double the number compared to 2022 – and a further 3660 were injured. Over 80% of the casualties were civilians, with children accounting for 37% of deaths.

Humanitarian "deminers" currently inspect suspected minefields with hand-held metal detectors. These devices use magnetic induction coils that respond to the metal components present in landmines. Unfortunately, they react to every random piece of metal and shrapnel in the soil, leading to high rates of false positives.

"It's not unreasonable with a metal detector to see 100 false alarms for every mine that you clear," says Matthew Abercrombie, research and development officer at the HALO Trust, a de-mining charity. "Each of these false alarms you still have to investigate as if it were a mine." For every mine excavated, about 50 hours is wasted on excavating false positives, meaning that clearing a single minefield could take months or years.

mRead

Safety first
In November 2014 engineers tested NMR detectors in a minefield in Angola where they could reliably sense explosives buried up to 15 cm underground – the typical depth of a deployed landmine.

Hope for the future

One alternative landmine-detecting technology option is NMR, which is already widely used to look for underground mineral resources and scan for drugs at airports. NMR results in nuclei inside atoms emitting a weak electromagnetic signal in the presence of a strong constant magnetic field and a weak oscillating field. As the frequency of the signal depends on the molecule's structure, every chemical compound has a specific electromagnetic fingerprint.

The problem using it to sniff out landmines is pervasive environmental radio noise, with the electromagnetic signal emitted by the excited molecules being 16 orders of magnitude weaker than that used to trigger the effect. Digital radio transmission, electricity generators and industrial infrastructure all produce noise at the same frequency as the detectors are listening for. Even thunderstorms trigger a radio hum that can spread across vast distances.

"It's easier to listen to the Big Bang at the edge of the universe," says Nick Cutmore, chief technology officer at mRead. "Because the signal is so small, every interference stops you. That has stopped a lot of practical applications of this technique in the past." Cutmore is part of a team that has been trying to cut the effects of noise since the early 2000s, eventually finding a way to filter out this persistent crackle through a proprietary sensor design. MRead's handheld detectors emit radio pulses at frequencies between 0.5 and 5 MHz, which are much higher than the kilohertz-range frequencies used by conventional metal detectors. The signal elicits the magnetic resonance response in atoms of sodium, potassium and chlorine, which are commonly found in explosives. A sensor inside the detector "listens out" for the particular fingerprint signal, locating a forgotten mine more precisely than is possible with conventional metal detectors.

It's easier to listen to the Big Bang at the edge of the universe

Given that the detected signal is so small, it has to be amplified, but this results in adding noise. The company says it has found a way to make sure the electronics in the detector do not exacerbate the problem. "Our current handheld system only consumes 40 to 50 W when operating," says Cutmore. "Previous systems have sometimes operated at a few kilowatts, making them power-hungry and bulky."

Having tested the prototype detectors in a simulated minefield in Australia in August 2024, mRead engineers have now deployed them in minefields in Angola in cooperation with the HALO Trust. As the detectors respond directly to the explosive substance, they almost eliminated false positives completely, allowing deminers to double-check locations flagged by metal detectors before time-consuming digging took place.

During the three-week trial, the researchers also detected mines that had a low content of metal, which are difficult to spot with metal detectors."Instead of doing 1000 metal detections and finding one mine, we can isolate those detections very quickly before people start digging," says Cutmore. Researchers at mRead plan to return to Angola later this year for further tests. They also want to fine-tune their prototypes and begin working on devices that could be produced commercially.

"I am tremendously excited by the results of these trials," says James Cowan, chief executive officer of the HALO Trust. "With over two million landmines laid in Ukraine since 2022, landmine clearance needs to be faster, and smarter."

Tereza Pultarova is a science and technology journalist based in London, UK

Research updates

Quantum properties are equivalent

A decade-old prediction that quantum uncertainty is the same as wave–particle duality has been confirmed using orbital angular momentum states of light, as **Tim Wogan** explains

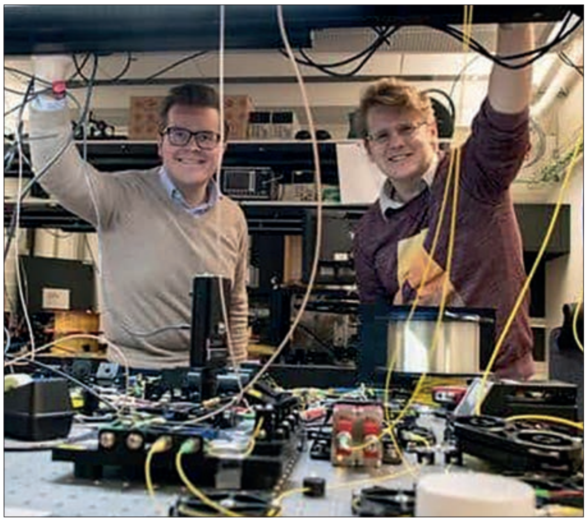
The orbital angular momentum states of light have been used to relate quantum uncertainty to wave–particle duality. The experiment confirms a 2014 theoretical prediction that a minimum level of uncertainty must always result when a measurement is made on a quantum object – regardless of whether the object is observed as a wave, as a particle, or anywhere in between (*Sci. Adv.* **10** eadr2007).

In a version of the famous double-slit experiment, quantum particles such as electrons can be fired one-by-one at two adjacent slits in a barrier. As time progresses, an interference pattern builds up on a detector behind the barrier. This is an example of wave–particle duality whereby each particle travels through both slits as a wave that interferes with itself. However, if the trajectories of the particles are observed such that it is known which slit each particle travelled through, no interference pattern is seen.

In 1979, William Wootters and his colleague Wojciech Zurek at the University of Texas at Austin showed that wave–particle duality is not a one-or-the-other phenomenon. Instead it is possible to observe partial particle and partial wave-like behaviour, with a trade-off between the two. This echoes another baffling element of quantum mechanics, namely preparation uncertainty. This is typified by Werner Heisenberg's uncertainty principle, which states that it is not possible to know the position and momentum of a quantum object beyond a certain degree of accuracy, and the more one knows about one, the more uncertain the other becomes.

When paths meet

There was no obvious theoretical connection between measurement uncertainty and preparation uncertainty until 2014 when Patrick Coles and colleagues at the National University of Singapore showed theoretically that the two were equivalent. In the new work, Guilherme Xavier at colleagues at Linköping University in Sweden set out to test the relationship between the visibility and the distinguishability of opposite states – which according to Coles' predictions should be conjugate variables analogous to position and momentum.



Magnus Johansson/LiU

Quantum duo Joakim Argillander and Daniel Spegel-Lexne from Linköping University say they are now planning to develop practical applications of the technique.

To do so, the researchers sent highly attenuated, mostly single-photon laser pulses in two possible orthogonal orbital angular momentum states down an optical fibre to an input beamsplitter. Photons with opposite angular momenta emerged through different output fibres. They then used a phase modulator to add a variable phase delay to photons travelling down one of the paths before directing the paths to meet again at a second, tunable beamsplitter.

By placing a second modulator before the tunable beamsplitter and thereby adjusting the phase with which the two paths met, it was possible to tune the extent to which the paths recombined. The researchers could therefore control the extent to which the second beamsplitter actually behaved as a beamsplitter.

"When the beamsplitter is fully inserted you get interference back – this corresponds to a value in the modulator of $\pi/2$," explains Xavier, "When you have zero in the modulator the upper path will always go to one detector and the lower path will always go to the other." This latter case corresponds to a particle picture, but it provides no information about which path a particular particle has taken through the detector. The only way one can obtain that information is to prevent one of the polarizations of light from entering the second beamsplitter completely – the equivalent of blocking one of the slits in the double slit experiment. However, in this case, half of the photons are never detected at all. There is thus an unbeatable trade-off between distinguishability and visibility.

They found that, no matter what they chose as the phase, there was a fixed lower bound on the measurement uncertainty that was consistent with the theory presented in 2014 by Coles and colleagues. The Linköping team now plans to develop practical applications of the technique. "We can change the settings quite fast," says Xavier, "so our goal is to look at the implementation of some actual quantum communication protocols using these kinds of measurements – we are looking at some delayed choice experiments based on this set-up."

Theoretical physicist Jonas Maziero of the Federal University of Santa Maria in Brazil, who was not involved in the research, is impressed by the work. "The experiment is innovative, it's precise, it agrees very well with theory and it confirms an important result that's been in the literature for more than ten years now," he says. He cautions, however, that the result does not fully confirm Coles' predictions and extending the research to cover all cases would be interesting follow-up work.

Astronomy

Immiscible ice layers may explain why Uranus and Neptune lack magnetic poles

When the Voyager 2 spacecraft flew past Uranus and Neptune in 1986 and 1989, it detected that neither of these "ice giant" planets had a well-defined north and south magnetic pole. This absence has remained mysterious ever since, but simulations performed at the University of California, Berkeley (UCB) in the US suggest that the disorganized magnetic fields of Uranus and Neptune may arise from a separation of the icy fluids that make up their interiors (*Proc. Natl. Acad. Sci.* 121 e2403981121).

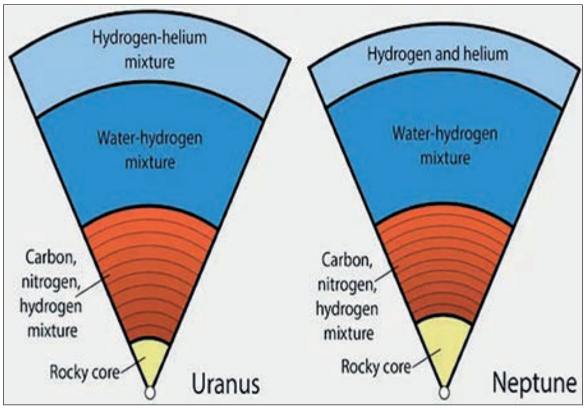
On Earth, the dipole magnetic field that loops from the North Pole to the South Pole arises from convection in the planet's liquid-iron outer core. Since Uranus and Neptune lack such a dipole field, this implies that the convective movement of material in their interiors must be different. In 2004, it was suggested that the planets' interiors might contain immiscible layers. This separation would make widespread convection impossible, preventing a global dipolar magnetic field from forming. Convection in just one layer, meanwhile, would produce the disorganized magnetic field that Voyager 2 observed.

However, the nature of these non-mixing layers was still unexplained – hampered, in part, by a lack of data. "Since both planets have been visited by only one spacecraft – Voyager 2 – we do not have many measurements to analyse," says UCB planetary scientist Burkhard Militzer. To investigate conditions deep beneath Uranus and Neptune's icy surfaces, Militzer developed computer models to simulate how a mixture of water, methane and ammonia will behave at the temperatures above 4750 K and pressures above 3×10^6 atmospheres that prevail there. He found that an initially homogeneous mixture of water, methane and ammonia could separate into two distinct layers.

The upper layer, he explains, is thin, rich in water and convecting. This allows it to generate the disordered magnetic field. The lower layer is magnetically inactive and composed of carbon, nitrogen and hydrogen (C-N-H).

Militzer's model shows that the hydrogen content in the methane-ammonia mixture gradually decreases with depth, transforming into a C-N-H fluid. This C-N-H layer is almost like a plastic polymer, Militzer explains, and cannot support even a disorganized magnetic field – unlike the upper, water-rich layer, which likely convects. A future mission to Uranus with the right instruments on board could provide observational evidence for this structure, Militzer adds.

Isabelle Dumé



Burkhard Militzer, UC Berkeley

Cool finding New computer simulations show that certain mixtures of icy fluids naturally separate into two layers at high pressure and temperature.

Sun-like stars produce 'superflares' about once a century

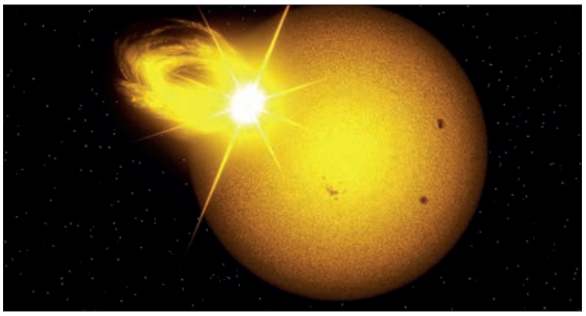
Stars like our own Sun produce "superflares" around once every 100 years, surprising astronomers who had previously estimated that such events were much rarer, occurring only every 3000 to 6000 years. The result, by a team of astronomers in Europe, Japan and the US, could be important not only for fundamental stellar physics but also for forecasting space weather (*Science* **386** 1301).

The Sun regularly produces solar flares – energetic outbursts of electromagnetic radiation that are sometimes accompanied by plasma – in events known as coronal mass ejections. Both activities can trigger powerful solar storms when they interact with the Earth's upper atmosphere. Despite their power, though, these events are much weaker than the "superflares" recently observed by NASA's Kepler and TESS missions in other Sun-like stars in our galaxy. The most intense superflares release energies of about 10^{25} J, which show up as short, sharp peaks in the stars' visible light spectrum.

To see if our Sun can also produce solar flares – and, if so, how often – researchers analysed Kepler space telescope data on the fluctuations of more than 56 000 Sun-like stars between 2009 to 2013. This dataset, which is much larger and more representative than previous datasets because it based on recent advances in our understanding of Sun-like stars, corresponds to around 220 000 years of solar observations. The team identified almost 3000 bright stellar flares in the population they observed, which implies that superflares occur roughly once per century, per star. The results also suggest that solar flares and stellar superflares are generated by the same physical mechanisms.

So could a superflare have occurred in the Sun in the past century but gone unnoticed? "While we have no evidence of such an event, excluding it with certainty would require continuous and systematic monitoring of the Sun," Valeriy Vasilyev from the Max Planck Institute for Solar System Research, Germany, told *Physics World*. The researchers now plan to investigate the conditions required to produce superflares.

Isabelle Dumé



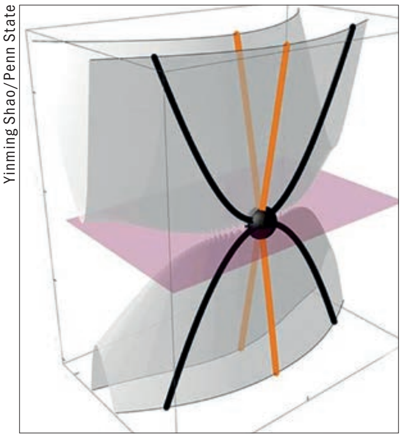
MPS/Alexey Chizhik

Hotting up To find out how often superflares happen in Sun-like stars, the team analysed Kepler space telescope data taken between 2009 to 2013.

Condensed-matter physics

Quasiparticles become massless when moving in one direction

Physicists at Penn State and Columbia universities in the US say they have seen the "smoking gun" signature of an elusive quasiparticle predicted by theorists 16 years ago. Known as semi-Dirac fermions, the quasiparticles only behave like they have mass when they're moving in a certain direction. They were spotted in a crystal of the topological semimetal ZrSiS (*Phys. Rev. X* **14** 041057).



Yinming Shao/Penn State

Crossing points Quasiparticles called semi-Dirac fermions have been spotted inside a crystal of semi-metal material called ZrSiS thanks to its unusual band structure.

The team performed the experiments using the 17.5 T magnet at the US National High Magnetic Field Laboratory in Florida. When applied to ZrSiS, a high field causes the material's electronic energy levels to become quantized into discrete (Landau) levels. The energy gap between these levels then depends on the electrons' mass and the strength of the field.

Normally, the energy levels of the electrons should increase by set amounts as the magnetic field increases, but in this case they didn't. Instead, they followed a unique power-law scaling, $B^{2/3}$, with B being the magnetic field. "This special power-law turns out to be the exact prediction from 16 years ago of semi-Dirac fermions," explains Yinming Shao, a physicist at Penn State and lead author of the study.

Previous efforts to create semi-Dirac fermions relied on stretching graphene until the material's two so-called Dirac points touch. These points occur in the region where the material's valence and conduction bands meet. At these points, the relationship between the energy and momentum of charge carriers in graphene is described by the Dirac equation, rather than the standard Schrödinger equation as is the case for most crystalline materials. The presence of these unusual band structures (known as Dirac cones) enables the charge carriers in graphene to behave like massless particles.

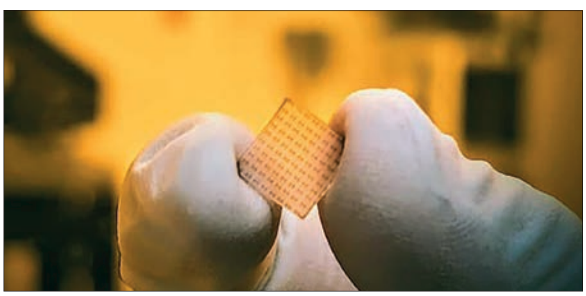
The problem is that making Dirac points touch in graphene turned out to require an unrealistically high level of strain. Shao and colleagues investigated ZrSiS because it also has Dirac points, but they exist continuously along a so-called nodal line. The researchers found evidence for semi-Dirac fermions at the crossing points of these nodal lines. Shao told *Physics World* that the team still has much to understand about the material's behaviour. "There are some unexplained fine electronic energy level-splitting in the data that we do not fully understand yet and which may originate from electronic interaction effects," says Shao.

ZrSiS is a layered material, much like graphite, and so could have applications. "Once we can figure out how to obtain a single layer cut of this compound, we can harness the power of semi-Dirac fermions and control its properties with the same precision as graphene," he says.

Isabelle Dumé

Thin films of a novel semimetal conduct electricity better than copper

A very thin film of niobium phosphide has been shown to conduct electricity better than copper even in non-crystalline films. While metals usually conduct less well as they get thinner, niobium phosphide – a non-crystalline topological semimetal – does otherwise and the surprising result could aid the development of ultrathin low-resistivity wires for nanoelectronics applications (*Science* 387 62).



A Khan

Great conductor The researchers have created a chip that is made of the non-crystalline topological semimetal niobium phosphide.

As today's electronic devices and chips become smaller and more complex, the ultrathin metallic wires that carry electrical signals within these chips could become a bottleneck when scaled down. One solution is to create ultrathin conductors with a lower electrical resistivity for the metal interconnects that enable dense logic and memory operations within neuromorphic and spintronic devices.

Unfortunately, the resistivity of conventional metals increases when they are made into thin films. Topological semimetals are different, carrying large amounts of current along their surface even when their structure is somewhat disordered. Crucially, they maintain this surface-conducting property even as they are thinned down.

In the new work, the researchers found that the effective resistivity of non-crystalline films of niobium phosphide decreases dramatically as the film thickness is reduced. Indeed, the thinnest films (< 5 nm) have resistivities lower than conventional metals like copper of similar thicknesses at room temperature.

These films can also can be created and deposited on substrates at relatively low temperatures (around 400 °C) and so are compatible with modern semiconductor and chip fabrication processes such as industrial back-end-of-line. Such materials would therefore be relatively easy to integrate into state-of-the-art nanoelectronics. The fact that the films are non-crystalline is also an important practical advantage.

The researchers now plan further tests on their material. "We also think niobium phosphide is not the only material with this property, so there's much more to discover," says Eric Pop from Stanford University, US.

Isabelle Dumé

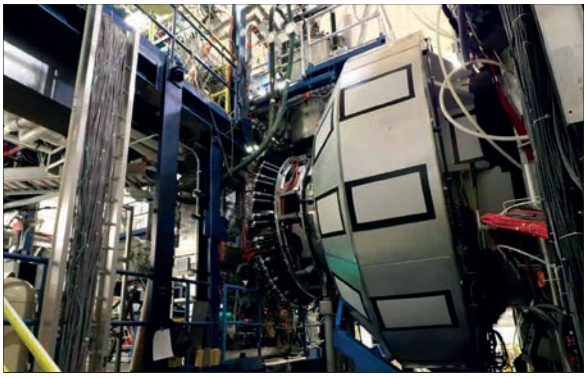
Nuclear physics

Inner workings of the neutron revealed by Jefferson Lab experiment

Researchers at the Jefferson Lab in the US have measured generalized parton distributions to reveal details about the internal structure of the neutron. An international collaboration used the CEBAF Large Acceptance Spectrometer (CLAS12) to study the scattering of high-energy electrons from a deuterium target to study how the neutron's constituent quarks contribute to its momentum and spin (*Phys. Rev. Lett.* 133 211903).

The theory of the strong force, called quantum chromodynamics (QCD), describes the interaction between quarks via the exchange of gluons. But it's so complex that it can't be used to compute the properties of bound states, such as neutrons and protons. To get around this, researchers use experimentally measurable functions called generalized parton distributions, which help connect the properties of the nucleons such as their spin to the dynamics of quarks and gluons.

The model assumes that a nucleon contains point-like constituents that represent the quarks and gluons of QCD. By measuring the distributions of these partons, physicists can examine correlations between a quark's longitudinal momentum – how much of the nucleon's total momentum it carries – and its transverse position within the nucleon. By analysing these relationships for varying momentum values, it is possible to create a tomographic-like scan of the nucleon's internal structure.



Jefferson Lab

In a spin
The Central Neutron Detector, which is part of CLAS12 at Jefferson Lab, has been used to measure details about the internal structure of neutrons.

Each type of quark is associated with its own set of generalized parton distributions, and the overarching aim of the experimental effort is to determine distributions for both protons and neutrons.

While these distributions are vital for understanding the strong interactions within both protons and neutrons, our understanding of protons is significantly more advanced. To address the deficiency regarding neutrons, the CLAS12 collaboration utilized the Central Neutron Detector to detect neutrons ejected from a deuterium target by high-energy electrons for the first time. By combining neutron detection with the simultaneous measurement of scattered electrons and energetic photons produced during the interactions, the team gathered comprehensive data on particle momenta. This was used to calculate the generalized parton distributions of quarks inside neutrons.

The CLAS12 team used electron beams with spins aligned both parallel and antiparallel to their momentum. This configuration resulted in slightly different interactions with the target, enabling the team to investigate subtle features of the generalized parton distributions related to angular momentum. By analysing these details, they successfully disentangled the contributions of up and down quarks to the angular momentum of the neutron.

Andrey Feldman

Optics

Laser beam casts a shadow in a ruby crystal

Researchers have discovered that photons can, under particular circumstances, cast a shadow. Jeff Lundeen of the University of Ottawa, Canada and colleagues found this occurred when a laser beam is illuminated by another light source as it passes through a highly nonlinear medium. The finding could have applications in laser fabrication and imaging (*Optica* **11** 1549).

Being massless, photons don't usually interact with each other and so cannot cast a shadow. Yet when the researchers sent a high-power beam of green laser light through a cube-shaped ruby crystal and illuminated this beam from the side with blue light, they saw the beam cast a shadow on a piece of white paper. This shadow extended through an entire face of the crystal.

R. A. Abrahao, H. P. N. Morin, J. T. R. Pagé, A. Safari, R. W. Boyd, J. S. Lundeen

Out of the shadows
A laser beam can sometimes act like a solid object and cast a shadow that is visible to the naked eye.

Key to the experiment was the use of ruby – an aluminium oxide crystal that contains impurities of chromium atoms. These impurities distort its crystal lattice and give it its familiar red colour. When green laser light (532 nm) is shone on ruby, it drives an electronic transition from the ground state (denoted $^4A_2$) to an excited state $^4T_2$. This excited state then decays rapidly via phonons (vibrations of the crystal lattice) to the ^2E state.

The electrons then absorb blue light (450 nm) and go from ^2E to a different excited state, denoted $^2T_1$. While electrons in the $^4A_2$ state could, in principle, absorb blue light directly, without any intermediate step, the absorption cross-section of the transition from ^2E to $^2T_1$ is larger.

In the presence of the green laser beam, the ruby absorbs more of the illuminating blue light. This leaves behind a lower-optical-intensity region of blue illumination within the ruby – in other words, the green laser beam's shadow. This laser shadow behaves like an ordinary shadow in that it follows the shape of the object (the green laser beam) and conforms to the contours of the surfaces it falls on.

Isabelle Dumé

Opinion

physicsworld

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Let's talk

Whether you're in research or business, outreach is a vital part of being a physicist

Back in November I went to an event at the Houses of Parliament in London celebrating companies who'd just won business awards from the Institute of Physics. The firms are doing amazing stuff, such as making medical devices to measure brain pressure and building muon detectors to keep the rail network safe (pp15–16).

Companies showcased their wares at a small exhibition, but there was also a brief awards do where a representative from each firm gave an "elevator pitch" about their work. Now if you're a small business seeking money from investors or publicity from journalists, you've got to be able to explain in a nutshell what your product is and how it can help customers.

iStock/Anna Stills

Perhaps unsurprisingly, all the speakers gave pithy, memorable and entertaining descriptions of their products, the science behind them and their value for customers. Gianluca Memoli, chief executive of Metasonixx, even sang a jokey version of John Lennon's *Imagine* to illustrate how its metamaterials are used for sound-proofing. Cheesy, yes; forgettable, no.

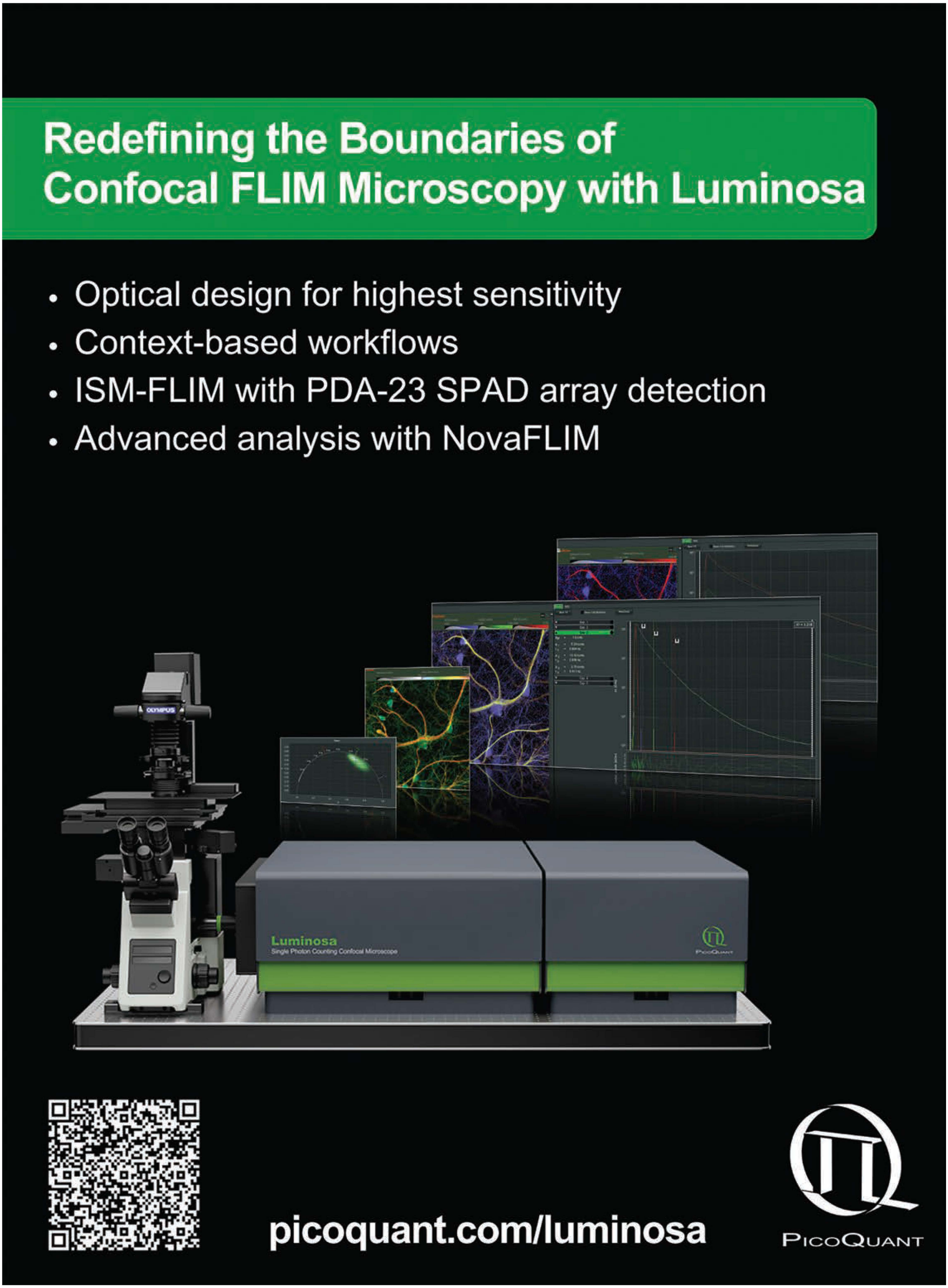
Now I'm not saying you need to sing when discussing your work, but a lot of physicists struggle with "outreach" activity, whether that's talking to school students, parents or members of the public. It's all too easy to wade into technical detail and ignore the wider context. Quite often, outreach attempts end up unimaginative and flat.

Here to help you this month are Melanie Gardner and Clare Harvey from The Ogden Trust – a UK-based charity that promotes the teaching and learning of physics. They've written a handy guide, with case studies, on how to plan, deliver and measure the success of outreach activities (pp30–33). Their advice will be particularly useful if you're new to outreach and want to avoid common pitfalls.

Of course, some parts of physics are easier to explain than others. Astronomy has pretty pictures. Metamaterials (pp20–23) has Harry Potter-style invisibility cloaks. And with the International Year of Quantum Science and Technology in full swing (pp36–38), you can expect quantum physicists to wheel out lots of references to "spookiness" and Schrödinger's cat over the coming months.

As for particle physics, we all know the "cocktail party" Higgs-boson metaphor, where the notion of a crowd gathering round a celebrity in a room is used to explain how particles acquire mass. But what would happen, wonders Robert P Crease (pp18–19), if the metaphor were tested? Now that is an outreach experiment someone should try.

Matin Durrani Editor-in-chief, *Physics World*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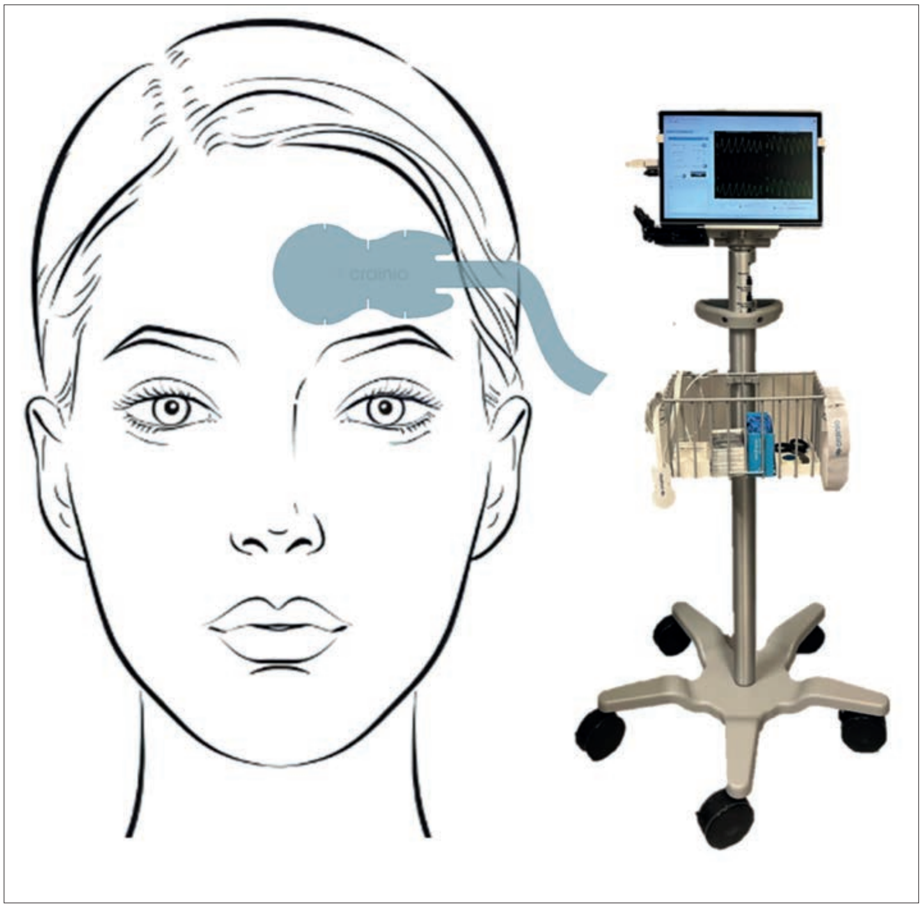
Transactions Business marvels

James McKenzie looks at some of the companies in imaging and medical-physics winning business awards from the Institute of Physics in 2024



Crainio

That winning feeling Crainio, which has found a non-invasive way to measure brain pressure, is one of the companies to have won business awards from the Institute of Physics in 2024. They were honoured at an event hosted by David Willetts – a former UK science minister – at the Houses of Parliament in London.

In my previous article, I highlighted some of the quantum and green-energy companies that won Business Innovation Awards from the Institute of Physics in 2024. But imaging and medical-physics firms did well too. Having sat on the judging panel for the awards, I saw some fantastic entries – and picking winners wasn't easy. Let me start, though, with Geoptic, which is one of an elite group of firms to win a second IOP business award, adding a Business Innovation Award to its start-up prize in 2020.

Geoptic is a spin-out from three collaborating groups of physicists at the universities of Durham, Sheffield and St Mary's Twickenham. The company uses cosmic-ray muon radiography and tomography to study large engineering structures. In particular, it was honoured by the IOP for using the technique to ensure the safety of tunnels on the UK's railway network.

Many of the railway tunnels in the UK date back to the mid-19th century. To speed up construction, temporary shafts were bored vertically down below the ground, allowing workers to dig at multiple points along the route of the tunnel. When the tunnel was complete, the shafts would be sealed, but their precise number and location is often unclear.

The shafts are a major hazard to the tunnel's integrity, which is not great for Network Rail – the state-owned body that's responsible for the UK's rail infrastructure. Geoptic has, however, been working with Network Rail to provide its engineers with a clear structural view of the dangers that lurk along its route. In my view, it's a really innovating imaging company, solving challenging real-world problems.

Another winner is Silveray, which was spun off from the University of Surrey. It's picked up an IOP Business Start-up Award for creating flexible, "colour" X-ray detectors based on proprietary semiconductor materials. Traditional X-ray images are black and white, but what Silveray has done is to develop a nano-particle semiconductor ink that can be coated on to any surface and work at multiple wavelengths.

The X-ray detectors, which are flexible, can simply be wrapped around pipes and other structures that need to be imaged. Traditionally, this has been done using analogue X-ray film that has to be developed in an off-site dark room. That's costly and time-consuming – especially if images failed to be recorded. Silveray's detectors instead provide digital X-ray images in real time, making it an exciting and innovative technology that could transform the $5bn X-ray detector market.

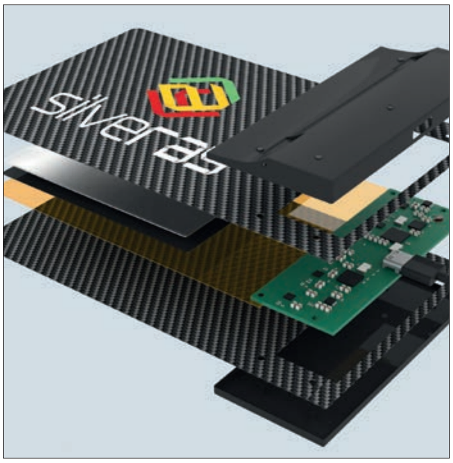
Phlux Technology, meanwhile, has won an IOP Business Start-up Award for developing patented semiconductor technology for infrared light sensors that are 12 times more sensitive than the best existing devices, making them ideal for fast, accurate 3D imaging. Set up by researchers at the University of Sheffield, Phlux's devices have many potential applications especially in light detection and ranging (LIDAR), laser range finders, optical-fibre test instruments and optical and quantum communications networks.

In LIDAR, Phlux's can have 12 times greater image resolution for a given transmitter power. Its sensors could also make vehicles much safer by enabling higher-resolution images to be created over longer distances, making safety systems more effective. The first volume market for the company is likely to be in communications and where a >10 dB increase in detector sensitivity is going to be well received by the market.

Given the number of markets that will benefit from an "over an order of magnitude" improvement, Phlux is one to watch for a future Business Innovation Award too.

Medical marvel

Let me finish by mentioning Crainio, a medical technology spin-off company from City, University of London, which has won the 2024 Lee Lucas award. This award



Silveray

Visionary idea Silveray won an IOP Business Start-up Award for creating flexible, "colour" X-ray detectors based on proprietary semiconductor materials.

honours promising start-up firms in the medical and healthcare sector thanks to a generous donation by Mike and Ann Lee (née Lucas). These companies need all the support, time and money they can get given the many challenging regulatory requirements in the medical sector.

Crainio's technology allows healthcare workers to measure intracranial pressure (ICP), a vital indicator of brain health after a head injury. Currently, the only way to measure ICP directly is for a neurosurgeon to drill a hole in a patient's skull and place an expensive probe in the brain. It's a highly invasive procedure that can't easily be carried out in the "golden hours" immediately after an accident, requiring access to scarce and expensive neurosurgery resources. The procedure is also medically risky, leading to potential infection, bleeding and other complications.

Crainio's technology eliminates these risks, enabling direct measurement of ICP through a simple non-invasive probe applied to the forehead. The technology – using infrared photoplethysmography (PPG) combined with machine learning – is based on years of research and development work conducted by Panicos Kyriacou and his team of biomedical engineers at City.

Good levels of accuracy have been demonstrated in clinical studies conducted at the Royal London Hospital. It certainly seems a much better plan than drilling a hole in your head as I am sure you can agree – making Crainio a worthy winner, with its non-invasive technology it should have a positive impact on patients globally. I hope the regulatory hurdles can be quickly cleared so the company can start helping patients as soon as possible.

As I have mentioned before, all physics-based firms require time and energy to develop products and become globally significant. There's also the perennial difficulty of explaining a product idea, which is often quite specialized, to potential investors who have little or no science background. An IOP start-up award can therefore show that your technology has won approval from judges with solid physics and business experience.

I hope, therefore, that your company, if you have one, will be inspired to apply. Also remember that the IOP offers three other awards (Katharine Burr Blodgett, Denis Gabor and Clifford Paterson) for individuals or teams who have been involved in innovative physics with a commercial angle. Good luck – and remember, you have to be in it to win it. Award entries for 2025 will be open in February 2025.

James McKenzie is a physicist who helps bring new technology and products to market. He is writing here in a personal capacity.

The Nobel fight for equity

Kate Shaw says that the Nobel prizes are continuing to damage science by indicating that only certain demographics can succeed

The 2024 Nobel prizes in both physics and chemistry were awarded, for the first time, to scientists who have worked extensively with artificial intelligence (AI). Computer scientist Geoffrey Hinton and physicist John Hopfield shared the 2024 Nobel Prize for Physics. Meanwhile, half of the chemistry prize went to computer scientists Demis Hassabis and John Jumper from Google DeepMind, with the other half going to the biochemist David Baker.

The chemistry prize highlights the transformation that AI has achieved for science. Hassabis and Jumper developed AlphaFold2 – a cutting-edge AI tool that can predict the structure of a protein based on its amino-acid sequence. It revolutionized this area of science and has since been used to predict the structure of almost all 200 million known proteins.

The physics prize was more controversial, given that AI is not traditionally seen as being physics. Hinton, with a background in psychology, works in AI and developed "backpropagation" – a key part of machine learning that enables neural networks to learn. For the work, he won the Turing award from the Association for Computing Machinery in 2018, which some consider the computing equivalent of a Nobel prize. The physics part mostly came from Hopfield who developed the Hopfield network and Boltzmann machines, which are based on ideas from statistical physics and are now fundamental to AI.

While the Nobels sparked debate in the community about whether AI should be considered physics or chemistry, I don't see an issue with the domains and definitions for subjects having moved on. Indeed, it is clear that the science of AI has had a huge impact. Yet the Nobel Prize for Physiology or Medicine, which was awarded to Victor Ambros and Gary Ruvkun for their work in microRNA, sparked a different albeit well-worn controversy. This being that no more than three people can share each science Nobel prize in a world where scientific breakthroughs are increasing highly collaborative.

No-one would doubt that Ambros and Ruvkin deserve their honour, but many complained that Rosalind Lee, who is married to Ambros, was overlooked for the award. She was the first author of the 1993 paper (*Cell* **75** 843) that was cited for the prize. While I don't see strong arguments for why Lee should have been included for being the first author or married to the last author (she herself also stated such), this case highlights the problem of how to credit teams and whether the lab lead should always be given the praise.

© Nobel Prize Outreach. Photo: Nanaka Adachi

Privileged positions Do the demographics of Nobel prize winners perpetuate biases in our political, educational and scientific systems? K Barry Sharpless receiving his Nobel Prize for Chemistry in 2022.

What sounded alarm bells for me was rather the demographics of this year's science Nobel winners. It was not hard to notice that all seven were white men born or living in the UK, the US or Canada. To put this year's Nobel winners in context, the number of white males in those three countries make up just 1.8% of the world's population. A 2024 study by the economist Paul Novosad from Dartmouth College in the US and colleagues examined the income rank of the fathers of previous Nobel laureates. It found, instead of a uniform distribution, that over half come from the top 5% in terms of wealth.

This is concerning because, taken with other demographics, it tells us that less than 1% of people in the world can succeed in science. We should not accept that such a tiny demographic are born "better" at science than anyone else. The Nobel prizes highlight that we have a biased system in science and little is being done to even out the playing field.

Non-white people in western countries have historically been oppressed and excluded from or discouraged from science, a problem that continues to be unaddressed today. The Global North is home to a quarter of the world's population but claims 80% of the world's wealth and dominates the Global South both politically and economically. The Global North continues to acquire wealth from poorer countries through resource extraction, exploitation and the use of transnational co-operations. Many scientists in the Global South simply cannot fulfil their potential due to lack of resources for equipment; are unable to attend conferences; and cannot even subscribe to journals.

Moreover, women and Black scientists worldwide and even within the Global North are not proportionally represented by Nobel prizes. Data show that men are more likely to receive grants than women and are awarded almost double the funding amount on average. Institutions like to hire and promote men more than women. The fraction of women employed by CERN in science-related areas, for example, is 15%. That's below the 20–25% of people in the field who are women (at CERN 22% of users are women), which is, of course, still half of the expected percentage of women given the global population.

AI will continue to play a stronger and more entangled role in the sciences, and it is promising that the Nobel prizes have evolved out of the traditional subject sphere in line with modern and interdisciplinary times. Yet the demographics of the winners highlight a discouraging picture of our political, educational and scientific system. Can we as a community help reshape a structure from the current version that favours those from affluent backgrounds, and work harder to reach out to young people – especially those from disadvantaged backgrounds?

Imagine the benefit not only to science – with a greater pool of talent – but also to society and our young students when they see that everyone can succeed in science, not just the privileged 1%.

Kate Shaw is a particle physicist at the University of Sussex, UK, and the International Centre for Theoretical Physics, Italy, e-mail kate.shaw@sussex.ac.uk

Critical Point Testing metaphors

We've all heard of the "cocktail party" Higgs-boson metaphor. But what would happen, wonders **Robert P Crease**, if it were truly put to the test?

Shutterstock AI

From idea to reality People crowding around a celebrity entering a room was said by Peter Higgs himself to be the best metaphor to describe how particles acquire mass, but in practice a crowd often stands back at an awed distance.

A few months ago, I received an e-mail from Mike Wilson, a professor of mathematics at the University of Vermont, which challenged my use of a physics metaphor. He found it in my 1986 book *The Second Creation: Makers of the Revolution in 20th-Century Physics*, where my co-author Charles Mann and I explained how accelerators slam particles into targets inside detectors and track fragments for clues about their structure. In a parenthetical remark, we likened this process "to firing a gun at a watch to see what is inside".

Wilson was dubious. "Has anyone ever tried that?" he asked. We had supposed that, in principle, one could "reverse engineer" the watch by applying conservation of momentum to the debris. But Wilson wondered if you could really deduce a watch's internal structure from such pieces. Mann and I hadn't done the watch experiment, nor had we any intention to. Why bother? We'd painted an imaginable picture.

Wilson was unconvinced. "Such experiments," he wrote, "could give a valuable check on the confidence we put in physicists' statements about what goes on inside atoms". His remark made me wonder if other physics metaphors could withstand empirical verification. I first thought of the one often wheeled out to explain the Higgs field and the Higgs boson. It was devised in 1993 by David Miller, a physicist at University College London, after the then UK science minister William Waldegrave promised a bottle of champagne for the best explanation of the Higgs boson on a single A4 sheet of paper (*Physics World* June 2024 p27).

The metaphor, which Peter Higgs admitted was the least objectionable of all those posited to describe his eponymous boson, begins with a room full of political-party workers. If a person nobody knows walks through, people keep their same positions – that's like a massless boson. But when a celebrity walks through (Miller envisaged ex-British prime minister Margaret Thatcher), people cluster around that person, who then has to move more slowly – that's like being massive.

Don Lincoln, a physicist at Fermilab in the US, once made an animated video of this metaphor. Attempting to make it more palatable to physicists, he cast Higgs as the entrant, but the video nevertheless posts the disclaimer "ANALOGY!" Still, I wonder what would have happened if Waldegrave had empirically tested Miller's metaphor using different kinds of celebrities.

Claim to fame

I've come within about two metres of several celebrities: filmmaker Spike Lee and actor Denzel Washington (I was an extra in a scene in their movie *Malcolm X*); jazz musician Sun Ra (I emceed one of his concerts); and Mia Farrow and Stephen Sondheim (I sat next to them in a club). The vibe in the room was very different in each case – sometimes with worshippers, sometimes with autograph hounds, and sometimes with people holding back at an awed and respectful distance. If hadronic mass depended on the vibe in the room, the universe would be a quite different place.

Gino Elia, a graduate philosophy student at Stony Brook University, ticked off a few other untested metaphors. He told me how Blake Stacey, a physicist at the University of Massachusetts, Boston, once described non-overlapping probability distributions as relatives staying away at Thanksgiving. In *Drawing Theories Apart*, David Kaiser – a science historian at the Massachusetts Institute of Technology – pictured the complementary variables of energy and time "as a kid running out of the classroom when the lights are off (breaking conservation of energy) and the kid being in their seat when the teacher turns the light back on".

The grandest, most extended, and awe-inspiring metaphor I have ever come across is at the start of chapter 20 of Leo Tolstoy's *War and Peace*, which describes Moscow just before its occupation by Napoleon's forces. "It was empty," Tolstoy writes, "in the sense that a dying queenless hive is empty". The beekeeper sees only "hundreds of dull, listless, and sleepy shells of bees." They have almost all perished, reeking of death. "Only a few of them still move, rise, and feebly fly to settle on the enemy's hand, lacking the spirit to die stinging him; the rest are dead and fall as lightly as fish scales," Tolstoy concludes.

I don't know a thing about beehives, but Tolstoy did because he was a beekeeper. Even if he didn't, I don't care. The metaphor worked for me, vivid and compelling.

The critical point

Early in 1849 the British poet Matthew Arnold published a poem entitled "The Forsaken Merman", in which the merman, the king of the sea, has married an earthly woman. At one point, she is at her spinning wheel when she remembers her former world. The "shuttle falls" from her hand as she decides to leave him. An alert friend – fellow poet Arthur Clough – wrote to Arnold that a shuttle is used in weaving and Arnold surely meant spindle.

Arnold realized Clough was right, insisted his publishers revise the poem, and when it was republished a quarter-century later it read that the "spindle drops" from the woman's hand. While Arnold wrote to Clough that he had a "great poetical interest" in both weaving and spinning, he admitted apologetically that his error was due to a "default of experience".

That flabbergasted me. Arnold writes a poem about a merman and then worries about the difference between a shuttle and a spindle? Furthermore, the person who picked it up was a fellow poet, not a weaver or spinster? Arnold's public seem not to have noticed the error – there is no record of anybody complaining – and only his poet-friend did? More importantly, does any of this really matter?

Love is not a rose – despite what Robert Burns or Neil Young might have claimed. Nor is a man a wolf – despite the ancient Latin proverb. So if it's acceptable to use incorrect metaphors in literature and music, then why not in physics? Are they any less effective? E-mail me your favourite physics metaphors and let me know if they have been empirically tested and why it matters. I'll write about your responses in a future column.

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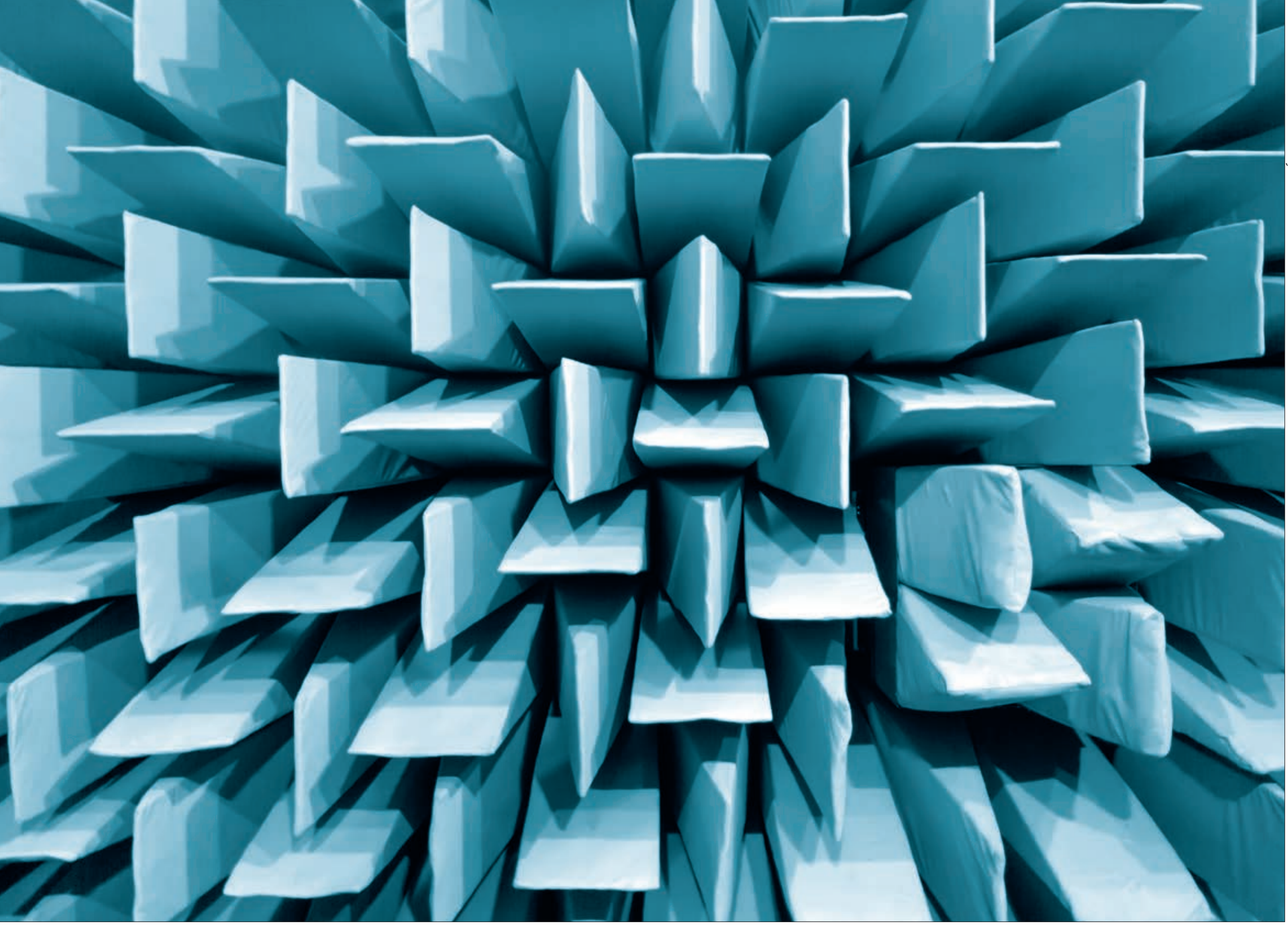
View this e-magazine online to watch Don Lincoln outline an analogy of a large dinner party, a raucous group of physicists, and Peter Higgs himself.

Express yourself Metaphors in physics and literature help us communicate our ideas more effectively, but how accurate do they need to be?.

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)



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Making metamaterials a commercial reality

Metamaterials are fast emerging from the research lab and turning up in real products. **Claire Dancer** and **Alastair Hibbins** tell Matin Durrani how the UK Metamaterials Network is helping to boost research into these fascinating structures and lower the barriers to commercialization

Claire Dancer is an associate professor and a 125th anniversary fellow at the University of Birmingham, UK; **Alastair Hibbins** is a professor and director of the Centre of Metamaterials Research and Innovation at the University of Exeter, UK

Metamaterials are artificial 3D structures that can provide all sorts of properties not available with "normal" materials. Pioneered around a quarter of a century ago by physicists such as John Pendry and David Smith, metamaterials can now be found in a growing number of commercial products.

Claire Dancer and Alastair Hibbins, who are joint leads of the UK Metamaterials Network, recently talked to Matin Durrani about the power and potential of these "meta-atom" structures.

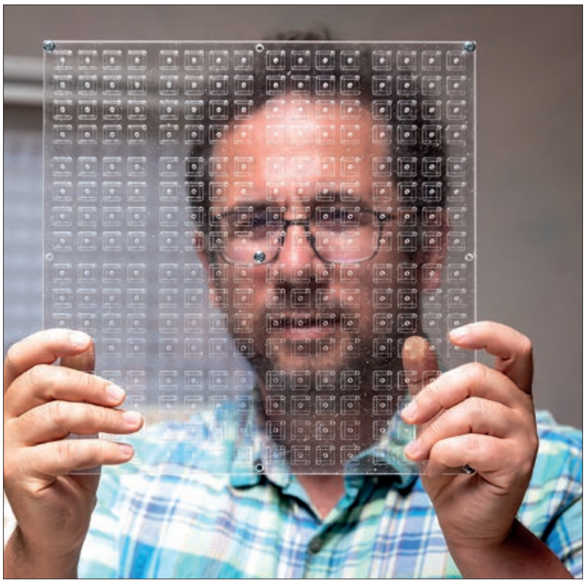
Let's start with the basics: what are metamaterials?

Alastair Hibbins (AH): If you want to describe a metamaterial in just one sentence, it's all about adding functionality through structure. But it's not a brand new concept. Take the stained-glass windows in cathedrals, which have essentially got plasmonic metal nanoparticles embedded in them. The colour of the glass is dictated by the size and the shape of those particles, which is what a metamaterial is all about. It's a material where the properties we see or hear or feel depend on the structure of its building blocks.

Physicists have been at the forefront of much recent work on metamaterials, haven't they?

AH: Yes, the work was reignited just before the turn of the century – in the late 1990s – when the theoretical physicist John Pendry kind of recrystallized this idea (see box "John Pendry: metamaterial pioneer"). Based at Imperial College, London, he and others were looking at artificial materials, such as metallic meshes, which had properties that were really different from the metal of which they were comprised.

Metasonixx Sonoblind Air



Sonic boom A spin-out firm from the universities of Bristol and Sussex, Metasonixx is turning metamaterials into commercial reality as noise-abatement products.

In terms of applications, why are metamaterials so exciting?

Claire Dancer (CD): Materials can do lots of fantastic things, but metamaterials add a new functionality on top. That could be cloaking or it might be mechanically bending and flexing in a way that its constituent materials wouldn't. You can, for example, have "auxetic metamaterials" with a honeycomb structure that gets wider – not thinner – when stretched. There are also nanoscale photonic metamaterials, which interact with light in unusual ways.

What sorts of possible applications can metamaterials have?

CD: There are lots, including some exciting innovations in body armour and protective equipment for sport – imagine customized "auxetic helmets" and protective devices for contact sports like rugby. Metamaterials can also be used in communications, exploiting available frequencies in an efficient, discrete and distinct way. In the optical range, we can create "artificial colour", which is leading to interesting work on different kinds of glitter and decorative substances. There are also loads of applications in acoustics, where metamaterials can absorb some of the incidental noise that plagues our world.

Have any metamaterials reached the commercial market yet?

AH: Yes. The UK firm Sonnobex won a Business Innovation Award from the Institute of Physics (IOP) in 2018 for its metamaterials that can reduce traffic noise or the annoying "buzz" from electrical power transformers. Another British firm – Metasonnix – won an IOP business award last year for its lightweight soundproofing metamaterial panels. They let air pass through so could be great as window blinds – cutting noise and providing ventilation at the same time.

High-end audio manufacturers, such as KEF, are using metamaterials as part of the baffle behind the main loudspeaker. There's also Metahelios, which was spun out from the University of Glasgow in 2022. It's making on-chip, multi-wavelength pixelated cameras that are also polarization-sensitive and could have applications in defence and aerospace.

The UK has a big presence in metamaterials but the US is strong too isn't it?

AH: Perhaps the most famous metamaterial company is Metalenz, which makes flat conformal lenses for mobile phones – enabling amazing optical performance in a compact device. It was spun off in 2021 from the work of Federico Capasso at Harvard University. You can already find its products in Apple and Samsung phones and they're coming to Google's devices too.

Other US companies include Kymeta, which makes metamaterial-based antennas, and Lumotive, which is involved in solid-state LIDAR systems for autonomous vehicles and drones. There's also Echodyne and Pivotal Commware. Those US firms have all received a huge

John Pendry:metamaterial pioneer

Per Henning/NTNU

Deep thinker John Pendry, whose work on negative refraction underpins metamaterials, was awarded the Isaac Newton medal from the Institute of Physics in 2013 and has often been tipped as a potential future Nobel laureate.

Metamaterials are fast becoming commercial reality, but they have their roots in physics – in particular, a landmark paper published in 2000 by theoretical physicist John Pendry at Imperial College, London (*Phys. Rev. Lett.* **85** 3966). In the paper, Pendry described how a metamaterial could be created with a negative index of refraction for microwave radiation, calculating that it could be used to make a "perfect" lens that would focus an image with a resolution not restricted by the wavelength of light (*Physics World* September 2001 pp47–51).

A metamaterial using copper rings deposited on an electronic circuit board was built the following year by the US physicist David Smith and colleagues at the University of California, San Diego (*Science* **292** 77). Pendry later teamed up with Smith and others to use negative-index metamaterials to create a blueprint for an invisibility cloak – the idea being that the metamaterial would guide light around an object to be hidden (*Science* **312** 1780). While the mathematics describing how electromagnetic radiation interacts with metamaterials can be complicated, Pendry realized that it could be described elegantly by borrowing ideas from Einstein's general theory of relativity.

Claire Dancer

Jim Wileman

Commercially minded
As joint leads of the UK Metamaterials Network, Claire Dancer (left) and Alastair Hibbins want to unleash the market potential of these structures.

Metamaterials: the official definition

One of the really big things the UK Metamaterials Network has done is to crowdsource the definition of a metamaterial, which has long been a topic of debate. A metamaterial, we have concluded, is:

> "a 3D structure with a response or function due to collective effects of their building blocks (or meta-atoms) that is not possible to achieve conventionally with any individual constituent material"

A huge amount of work went into this definition. We talked with the community and there was lots of debate about what should be in and what should be out. But I think we've emerged with a really nice definition there that's going to stay in place for many years to come. It might seem a little trivial but it's one of our great achievements.

Alastair Hibbins

amount of start-up and venture funding, and are doing really well at showing how metamaterials can make money and sell products.

What are the aims of the UK Metamaterials Network?

CD: One important aim is to capitalize on all the work done in this country, supporting fundamental discovery science but driving commercialization too. We've been going since 2021 and have grown to a community of about 900 members – largely UK academics but with industry and overseas researchers too. We want to provide outsiders with a single source of access to the community and – as we move towards commercialization – develop ways to standardize and regulate metamaterials.

As well as providing an official definition of metamaterials (see box "Metamaterials: the official definition"), we also have a focus on talent and skills, trying to get the next generation into the field and show them it's a good place to work.

How is the UK Metamaterials Network helping get products onto the market?

CD: The network wants to support the beginning of the commercialization process, namely working with start-ups and getting industry engaged, hopefully with government backing. We've also got various special-interest groups, focusing on the commercial potential of acoustic, microwave and photonics materials. And we've set up four key challenge areas that cut across different areas of metamaterials research: manufacturing; space and aviation; health; and sustainability.

What practical support can you give academics?

CD: The UK Metamaterials Network has been funded by the Engineering and Physical Sciences Research Council to set up a Metamaterials Network Plus programme. It aims to develop more research in these areas so that metamaterials can contribute to national and global priorities by, for example, being sustainable and ensuring we have the infrastructure for testing and manufacturing metamaterials on a large scale. In particular, we now have "pump prime" funding that we can distribute to academics who want to explore new applications of – and other research into – metamaterials.

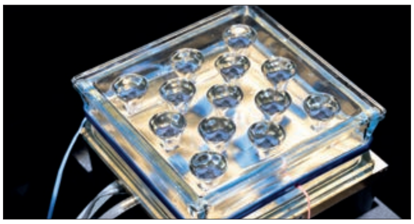
What are the challenges of commercializing metamaterials?

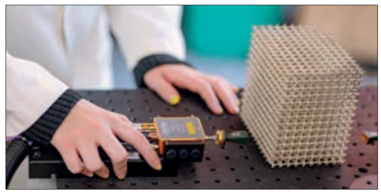
CD: Commercializing any new scientific idea is difficult and metamaterials are no exception. But one issue with metamaterials is to ensure industry can manufacture them in big volumes. Currently, a lot of metamaterials are made in research labs by 3D printing or by manually sticking and gluing things together, which is fine if you just want to prove some interesting physics. But to make metamaterials in industry, we need techniques that are scalable – and that, in turn, requires resources, funding, infrastructure and a supply of talented, skilled workers. The intellectual property also needs to be carefully managed as much of the underlying work is done in collaborations with universities. If there are too many barriers, companies will give up and not bother trying.

Looking ahead, where do you think metamaterials will be a decade from now?

AH: If we really want to fulfil their potential, we'd ideally fund metamaterials as a national UK programme, just as we do with quantum technology. Defence has been one of the leaders in funding metamaterials because of their use in communications, but we want industry more widely to adopt metamaterials, embedding them in everyday devices. They offer game-changing control and I can see metamaterials in healthcare, such as for artificial limbs or medical imaging. Metamaterials could also provide alternatives in the energy sector, where we want to reduce the use of rare-earth and other minerals. In space and aerospace, they could function as incredibly lightweight, but really strong, blast-resistant materials for satellites and satellite communications, developing more capacity to send information around the world.

We want industry more widely to adopt metamaterials, embedding them in everyday devices


View this e-magazine online to watch a video of KEF's Metamaterial Absorption Technology (MAT).


View this e-magazine online to watch a video about Polar ID, which uses meta-optic capability to enable the next level of biometric security.


This video shows how the University of Exeter has used metamaterials to slow, stop or redirect incoming sound or vibration waves.

All images: Centre for Metamaterials Research and Innovation

How are you working with the IOP to promote metamaterials?

AH: The IOP has an ongoing programme of "impact projects", informed by the physics community in the UK and Ireland. Having already covered semiconductors, quantum tech and the green economy through such projects, the IOP is now collaborating with the UK Metamaterials Network on a "pathfinder" impact project. It will examine the commercialization and exploitation of metamaterials in ICT, sustainability, health, defence and security.

Have you been able to interact with the research community?

CD: We've so far run three annual industry events showcasing the applications of metamaterials. The first two were at the National Physical Laboratory in Teddington, and in Leeds, with last year's held at the IOP in December. It included a panel discussion about how to overcome barriers to commercialization along with demonstrations of various technologies, and presentations from academics and industrialists about their innovations. We also discussed the pathfinder project with the IOP as we'll need the community's help to exploit the power of metamaterials.

What's the future of the UK Metamaterials Network?

AH: It's an exciting year ahead working with the IOP and we want to involve as many new sectors as possible. We're also likely to hit a thousand members of our network: we'll have a little celebration when we reach that milestone. We'll be running a 2025 showcase event as well so there's a lot to look forward to. ■

● This article is an edited version of an interview on the *Physics World Weekly* podcast of 5 December 2024

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

Access all areas
Metamaterials have applications in everything from energy (left) to acoustics (centre) while also offering plenty of fundamental challenges (right).

When Bohr got it wrong

INTERNATIONAL YEAR OF
Quantum Science
and Technology

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

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

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

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

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

Genesis of a crisis

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

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

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

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

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

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

Reckless and radical

One of the most vexing question for Bohr and his Copenhagen circle in the early 1920s was how to think about electron orbits in atoms. Try as they might, they couldn't find a way to make the orbits "fit" with experimental

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

Sam Falconer, Debut Art/Science Photo Library

Paul Ehrenfest/Wikimedia Commons

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

Wikimedia Commons

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

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

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

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

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

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

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

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

Go where the waves take you

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

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

Emilio Segrè Visual Archives General Collection/MIT News Office

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

IPP/© Archives of the Max Planck Society

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

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

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

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

Causality and conservation, abandoned

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

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

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

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

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

Shutterstock/Vink Fan

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

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

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

Revolutionary defeat… singularly important

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

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

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

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

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

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

Failed connections

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

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

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

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

Opening doors with outreach

iStock/Anna Stills

Physics outreach builds vital links between scientists and the public, but it can be hard to know where to start. In this demystifying guide, Melanie Gardner and Clare Harvey from The Ogden Trust explain how to plan and deliver effective outreach activities with your available time and resources

Melanie Gardner is the communications manager and **Clare Harvey** is the chief executive for The Ogden Trust

Physics takes us from the far reaches of the universe to the subatomic scale. A passion for physics also takes us further than we imagined possible, building skills that set us up for life, no matter what path we follow in our careers.

If you're a physicist or physics professional, your drive for the subject is invaluable. By sharing your passion, you show others how far physics could take them. It can be intimidating, but outreach is vital for nurturing the next generation of physicists, promoting public understanding of science and building a skilled physics community.

Outreach is also an important part of the mission of The Ogden Trust – a UK-based charitable organization that promotes the teaching and learning of physics. The trust has been supporting university physics outreach since 2005, with nearly all universities in England that offer physics undergraduate degrees – and several in Scotland and Wales too – having worked with the trust.

As well as providing funding for public engagement and outreach initiatives, the trust also supports universities through the Outreach Officer Network and annual Outreach Awards. So as a physicist, how can you get involved in outreach? Here are some tips and case studies to inspire you along your journey.

Starting out strong

Just as collaboration and shared tools are vital for physics research, there is also a wealth of support that physicists interested in outreach can draw on. No matter how ambitious your idea is, remember that others have been in your position before. Accessing shared resources and training will make starting out much easier (see box "The Physics Mentoring Project" on p32).

You could begin by signing up for The Interact Symposium, a biennial event for physical scientists seeking to gain new skills and share their experiences of public engagement. Run by the Science and Technology

The Institute of Cosmology and Gravitation

Glenn Harris, 2019

Coleman Krawczyk, 2023

A feel for cosmology Students using 3D models of galaxies as part of the Tactile Universe outreach programme, which delivers events and resources to engage the visually impaired community with astronomy.

In 2017 the Institute of Cosmology and Gravitation (ICG) at the University of Portsmouth, UK, introduced an outreach and public engagement strategy, which has since guided significant changes in Portsmouth. The strategy was a short, easy-to-use resource, intended as a working document that could be updated if needed. It outlined outreach and engagement goals over a five-year period, with budget and staffing allocated accordingly.

A crucial part of the process involved consulting people across the department, particularly the ICG directors and those doing innovation and impact work, as well as external supporters of the department's outreach and public engagement. Since the strategy was introduced, the department has created a new school outreach programme focusing on a small number of schools where the need for outreach is greatest. The ICG has also invested significantly in Tactile Universe, a project that engages visually impaired school pupils with astronomy research (see pictures).

Thanks to this new approach, outreach and public engagement have become firmly embedded in the ICG. An updated OPE strategy was introduced in 2022.

Facilities Council (STFC), the Institute of Physics (IOP), The Ogden Trust, the Royal Astronomical Society and the South East Physics Network (SEPnet), a bank of resources from the 2024 symposium is available online, including lots of examples of successful projects.

Meanwhile, many departments in universities, schools and workplaces have a specialist outreach co-ordinator whose experience you could tap into. If there isn't, you might have a more experienced colleague who can advise you and share community or school links. You could also contact your local IOP branch committee or join the IOP's Physics Communicators Group.

As with any scientific endeavour, it's important to do your research. Attending local science festivals and community events will give you great ideas and inspiration. One day, they may even provide an opportunity to deliver your own outreach.

Strategic thinking

So, you've tried outreach for the first time and are eager to do more. It's tempting to jump straight in. But before making any big commitments, it is worth making a long-term strategic plan.

Your department might have an engagement-specific strategy or other priorities that could be linked to your activities. If there is a dedicated outreach or public engagement professional in your organization, they can advise on this. If your workplace doesn't have a strategy for outreach and engagement, you could advocate for one to be written (see the box "The Institute of Cosmology and Gravitation").

In the UK, the quality of research in higher-education institutions is assessed by the Research Excellence Framework (REF), the results of which informs research funding allocations. Part of the exercise considers the impact of research on people, culture and environment. In REF 2021 around half the impact case studies submitted featured outreach and engagement activities.

In 2021 The Ogden Trust released the *Taking a Strategic Approach to Outreach* guide. In partnership with the STFC, the trust also funds an annual leadership training course for outreach and public engagement which equips academics and teaching staff with the skills to plan and deliver effective outreach.

At this point, you should also consider whether you have all the resources you need. It is often possible to deliver activities with equipment from your institution but, as you do more, the cost of travel, time and equipment can add up. You may be able to fund activities from your existing budgets, particularly if they are closely related to your work. However, you may also need to consider external funding opportunities.

Engagement funding is available through a number of organizations. For example, the STFC has created the Spark awards (£1000–£15 000), Nucleus awards (£15 000–£125 000) and other grants to engage the public with STFC science. The IOP public-engagement grant scheme awards £500–£4000 to improve young people's relationship with physics. The Royal Academy of Engineering, meanwhile, has its Ingenious grant scheme, which offers funding of £3000–£30 000 for projects that engage under-represented audiences.

Remember that while one-off outreach activities can spark your audience's interest, building long-term

Orbyts

Orbyts

Out of this world Students participating in the Orbyts outreach programme, where universities partner with schools on research projects.

Orbyts links university researchers with pupils in some of the most deprived areas of the UK, empowering them to do original research. Projects last a minimum of five months and involve regular meetings between pupils and researchers. Orbyts projects currently run in three universities across England and received funding from The Ogden Trust to scale their approach.

So far, Orbyts has created over 100 partnerships between researchers and schools, enabling more than 1500 school students to undertake research projects. Topics have included life in the universe, black holes, quantum computing and cancer. Here are some comments from those involved.

"In a tough year with significant professional challenges to overcome, this has been a real 'get me out of bed in the morning' kind of project."
Orbyts partner teacher

"The high-level provision offered by the Orbyts researchers raised enthusiasm and interest in STEM disciplines among our students. The researchers introduced our students to Python programming, as well as analysis and interpretation techniques of large data sets, skills that are of fundamental importance at research level in all areas of physics and STEM. Several of the female students taking part in Orbyts decided to apply to physics at university. They were inspired by the content and the overall experience, as well as by the high-calibre female researchers from Orbyts who visited our school every week for several months and acted as role models for them. Most of the students who took part in 2021/22 are now studying physics, engineering or material science at universities. Their participation in Orbyts was pivotal in making informed decisions about their academic future."
Physics and maths teacher, Newham Collegiate Sixth Form, UK

"I've been fortunate enough to have been a part of Orbyts for the last two years. It has helped me gain invaluable skills and develop as a researcher in more ways than I ever expected. Orbyts has enabled me to gain confidence and ownership in my research, as well as providing opportunities to project manage and improve my public speaking and teaching skills in a proactive yet fun way. Working with students on an Orbyts project has been one of the most rewarding experiences of my research career. It has been incredible to see the students become more confident in their work and become enthusiastic researchers themselves across the short 14-week programme."
Shannon Killey, space physics PhD student, Northumbria University

The Physics Mentoring Project

Set up in 2019, the Physics Mentoring Project is a collaboration across Wales – led by Cardiff University – that mentors school students, encouraging them to continue studying physics. It has so far delivered more than 7000 hours of mentoring in 36% of all secondary schools in the country.

Students at any of the eight participating universities who have a post-16 qualification in a physical science can sign up as a mentor. All receive a weekend of intense interactive training that covers mentoring theory, relationship building, and session planning, as well as safeguarding and health and safety.

Now in its seventh year, the project has developed into an active network. Mentors have access to an online community with peers and the project team. There are also "lead mentors" who give extra support to a small group of mentors (both new and experienced).

"[My] confidence in public speaking and the confidence in articulating points has come on leaps and bounds," reported one mentor on the project. "Mentoring helped me understand a bit more about what teaching will be like," added another.

Originally aimed at 15 and 16-year-olds, the project also mentors 17–18-year-olds doing A-levels and focuses on alternative routes into physics. Optionally, mentors can even take a Level 4 Unit in Increasing Engagement with Physics Through Mentoring, accredited by Agored Cymru as part of the Credit and Qualifications Framework for Wales.

The Physics Mentoring Project won an Ogden Outreach Award in 2022 for "supporting undergraduate ambassadors".

partnerships is often more effective. Outreach work with schools is ideally suited for this kind of approach – in fact, regular interactions with a school can tackle systemic inequalities in UK STEM education (see box "Orbyts").

You should also think about your target audience. A lot of physics engagement takes place in schools but partnerships with community organizations can reach those who may not attend science festivals or talks. There may be an increased willingness to engage in physics outside of the classroom, where it can capture the imagination of young people who find a school environment challenging (see box "My Place, My Science").

Steps to success

As with any activity in which you are investing your time and energy, it is important to know whether you are achieving your outreach goals. Having a clear strategy will give you a clear idea of what success looks like, but effective evaluation should also be built into your project from the start.

This will also be valuable if you have to justify the time and money spent on a project or make funding applications. The STFC has a useful public engagement evaluation framework that you can follow. The Ogden Trust has also published an evaluation toolkit for working with young people that uses the science capital framework.

Bear in mind that evaluation doesn't always mean surveys and quantitative data. You might instead get verbal feedback from participants or ask someone else to observe you. In a university, you could consult colleagues in education or social-science departments who are familiar with such methodologies. For larger projects or those

Katka Photography, 2022

Crossing divides University outreach officers at a meeting of The Ogden Trust's Outreach Officer Network. The network provides an opportunity for outreach professionals to share good practice.

for REF or business cases, you could turn to an external evaluator to provide an independent perspective.

Physicists know that their subject impacts everything from space exploration to sustainable technology, but unfortunately many people don't think physics is for them. Young people from disadvantaged backgrounds, in particular, struggle to see themselves as future physicists. Outreach can make a real difference by showing that you don't need to belong to a specific group or demographic to be a physicist – all you need is a passion for the subject.

My Place, My Science

My Place, My Science is an initiative to support young people of African and Black Caribbean heritage in the UK to enjoy science and build cultural connections. It is a partnership between the physics, rheumatology and biochemistry departments at the University of Oxford, the History of Science Museum and the community organization African Families in the UK (AFiUK).

Launched in 2023, My Place, My Science has delivered a programme of activities where participants learn about topics including stargazing, magnets and sickle cell disease. It was also the winner of the Ogden Outreach Award for Engaging Communities in 2024.

"AFiUK has a deep understanding of local needs, priorities, and challenges," says Sian Tedaldi, outreach programmes manager in Oxford's physics department. "This understanding continues to shape and inform the development of the project. They have provided a familiar and trusted organization for participants, leading to greater participation and impact."

"I have developed a toolkit of interactive activities to engage audiences with planetary research. I have been able to reach thousands of young people, families and adults through my work and have engaged with traditionally under-represented groups within physics, such as girls and children from disadvantaged backgrounds. I love talking to young people about space and the opportunity to speak with the enthusiastic and curious AFiUK community has been incredibly rewarding."

Katherine Shirley, planetary-physics postdoc at the University of Oxford

● For more information about The Ogden Trust or to sign up for its Physics Outreach Network newsletter, visit its website or e-mail outreach@ogdentrust.com.

Reviews

James Gillies discusses how his team handled unprecedented global interest in the Large Hadron Collider (LHC) and the hunt for the Higgs boson

Unclear nature

Achintya Rao reviews *Unfinished Nature: Particle Physics at CERN* by Arpita Roy

CERN

History-making Scientists at CERN celebrate the announcement of the discovery of the Higgs boson in 2012.

Unfinished Nature: Particle Physics at CERN
Arpita Roy
2024 Columbia University Press
296pp £30.00

When I was asked to review *Unfinished Nature: Particle Physics at CERN*, a new ethnography of CERN by Arpita Roy, an anthropologist at the University of California Berkeley, US, I was excited. Having recently completed a PhD in science communication where I studied the researchers at CERN – albeit from a very different, quantitative-heavy, perspective – the subject is close to my heart.

Roy spent two-and-a-half years doing fieldwork at CERN, around the time of the discovery of the Higgs boson in 2012. The book examines this event through an anthropological lens, asking questions such as how are scientific advances made and how do scientists understand their work? Unfortunately, although I read many books and papers of a similar nature for my doctoral studies, I struggled with *Unfinished Nature*.

A good book makes you pause to reflect. You may find yourself enlightened by the author's perspectives or disagree with their arguments, but comprehension is key in either case. A book that has you stumbling through the pages without clarity, re-reading sentences over and over again in an effort to make sense of them, is frustrating. I may lack the expertise to appreciate the finer points of the subject, but I struggled despite repeated, earnest attempts to read the book with the care and attention the topic deserves.

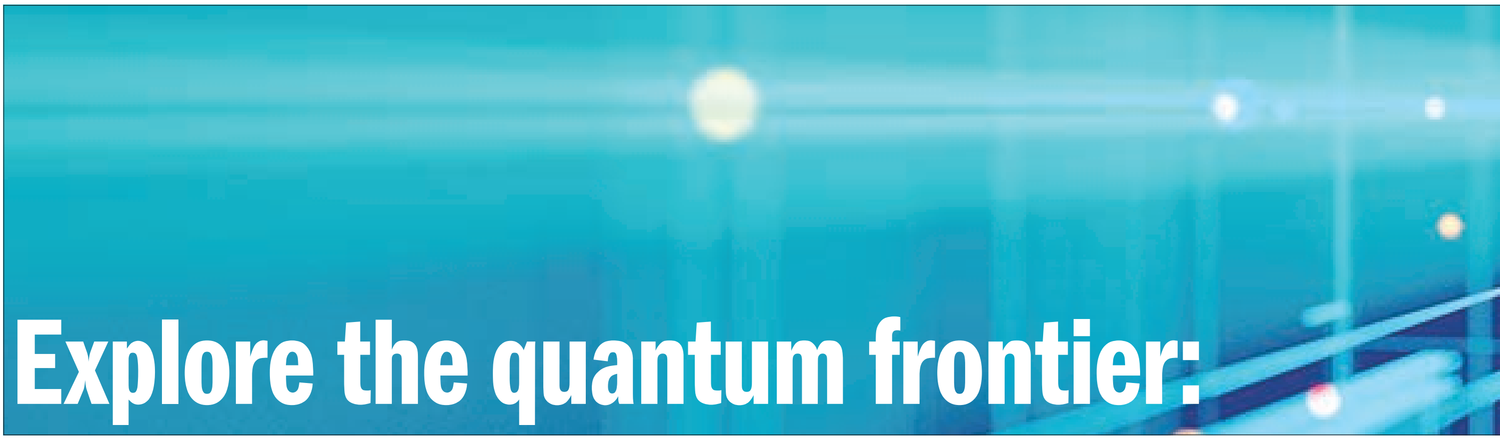
Take the following snippet from the first page of the introduction, which sets the tone for what is to come: "But what has been lost to sight is the elucidation of how a science like particle physics may incorporate elements into its domain beyond what its epistemic assumption would lead us to expect, which deepens the mystery of what logic of classification it obeys. It is far from easy, however, to explicate the notion of classification, if only for the reason that it engenders notions of system, category, or context whose lucidity is hard to pinpoint in the scientific realm." While I eventually understood (or at least think I did) what Roy is trying to say, the phrasing is unnecessarily convoluted.

None of this is criticism of Roy as a researcher but reflects the seemingly intentionally confusing language that academics – and my fellow social scientists in particular – are expected to use, despite increased calls to make research more accessible to those without specialist knowledge.

The ideas and stories Roy covers are no doubt interesting, even if the book itself isn't an easy read. *Unfinished Nature* is more suited to the invested social scientist familiar with the particular flavour of academic prose adopted by anthropologists than physicists or physics enthusiasts indulging a more superficial interest in the lives of researchers at CERN.

Achintya Rao is a science communicator based in Bristol, UK

Careers



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

INTERNATIONAL YEAR OF
Quantum Science
and Technology

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

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

Now, a century later, we are on the cusp of a second quantum revolution, with quantum science and technologies growing rapidly across the globe. According to the *State of Quantum 2024* report, a total of 33 countries around the world currently have government initiatives in quantum technology, of which more than 20 have national strategies with large-scale funding. The report estimates that up to $50bn in public cash has already been committed.

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

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

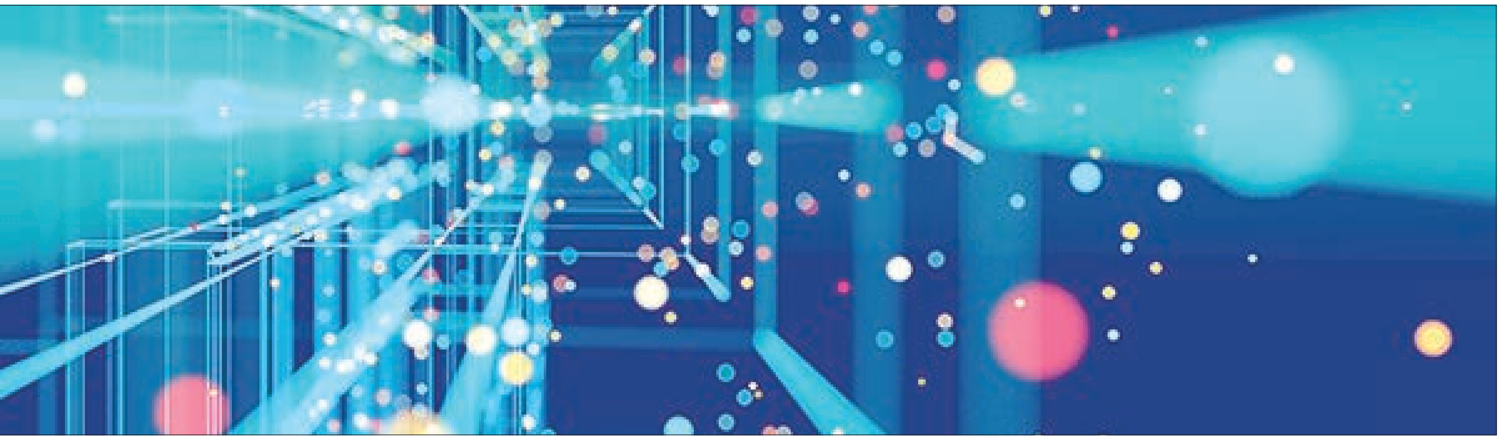
"IYQ provides the opportunity for societies and organizations around the world to come together in marking both the 100-year history of the field, as well as the longer-term real-world impact that quantum science is certain to have for decades to come," says Tim Smith, head of portfolio development at IOP Publishing. "Quantum science and technology represents one of the most exciting and rapidly developing areas of science today, encompassing the global physical-sciences community in a way that connects scientific wonder with fundamental research, technological innovation, industry, and funding programmes worldwide."

Taking shape

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

In late February, meanwhile, the Royal Society – the world's oldest continuously active learned society – will host a two-day quantum conference. Dubbed "Quantum Information", it will bring together scientists, industry leaders and public-sector stakeholders to discuss the current challenges involved in quantum computing, networks and sensing systems.

In Scotland, the annual Edinburgh Science Festival , which takes place in April, will include a special "quantum explorers" exhibit and workshop by the UK's newly launched National Quantum Computing Centre. Elsewhere, the Quantum Software Lab at the School of Informatics at



iStock/piranka

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

In June, the Institution of Engineering and Technology is hosting a Quantum Engineering and Technologies conference, as part of its newly launched Quantum technologies and 6G and Future Networks events. The event's themes include everything from information processing and memories to photon sources and cryptography.

Further IYQ-themed events will take place at QuAMP, the IOP's biennial international conference on quantum, atomic and molecular physics in September. Activities culminate in a three-part celebration in November, with a quantum community event led by the IOP's History of Physics and quantum Business and Innovation Growth (qBIG) special interest groups, a schools event at the Royal Institution, and a public celebration with a keynote speech from University of Surrey quantum physicist and broadcaster Jim Al-Khalili. "The UK and Ireland already have a globally important position in many areas of quantum research, with the UK, for instance, having established one of the world's first National Quantum Technology Programmes," explains Grinyer. "We will also be using the focus this year gives us to continue to make the case for the investment in research and development, and support for physics skills, which will be crucial if we are to fully unlock the economic and social potential of what is both a fascinating area of research, and a fast growing physics-powered business sector," he adds.

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

Quantum careers

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

If you plan to join the quantum workforce, then choosing the right PhD programme, having the right skills for a specific role and managing risk and reward in the emerging quantum industry are all crucial. There are a number of careers events on the IYQ calendar, to learn more about the many career prospects for physicists in the sector. In April, for example, the University of Bristol's Quantum Engineering Centre for Doctoral Training is hosting a Careers in Quantum event, while the *Economist* magazine is hosting its annual Commercialising Quantum conference in May.

There will also be a special quantum careers panel discussion, including top speakers from the UK and the US, as part of our newly launched Physics World Live panel discussions in April. This year's *Physics World Careers 2025* guide has a special quantum focus, and there'll also be a bumper, quantum-themed issue of the *Physics World Briefing* in June. The *Physics World* quantum channel (physicsworld.com/quantum) will be regularly updated throughout the year so you don't miss a thing.

Read all about it

IOP Publishing's journals will include specially curated content – from a series of Perspectives articles – personal viewpoints from leading quantum scientists – in *Quantum Science and Technology*. The journal will also be publishing roadmaps in quantum computing, sensing and communication, as well as focus issues on topics such as quantum machine learning and technologies for quantum gravity and thermodynamics in quantum coherent platforms.

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

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

Tushna Commissariat is a features editor of *Physics World*

Ask me anything: Nadya Mason

Nadya Mason is dean of the Pritzker School of Molecular Engineering (UChicago PME) at the University of Chicago, US, where her research into quantum materials focuses on the electronic properties of nanoscale and correlated systems, including nanoscale wires, atomically thin membranes and nanostructured superconductors. Elected to both the National Academy of Sciences and the American Academy of Arts and Sciences in 2021, she also received the American Physical Society's Edward A Bouchet Award in 2020, which recognizes distinguished physicists from underrepresented communities who have made significant contributions to physics research and to the advancement of minority scientists

UChicago Pritzker School of Molecular Engineering/Jason Smith

What skills do you use every day in your job?

Right now, I spend 95% of my time being a dean, and in that job the skill I use every day is problem-solving. That's one of the first things we learn as physicists: it's not enough just to know the technical background, you have to be able to apply it. I find myself looking at everything as systems of equations – this person wants this, this thing needs to go there, we need money to do that thing – and thinking about how to put them together. We do a really good job in physics of teaching people how to think, so they can take a broad look at things and make them work.

What do you like best and least about your job?

The thing I like best is the opportunity to have a wide impact, not just on the faculty who are doing amazing research, but also on students – our next generation of scientific leaders – and people in the wider community. We do a lot of public service outreach at UChicago PME. Outreach has had a big impact on me so it's incredibly satisfying that, as dean, I can provide those opportunities at various levels for others.

The thing I like least is that because we have so much to do, figuring out who can do what, and how – within what are always limited resources – often feels like trying to solve a giant jigsaw puzzle. Half the time, it feels like the puzzle board is bigger than the number of pieces, so I'm figuring out how to make things work in ways that sometimes stretch people thin, which can be very frustrating for everybody. We all want to do the best job we can, but we need to understand that we sometimes have limits.

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

I feel a little guilty saying this because I'm going to label myself as a true "in the lab" scientist, but I wish I'd known how much relationships matter. Early on, when I was a junior faculty member, I was focused on research; focused on training my students; focused on just getting the work done. But it didn't take long for me to realize that of course, students aren't just workers. They are twenty-somethings with lives and aspirations and goals.

Thankfully, I figured that out pretty quickly, but at every step along the way, as I try to focus on the problem to solve, I have to remind myself that people aren't problems. People are people, and you have to work with them to solve problems in ways that work for everybody. I sometimes wish there was more personnel training for faculty, rather than a narrow focus on papers and products, because it really is about people at the end of the day.

Outreach has had a big impact on me so it's incredibly satisfying that, as dean, I can provide those opportunities at various levels for others

‘Why do we have to learn this?’

In his years as a physics teacher, students often asked **Mark Whalley** why they had to learn the subject when most of them would never directly use it in their careers. Having never been satisfied with the answers he gave, he here sets out the case for learning physics, even for students who don’t pursue the subject further

Several years ago I was sitting at the back of a classroom supporting a newly qualified science teacher. The lesson was going well, a pretty standard class on Hooke’s law, when a student leaned over to me and asked “Why are we doing this? What’s the point?”

Having taught myself, this was a question I had been asked many times before. I suspect that when I was a teacher, I went for the knee-jerk “it’s useful if you want to be an engineer” response, or something similar. This isn’t a very satisfying answer, but I never really had the time to formulate a real justification for studying Hooke’s law, or physics in general for that matter.

Who is the physics curriculum designed for? Should it be designed for the small number of students who will pursue the subject, or subjects allied to it, at the post-16 and post-18 level? Or should we be reflecting on the needs of the overwhelming majority who will never use most of the curriculum content again? Only about 10% of students pursue physics or physics-rich subjects post-16 in England, and at degree level, only around 4000 students graduate with physics degrees in the UK each year.

One argument often levelled at me is that learning this is “useful”, to which I retort – in a similar vein to the student from the first paragraph – “In what way?” In the 40 years or so since first learning Hooke’s law, I can’t remember ever explicitly using it in my everyday life, despite being a physicist. Whenever I give a talk on this subject, someone often pipes up with a tenuous example, but I suspect they are in the minority. An audience member once said they consider the elastic behaviour of wire when hanging pictures, but I suspect that many thousands of pictures have been successfully hung with no recourse to $F = -kx$.

Hooke’s law is incredibly important in engineering but, again, most students will not become engineers or rely on a knowledge of the properties of springs, unless they get themselves a job in a mattress factory.

Looking to the future

From a personal perspective, Hooke’s law fascinates me. I find it remarkable that we can see the macroscopic properties of materials being governed by microscopic interactions and that this can be expressed in a simple linear form. There is no utilitarianism in this, simply awe, wonder and aesthetics. I would always share this “joy of physics” with my students, and it was incredibly rewarding when this was reciprocated. But for many, if not most, my personal perspective was largely irrelevant, and they knew that the curriculum content would not directly support them in their future careers.

At this point, I should declare my position – I don’t think we should take Hooke’s law, or physics, off the curriculum, but my reason is not the one often given to students.

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Stretch yourself Have you ever used Hooke’s law in your everyday life? Maybe not, but a physics education nevertheless builds valuable skills that set students up for life.

A series of lessons on Hooke’s law is likely to include: experimental design; setting up and using equipment; collecting numerical data using a range of devices; recording and presenting data, including graphs; interpreting data; modelling data and testing theories; devising evidence-based explanations; communicating ideas; evaluating procedures; critically appraising data; collaborating with others; and working safely.

Science education must be about preparing young people to be active and critical members of a democracy, equipped with the skills and confidence to engage with complex arguments that will shape their lives. For most students, this is the most valuable lesson they will take away from Hooke’s law. We should encourage students to find our subject fascinating and relevant, and in doing so make them receptive to the acquisition of scientific knowledge throughout their lives.

At a time when pressures on the education system are greater than ever, we must be able to articulate and justify our position within a crowded curriculum. I don’t believe that students should simply accept that they should learn something because it is on a specification. But they do deserve a coherent reason that relates to their lives and their careers. As science educators, we owe it to our students to have an authentic justification for what we are asking them to do. As physicists, even those who don’t have to field tricky questions from bored teenagers, I think it’s worthwhile for all of us to ask ourselves how we would answer the question “What is the point of this?”

Mark Whalley is a senior lecturer in educational leadership at the University of Chester. He is also a former physics teacher, school leader, and Institute of Physics manager


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