physicsworld

January 2026

Forgotten heroes Celebrating the pioneers of computational physics

Business decision When is good enough really "good enough"?

Sensitive approach How UK start-up Crainio is tackling brain injury

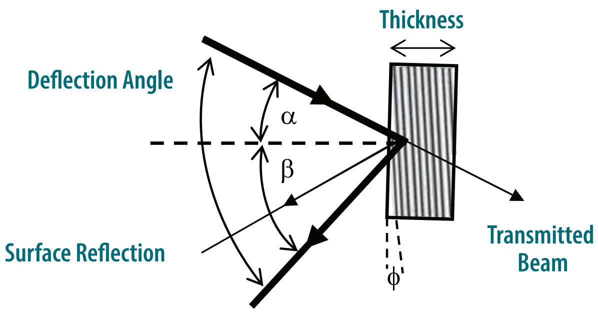
Cosmic dawn

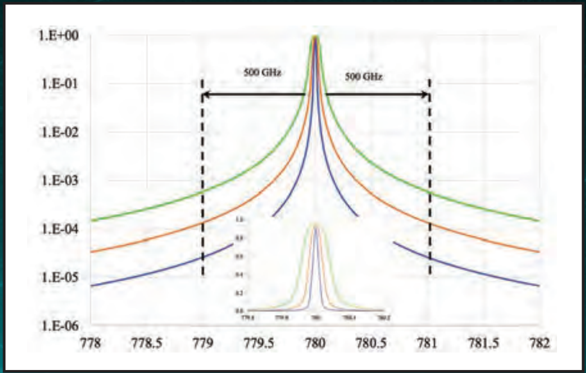
Seeking the elusive signal from the earliest atoms

Volume Bragg Gratings (VBGs) for
Quantum Optics

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

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

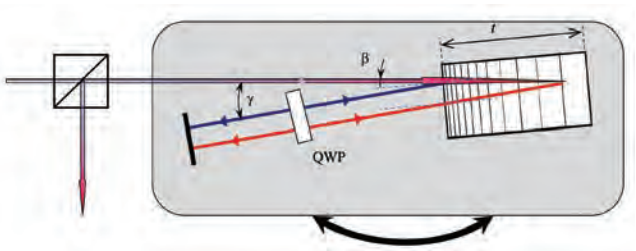




Spectral Shape of Reflecting VBG Filters with Bandwidth:
10 GHz; 25 GHz and 50 GHz

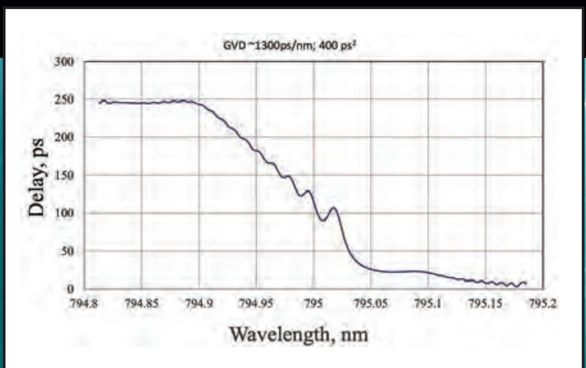
Chirped Bragg Gratings (CBGs) for
Qubit Control

Extremely Large Dispersion 800 ps² enables effective and fast amplitude modulation
Spectral Range: 530-2500 nm; High Efficiency> 95%; Wavelength Tunable



Schematic Diagram of CBG deployment for Qubit Filtering and Control

Group delay dispersion of Chirped Bragg grating (CBG)



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

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

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Cover image
Seeking the elusive signal from the earliest atoms 28 (Raul Monsalve)

News & Analysis

JUNO neutrino observatory complete

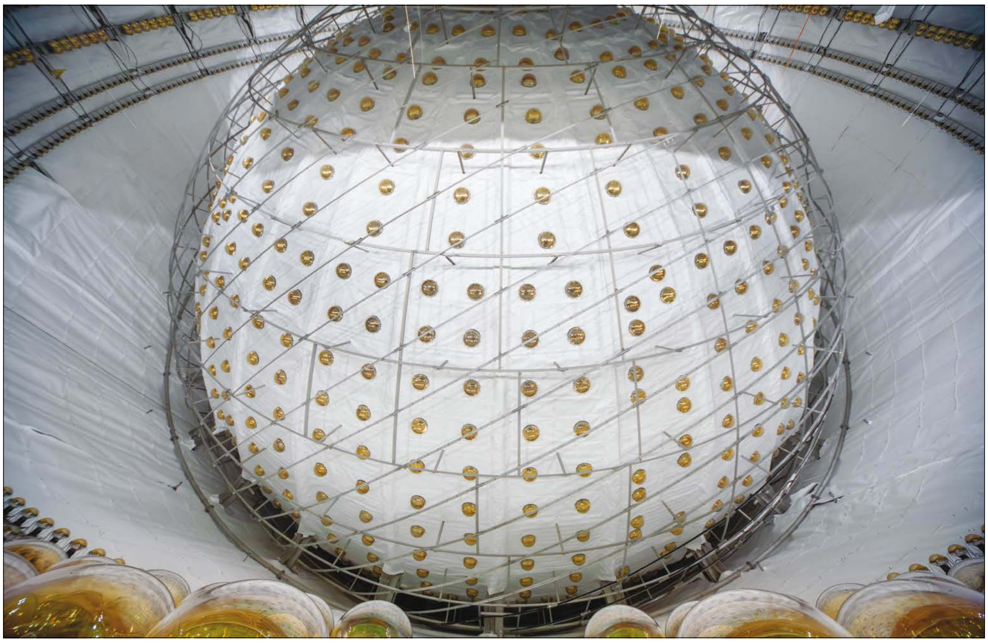
Scientists are celebrating the first results from China's huge JUNO underground facility, which will aim to probe the relationship between the three types of known neutrino, as **Michael Banks** reports

The $330m Jiangmen Underground Neutrino Observatory (JUNO) has released its first results following the completion of the huge underground facility in August. On 18 November 2025 a paper was submitted to the arXiv preprint server concluding that the detector's key performance indicators fully meet or surpass design expectations (arXiv:2511.14590).

JUNO is located in Kaiping City, Guangdong Province, in the south of the country around 150 km west of Hong Kong. Construction of the facility began in 2015 and was set to be complete some five years later. But the project suffered from serious flooding, which delayed construction.

JUNO, which is expected to run for more than 30 years, aims to study the relationship between the three types of neutrino: electron, muon and tau. Although JUNO will be able to detect neutrinos produced by supernovae as well as those from Earth, the observatory will mainly measure the energy spectrum of electron antineutrinos released by the Yangjiang and Taishan nuclear power plants, which both lie about 50 km away.

To do this, the facility has an 80 m high and 50 m diameter experimental hall located 700 m underground. Its main feature is a 35 m radius spherical neutrino detector, containing 20 000 tonnes of liquid scintillator. When an electron antineutrino occasionally bumps into a proton in the liquid, it triggers a reaction that results in two flashes of light. They are detected by the 43 000 photomultiplier tubes that observe the scintillator.



JUNO Collaboration

Next-generation success
The Jiangmen Underground Neutrino Observatory features a 35 m radius spherical neutrino detector, containing 20 000 tonnes of liquid scintillator.

New measurement

Neutrinos oscillate from one flavour to another as they travel near the speed of light, rarely interacting with matter. This oscillation is a result of each flavour being a combination of three neutrino mass states. Scientists do not know the absolute masses of the three neutrinos but can measure neutrino oscillation parameters, known as θ_{12}, θ_{23} and θ_{13}, as well as the square of the mass differences (Δm^2) between two different types of neutrinos.

A second JUNO paper submitted on 18 November used data collected between 26 August and 2 November to measure the solar neutrino oscillation parameter θ_{12} and Δm^2_{21} with a factor of 1.6 better precision than previous experiments (arXiv: 2511.14593). Those earlier results, which used solar neutrinos instead of reactor antineutrinos, showed a 1.5 "sigma" discrepancy with the Standard Model of particle physics. The new JUNO measurements confirmed this difference, dubbed the solar neutrino tension, but further data will be needed to prove or disprove the finding.

"Achieving such precision within only two months of operation shows that JUNO is performing exactly as designed," says Yifang Wang from the Institute of High Energy Physics of the Chinese Academy of Sciences, who is JUNO project manager and spokesperson. "With this level of accuracy, JUNO will soon determine the neutrino mass ordering, test the three-flavour oscillation framework, and search for new physics beyond it."

JUNO, which is an international collaboration of more than 700 scientists from 75 institutions across 17 countries including China, France, Germany, Italy, Russia, Thailand and the US, is the second neutrino experiment in China, after the Daya Bay Reactor Neutrino Experiment. It successfully measured the key neutrino oscillation parameter θ_{13} in 2012 before being closed down in 2020.

JUNO is also one of three next-generation neutrino experiments, the other two being the Hyper-Kamiokande in Japan and the Deep Underground Neutrino Experiment in the US. Both are expected to become operational later this decade.

Michael Banks is news editor of *Physics World*

Awards

IOP celebrates 2025 Business Award winners

A total of 14 physics-based firms in sectors from quantum and energy to healthcare and aerospace have won 2025 Business Awards from the Institute of Physics (IOP). The awards were presented at a reception in the Palace of Westminster last month attended by senior parliamentarians and policymakers as well as investors, funders and industry leaders.

The IOP Business Awards, which have been running since 2012, recognize the role that physics and physicists play in the economy, creating jobs and growth "by powering innovation to meet the challenges facing us today, ranging from climate change to better healthcare and food production". More than 100 firms have now won Business Awards, with around 90% of those companies still commercially active.

Seven firms were awarded 2025 IOP Business Innovation Awards, which recognize companies that have "delivered significant economic and/or societal impact through the application of physics". They include Oxford-based Tokamak Energy, which has developed "compact, powerful, robust, quench-resilient" high-temperature superconducting magnets for commercial fusion energy and for propulsion systems, accelerators and scientific instruments.

Carmen Valino

Spotlight on innovation Tom Grinyer, chief executive officer of the Institute of Physics, welcomes attendees to a reception in the Palace of Westminster to mark the 2025 IOP Business Awards.

Oxford Instruments was honoured for developing a novel analytical technique for scanning electron microscopes, enabling new capabilities and accelerating time to results by at least an order of magnitude. Ionoptika, meanwhile, was recognized for developing Q-One, which is a new generation of focused ion-beam instrumentation, providing single atom through to high-dose nanoscale advanced materials engineering for photonic and quantum technologies. The other four winners were FlexEnable, Lynkeos Technology, Sunamp and Thales UK.

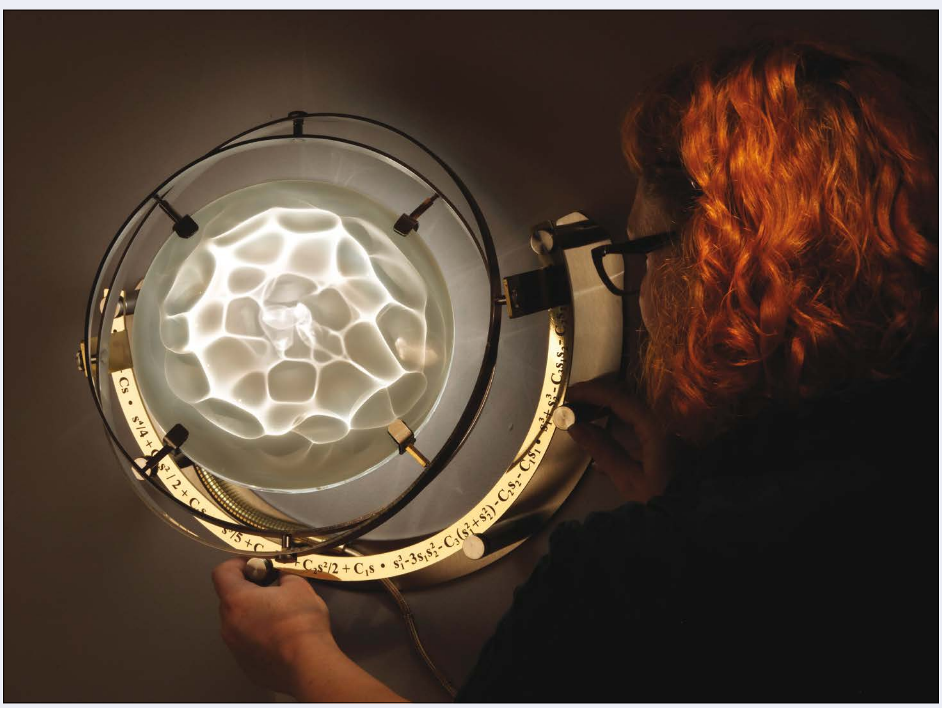
Six other companies have won an IOP Start-up Award, which celebrates young companies "with a great business idea founded on a physics invention, with the potential for business growth and significant societal impact". They include Astron Systems, MirZyme Therapeutics, Celtic Terahertz Technology, Nellie Technologies, Quantum Science and Wayland Additive.

iFAST Diagnostics was awarded the IOP Lee Lucas Award, which recognizes early-stage companies taking innovative products into the medical and healthcare sector. The firm, which was spun out of the University of Southampton, develops blood tests that can test the treatment of bacterial infections in a matter of hours rather than days. The company is expecting to have approval for testing next year.

● For the full list of winners, see: ow.ly/wPxa50XJtKH

Michael Banks

'Caustic' light patterns inspire new glass artwork



Alison Stott

UK artist Alison Stott has created a new glass and light artwork – entitled *Naturally Focused* – inspired by the work of theoretical physicist Michael Berry from the University of Bristol. The new artwork, now on display at the university, is based on "caustics" – the curved patterns that form when light is reflected or refracted by curved surfaces or objects. The focal point of the artwork is a hand-blown glass lens that was waterjet-cut into a circle and polished so that its internal structure and optical behaviour are clearly visible. The lens is suspended within stainless steel gyroscopic rings and held by a brass support and stainless steel backplate. The work is inspired by Berry's research into the relationship between classical and quantum behaviour and how subtle geometric structures govern how waves and particles behave. Stott says that working with Berry has pushed her understanding of caustics. "The more I learn about how these structures emerge, the more compelling they become," notes Stott.

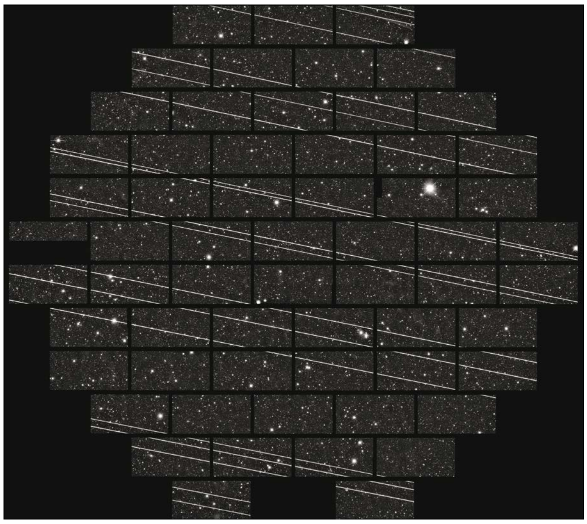
Michael Banks

Astronomy

Satellite constellations pollute space observations

Almost every image that will be taken by future space observatories in low-Earth orbit could be tainted due to light contamination from satellites. That is according to a new analysis from researchers at NASA, which stresses that light pollution from satellites orbiting Earth must be reduced to guarantee astronomical research is not affected (*Nature* **648** 51).

The number of satellites orbiting Earth has increased from about 2000 in 2019 to 15 000 today. Many of these are part of so-called mega-constellations that provide services such as Internet coverage around the world, including in areas that were previously unable to access it. Including SpaceX's Starlink as well as Amazon's Kuiper and Eutelsat's OneWeb, many of these mega-constellations share the same space as space-based observatories such as NASA's Hubble Space Telescope. This means that the telescopes can capture streaks of reflected light from the satellites that render the images or data completely unusable for research purposes. That is despite anti-reflective coating that is applied to some newer satellites in SpaceX's Starlink constellation, for example.



CTIO/NOIRLab/NSF/AURA/DECam DELVE Survey

Obstructed view The study finds that 96% of images from planned telescopes could be compromised by the presence of satellite constellations.

Alejandro Borlaff from NASA's Ames Research Center, and colleagues simulated the view of four space-based telescopes: Hubble and the near-infrared observatory SPHEREx, which launched in 2025, as well at the European Space Agency's proposed near-infrared ARRAKIHS mission and China's planned Xuntian telescopes. These observatories are, or will be placed, between 400 and 800 km from the Earth's surface.

The authors found that if the population of mega-constellation satellites grows to the 56 000 that is projected by the end of the decade, it would contaminate about 39.6% of Hubble's images and 96% of images from the other three telescopes. Borlaff and colleagues predict that the average number of satellites observed per exposure would be 2.14 for Hubble, 5.64 for SPHEREx, 69 for ARRAKIHS, and 92 for Xuntian. The authors note that one solution could be to deploy satellites at lower orbits than the telescopes operate, which would make them about four magnitudes dimmer. The downside is that emissions from these lower satellites could have implications for Earth's ozone layer.

Katherine Courtney, chair of the steering board for the Global Network on Sustainability in Space, says that without astronomy, the modern space economy "simply wouldn't exist". She adds that there is now "an urgent need for greater dialogue and collaboration between astronomers and satellite operators to mitigate those impacts".

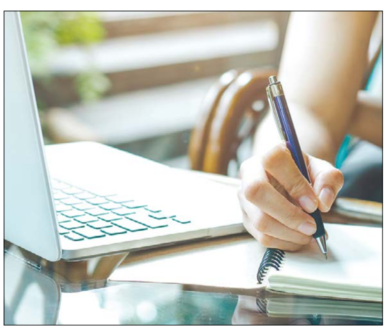
Michael Banks

Publishing

Remote work expands collaboration but reduces impact

Academics who switch to hybrid working and remote collaboration do less impactful research. That's according to an analysis of how scientists' collaboration networks and academic outputs evolved before, during and after the COVID-19 pandemic (arXiv: 2511.18481). It involved studying author data from the arXiv preprint repository and the online bibliographic catalogue OpenAlex.

To explore the geographic spread of collaboration networks, Sara Venturini from the Massachusetts Institute of Technology and colleagues looked at the average distance between the institutions of co-authors. They found that while the average distance between team members on publications increased from 2000 to 2021, there was a particularly sharp rise after 2022.



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Working from home The authors argue that remote and hybrid working negatively affects research quality by reducing spontaneous, serendipitous in-person interactions.

This pattern, the researchers claim, suggests that the pandemic led to scientists collaborating more often with geographically distant colleagues. They found consistent patterns when they separated papers related to COVID-19 from those in unrelated areas, suggesting the trend was not solely driven by research on COVID-19. The researchers also examined how the number of citations a paper received within a year of publication changed with distance between the co-authors' institutions. In general, as the average distance between collaborators increases, citations fall, the authors found.

They suggest that remote and hybrid working hampers research quality by reducing spontaneous, serendipitous in-person interactions that can lead to deep discussions and idea exchange. Despite what the authors say is a "concerning decline" in citation impact, there are, however, benefits to increasing remote interactions. In particular, as the geography of collaboration networks increases, so too does international partnerships and authorship diversity.

Michael Allen

Awards

Susumu Noda wins Rank Prize for Optoelectronics

Susumu Noda of Kyoto University has won the 2026 Rank Prize for Optoelectronics for creating the photonic crystal surface emitting laser (PCSEL). Noda spent more than 25 years developing this new form of laser, which could be used in high-precision manufacturing as well as in LIDAR technologies.

Following the development of the laser in 1960, optical fibre lasers and semiconductor lasers have become competing technologies. A semiconductor laser works by pumping an electrical current into a region where an n-doped (excess of electrons) and a p-doped (excess of holes) semiconductor material meet, causing electrons and holes to combine and release photons. Semiconductors have several advantages in terms of their compactness, high "wallplug" efficiency, and ruggedness, but lack in other areas such as having a low brightness and functionality. Conventional semiconductor lasers therefore need external optical and mechanical elements to improve their performance, which results in large and impractical systems.

Kyoto University Institute for Advanced Study

Electronics pioneer Susumu Noda of Kyoto University has spent over 25 years improving photonic crystal surface emitting lasers.

In the late 1990s Noda began working on a new type of semiconductor laser that could challenge the performance of optical fibre lasers. These so-called PCSELs employ a photonic crystal layer in between the semiconductor layers. Photonic crystals are nanostructured materials in which a periodic variation of the dielectric constant – formed, for example, by a lattice of holes – creates a photonic band-gap. Noda and his colleagues made a series of breakthrough in the technology such as expansion into blue–violet wavelengths. The resulting PCSELs emit a high-quality, symmetric beam with narrow divergence and boast high brightness and high functionality while maintaining the benefits of conventional semiconductor lasers. In 2013, 0.2 W PCSELs became available and a few years later Watt-class PCSEL lasers became operational.

Noda says that it is "a great honour and a surprise" to receive the prize. "I am extremely happy to know that more than 25 years of research on photonic-crystal surface-emitting lasers has been recognized in this way," he adds. "I do hope to continue to further develop the research and its social implementation." Noda received his BSc and then PhD in electronics from Kyoto University in 1982 and 1991, respectively. From 1984 he worked at Mitsubishi Electric Corporation, before joining Kyoto University in 1988 where he is currently based.

Founded in 1972 by the British industrialist and philanthropist Lord J Arthur Rank, the Rank Prize is awarded biennially in nutrition and optoelectronics. The 2026 Rank Prize for Optoelectronics, which has a cash award of £100 000, will be awarded formally at an event held in June.

Michael Banks

Facilities

New Fermilab building honours Tevatron pioneer Helen Edwards

Officials at Fermilab and the US Department of Energy (DOE) officially opened the Helen Edwards Engineering Research Center at a ceremony held on 5 December. The new building is Fermilab's largest purpose-built lab and office space since its iconic Wilson Hall was completed in 1974.

Construction of the Helen Edwards Engineering Research Center began in 2019 and was completed three years later. The centre is a 7500 m^2 multi-storey lab and office building that is adjacent and connected to Wilson Hall. The new centre is intended to let engineers, scientists and technicians design, build and test technologies across several areas of research such as neutrino science, particle detectors, quantum science and electronics. The centre also features clean rooms, vibration-sensitive labs and cryogenic facilities.

Ryan Postel, Fermilab

Solid foundation The Helen Edwards Engineering Research Center is designed to act as a collaborative space for scientists and engineers.

With a PhD in experimental particle physics from Cornell University, Edwards was heavily involved with commissioning the university's 10 GeV electron synchrotron. In 1970 Fermilab's director Robert Wilson appointed Edwards as associate head of the lab's booster section and she later became head of the accelerator division. While at Fermilab, Edwards' primary responsibility was designing, constructing, commissioning and operating the Tevatron, which led to the discoveries of the top quark in 1995 and the tau neutrino in 2000. Edwards retired in the early 1990s but continued to work as guest scientists at Fermilab and officially switched the Tevatron off during a ceremony held on 30 September 2011. Edwards died in 2016.

Darío Gil, the undersecretary for science at the DOE, says that Edwards' scientific work "is a symbol of the pioneering spirit of US research". "Her contributions to the Tevatron and the lab helped the US become a world leader in the study of elementary particles," notes Gil.

Michael Banks

Research updates

Listen to *Physics World*'s Hamish Johnston speaking with Guangyu Zhang, this year's Breakthrough of the Year winner

AUDIO

Top 10 breakthroughs revealed

The *Physics World* 2025 Breakthrough of the Year goes to researchers in China who have made the first 2D sheets of metals, as **Hamish Johnston** reports

The *Physics World* 2025 Breakthrough of the Year has been awarded to Guangyu Zhang, Luojun Du and colleagues at the Institute of Physics of the Chinese Academy of Sciences for producing the first 2D sheets of metal. The team produced five atomically thin 2D metals – bismuth, tin, lead, indium and gallium – with the thinnest being around 6.3 Å. The researchers say their work is just the "tip of the iceberg" and now aim to study their properties as well as fundamental physics with the new materials (*Nature* **639** 354).

Since the discovery of graphene – a sheet of carbon just one atom thick – in 2004, hundreds of other 2D materials have been fabricated and studied. In most of these, layers of covalently bonded atoms are separated by gaps where neighbouring layers are held together only by weak van der Waals (vdW) interactions, making it relatively easy to "shave off" single layers to make 2D sheets. Many thought that making atomically thin metals would be impossible given that each atom in a metal is strongly bonded to surrounding atoms in all directions.

The technique developed by Zhang, Du and colleagues involves heating powders of pure metals between two monolayer-MoS_2/sapphire vdW anvils. Once the metal powders are melted into a droplet, the researchers applied a pressure of 200 MPa and continued this "vdW squeezing" until the opposite sides of the anvils cooled to room temperature and 2D sheets of metal were formed. "Right now, we have reported five single element metals, but actually we can do more because of the 88 metals in the periodic table," Zhang told *Physics World*.

This year's top 10 breakthroughs were selected by a panel of *Physics World* editors, who sifted through hundreds of research updates published on the website this year across all fields of physics. In addition to having been reported in *Physics World* in 2025, the winner and nine other highly commended pieces of research had to represent a significant advance in knowledge or understanding; be important for scientific progress and/or development of real-world applications; and be of general interest to *Physics World* readers.

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

Top physics breakthrough of 2025
The researchers based in China produced atomically thin sheets of bismuth, tin, lead, indium and gallium.

Breakthrough physics

The nine other highly commended breakthroughs follow in no particular order.

ASTRONOMY

Tim McCoy, Danny Glavin, Jason Dworkin, Yoshihiro Furukawa, Ann Nguyen, Scott Sandford, Zack Gainsforth and an international team of collaborators are honoured for identifying salt, ammonia, sugar, nitrogen- and oxygen-rich organic materials, and traces of metal-rich supernova dust, in samples returned from the near-Earth asteroid 101955 Bennu (*Nature* **637** 1072). The incredible chemical richness of this asteroid, which NASA's OSIRIS-Rex spacecraft visited in 2020, supports the longstanding hypothesis that asteroid impacts could have "seeded" the early Earth with the raw ingredients needed for life to form. The discoveries also enhance our understanding of how Bennu and other objects in the solar system formed out of the disc of material that coalesced around the young Sun.

Another breakthrough in astronomy goes to Lisa Nortmann at Germany's University of Göttingen and colleagues for creating the first detailed "weather map" of an exoplanet (*Astronomy and Astrophysics* **693** A213). WASP-127b is a gas giant exoplanet located about 520 light–years from Earth. Its forecast is brutal with winds reaching 33 000 km/hr, which is much faster than winds found anywhere in the Solar System. The team used the CRIRES+ instrument on the European Southern Observatory's Very Large Telescope to observe the exoplanet as it transited across its star in less than 7 h. Spectral analysis of the starlight that filtered through WASP-127b's atmosphere revealed Doppler shifts caused by supersonic equatorial winds. By analysing the range of Doppler shifts, the team created a rough weather map of WASP-127b, even though they could not resolve light coming from specific locations on the exoplanet.

CONDENSED MATTER

Takamasa Momose of the University of British Columbia, Canada, and Susumu Kuma of the RIKEN Atomic, Molecular and Optical Physics Laboratory, Japan are recognized for observing superfluidity in a molecule for the first time (*Sci. Adv.* **11** eadu1093). Molecular hydrogen is the simplest and lightest of all molecules, and theorists predicted that it would enter a superfluid state at a temperature between 1–2 K. Yet this is well below the molecule's freezing point of 13.8 K, so Momose, Kuma and colleagues first had to develop a way to keep the hydrogen in a liquid state. Once they did that, they then had to work out how to detect the onset of superfluidity. It took them nearly 20 years, but by confining clusters of hydrogen molecules inside helium nanodroplets, embedding a methane molecule within the clusters, and monitoring the methane's rotation, they were finally able to do it. They now plan to study larger clusters of hydrogen, with the aim of exploring the boundary between classical and quantum behaviour in this system.

These top 10 breakthroughs represent a significant advance in knowledge or understanding; be important for scientific progress and/or development of real-world applications; and be of general interest to *Physics World* readers

OPTICS

Researchers at the University of Southampton and Microsoft Azure Fibre in the UK, are honoured for developing a new type of optical fibre that reduces signal loss, boosts bandwidth and promises faster, greener communications (*Nature Photon.* **19** 1203). The team, led by Francesco Poletti, achieved this feat by replacing the glass core of a conventional fibre with air and using glass membranes that reflect light at certain frequencies back into the core to trap the light and keep it moving through the fibre's hollow centre. Their results show that the hollow-core fibres exhibit 35% less attenuation than standard glass fibres – implying that fewer amplifiers would be needed in long cables – and increase transmission speeds by 45%. Microsoft has begun testing the new fibres in real systems, installing segments in its network and sending live traffic through them. These trials open the door to gradual rollout and Poletti suggests that the hollow-core fibres could one day replace existing undersea cables.

MEDICAL PHYSICS

Francesco Fracchiolla and colleagues at the Trento Proton Therapy Centre in Italy are chosen for delivering the first clinical treatments using proton arc therapy (PAT). Proton therapy – a precision cancer treatment – is usually performed using pencil-beam scanning to precisely paint the dose onto the tumour. But this approach can be limited by the small number of beam directions deliverable in an acceptable treatment time. PAT overcomes this by moving to an arc trajectory with protons delivered over a large number of beam angles with the potential to optimize the number of energies used for each beam direction. Working with researchers at RaySearch Laboratories in Sweden, the team performed successful dosimetric comparisons with clinical proton therapy plans (*Medical Physics* **52** 3191). The researchers used PAT to treat nine cancer patients.

BIOPHYSICS

Peter Maurer and David Awschalom at the University of Chicago Pritzker School of Molecular Engineering and colleagues designed a protein quantum bit (qubit) that can be produced directly inside living cells and used as a magnetic field sensor (*Nature* **645** 73). While many of today's quantum sensors are based on nitrogen–vacancy (NV) centres in diamond, they are large and hard to position inside living cells. Instead, the team used fluorescent proteins, which are just 3 nm in diameter and can be produced by cells at a desired location with atomic precision. These proteins possess similar optical and spin properties to those of NV centre-based qubits – namely that they have a metastable triplet state. The researchers used a near-infrared laser pulse to optically address a yellow fluorescent protein and read out its triplet spin state with up to 20% spin contrast. They then genetically modified the protein to be expressed in bacterial cells and measured signals with a contrast of up to 8%. Although this performance does not match that of NV quantum sensors, it could enable magnetic resonance measurements directly inside living cells.

PARTICLE PHYSICS

CERN's BASE collaboration are honoured for being the first to perform coherent spin spectroscopy on a single antiproton – the antimatter counterpart of the proton (*Nature* **644** 64). Their breakthrough is the most precise measurement yet of the antiproton's magnetic properties, and could be used to test the Standard Model of particle physics. The experiment begins with the creation of high-energy antiprotons in an accelerator. Then, a single antiproton is held in an ultracold electromagnetic trap, where microwave pulses manipulate its spin state. The resulting resonance peak was 16 times narrower than previous measurements, enabling a significant leap in precision. This level of quantum control opens the door to highly sensitive comparisons of the properties of matter (protons) and antimatter (antiprotons).

GEOPHYSICS

Richard Allen, director of the Berkeley Seismological Laboratory at the University of California, Berkeley, and Google's Marc Stogaitis and colleagues are chosen for creating a global network of Android smartphones that acts as an earthquake early warning system (*Science* **389** 254) . Traditional early warning systems use networks of seismic sensors that rapidly detect earthquakes in areas close to the epicentre and issue warnings across the affected region. Building such seismic networks, however, is expensive, and many earthquake-prone regions do not have them. The researchers utilized the accelerometer in millions of phones in 98 countries to create the Android Earthquake Alert (AEA) system. Testing the app between 2021 and 2024 led to the detection of an average of 312 earthquakes a month, with magnitudes ranging from 1.9 to 7.8. The team now aims to produce maps of ground shaking, which could assist the emergency response services following an earthquake.

ATOMIC PHYSICS

A team led by Yichao Zhang at the University of Maryland and Pinshane Huang of the University of Illinois at Urbana-Champaign are chosen for capturing the highest-resolution images ever taken of individual atoms in a material (*Science* **389** 423). The team used an electron-microscopy technique called electron ptychography to achieve a resolution of 15 pm, which is about 10 times smaller than the size of an atom. They studied a stack of two atomically-thin layers of tungsten diselenide, which were rotated relative to each other to create a moiré superlattice. These twisted 2D materials have electronic properties that change dramatically with small changes in rotation angle. The extraordinary resolution of their microscope allowed them to visualize collective vibrations in the material called moiré phasons. These are similar to phonons, but had never been observed directly until now. Their microscopy technique should boost our understanding of the role that moiré phasons and other lattice vibrations play in the physics of solids, potentially leading to new and useful materials.

Additional reporting by **Tami Freeman**, **Margaret Harris** and **Michael Banks**

Particle physics

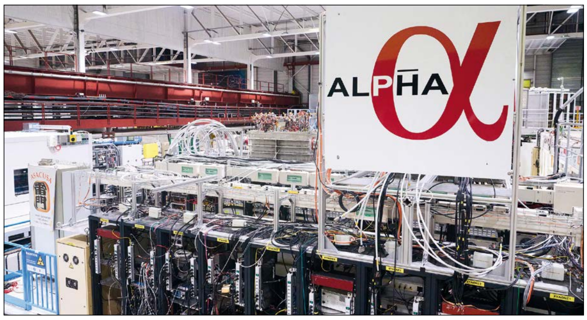
Sympathetic cooling gives antihydrogen experiment a boost

Physicists working on the Antihydrogen Laser Physics Apparatus (ALPHA) experiment at CERN have trapped and accumulated 15 000 antihydrogen atoms in less than seven hours – an accumulation rate more than 20 times the previous record. Large ensembles of antihydrogen could be used to search for physics beyond the Standard Model (*Nature Comms* **16** 10106).

Why there is much more matter than antimatter in the visible universe, and the reason for this "baryon asymmetry" is a big mystery. If physicists could find discrepancies between the measured and predicted properties of antimatter it could help explain the baryon asymmetry and point to other new physics beyond the Standard Model.

An antihydrogen antiatom comprises an antiproton bound to an antielectron (positron). Antihydrogen offers physicists several powerful ways to probe antimatter at a fundamental level. Trapped antiatoms can be released in freefall to determine if they respond to gravity in the same way as atoms. Spectroscopy can be used to make precise measurements of how the electromagnetic force binds the antiproton and positron in antihydrogen with the aim of finding differences compared to hydrogen.

So far, antihydrogen's gravitational and electromagnetic properties appear to be identical to hydrogen. However, these experiments were done using small numbers of antiatoms, and having access to much larger ensembles would improve the precision of such measurements. Today, antihydrogen can only be made in significant quantities at CERN, where a beam of protons is fired at a solid target, creating antiprotons that are then cooled and stored using electromagnetic fields.



2023-2025 CERN/Brice, Maximilien

Precision probe
Creating larger ensembles of antihydrogen atoms could provide a better probe of its gravitational and electromagnetic properties.

Positrons, meanwhile, are gathered from the decay of radioactive nuclei and cooled and stored using electromagnetic fields. These antiprotons and positrons are then combined in a special electromagnetic trap to create antihydrogen.

This process works best when the antiprotons and positrons have very low kinetic energies when combined. If the energy is too high, many antiatoms will escape the trap. So, it is crucial that the positrons and antiprotons are as cold as possible. Recently, ALPHA physicists have used a technique called sympathetic cooling on positrons. Using beryllium ions, they cooled the positrons to 10 K, which is five degrees colder than previously achieved using other techniques. These cold positrons boosted the efficiency of the creation and trapping of antihydrogen, allowing the team to accumulate 15 000 antihydrogen atoms in less than 7 h. "These numbers would have been considered science fiction 10 years ago," says ALPHA spokesperson Jeffrey Hangst from Denmark's Aarhus University.

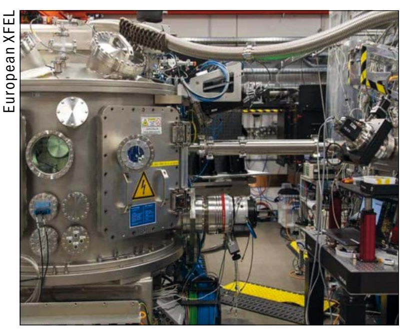
Hamish Johnston

Condensed-matter physics

Cool result as researchers produce the 21st known phase of water ice

A new phase of water ice, dubbed ice XXI, has been discovered by researchers working at the European XFEL and PETRA III facilities in Germany. The ice, which exists at room temperature and is structurally distinct from all previously observed phases of ice, was produced by rapidly compressing water to high pressures. The finding could shed light on how different ice phases form at high pressures, including on icy moons and planets (*Nature Mater.* 10.1038/s41563-025-02364-x).

On Earth, ice can take many forms, and its properties depend strongly on its structure. The main type of naturally-occurring ice is hexagonal ice. However, under certain conditions – usually involving very high pressures and low temperatures – ice can take on other structures. Indeed, 20 different forms of ice have been identified so far.



European XFEL

On thin ice
Ice XXI was produced by rapidly compressing water to high pressures.

Researchers from the Korea Research Institute of Standards and Science (KRISS) have now produced a 21st form of ice by applying pressures of up to 2 GPa in a diamond anvil cell. To study how the new ice sample formed, the researchers rapidly compressed and decompressed it over 1000 times while imaging it every microsecond using the European XFEL, which produces megahertz frequency X-ray pulses at extremely high rates. They found that the liquid water crystallizes into different structures depending on how supercompressed it is.

The KRISS team then used the PETRA III synchrotron to determine that ice XXI has a body-centred tetragonal crystal structure with a large unit cell ($a = b = 20.197$ Å and $c = 7.891$ Å) at approximately 1.6 GPa. This unit cell contains 152 water molecules, resulting in a density of 1.413 $g\,cm^{-3}$.

The structure of ice XXI is different from all previously observed phases of ice because its molecules are much more tightly packed. This, says KRISS scientist Geun Woo Lee, gives it the largest unit cell volume of all currently known types of ice. It is also metastable, meaning that it can exist even though another form of ice (in this case ice VI) would be more stable under the conditions in the experiment.

Isabelle Dumé

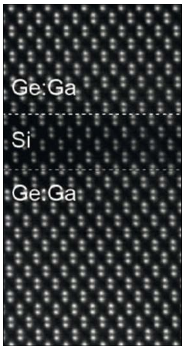
Condensed-matter physics

Scientists realize superconductivity in semiconductors

Researchers have managed to induce superconductivity in germanium and gallium films – materials that are inherently semiconducting. Improving the conductivity of semiconductor materials could help develop quantum technologies with a high speed and energy efficiency, including superconducting quantum bits (qubits) and cryogenic CMOS control circuitry (*Nature Nanotechnol.* 10.1038/s41565-025-02042-8).

Germanium is a group IV element, so its properties bridge those of both metals and insulators. Superconductivity can be induced in germanium by manipulating its atomic structure to introduce more electrons into the atomic lattice. These extra electrons interact with the germanium lattice to create electron pairs that move without resistance, or in other words, they become superconducting.

Hyperdoping germanium (at concentrations well above the solid solubility limit) with gallium induces a superconducting state. However, this material is traditionally unstable due to the presence of structural defects, dopant clustering and poor thickness control. There have also been many questions raised as to whether these materials are intrinsically superconducting, or whether it is actually gallium clusters and unintended phases that are solely responsible for the superconductivity of gallium-doped germanium.



Salva Salmani-Rezaie

That's dope The germanium: gallium (Ge:Ga) materials were found to have a superconducting transition temperature of 3.5 K.

In a new approach, the team used molecular beam epitaxy (MBE) to grow the crystals instead of relying on ion implantation techniques, allowing the germanium to by hyperdoped with gallium. Using MBE forces the gallium atoms to replace germanium atoms within the crystal lattice at levels much higher than previously seen. The process also provided better control over parasitic heating during film growth. This allowed the researchers to achieve the structural precision required to understand and control the superconductivity of these germanium:gallium (Ge:Ga) materials, which were found to become superconducting at 3.5 K with a carrier concentration of 4.15×10^{21} holes/cm^3. The critical gallium dopant threshold to achieve this was 17.9%.

Using synchrotron-based X-ray absorption, the team found that the gallium dopants were substitutionally incorporated into the germanium lattice and induced a tetragonal distortion to the unit cell. Density functional theory calculations showed that this causes a shift in the Fermi level into the valence band and flattens electronic bands. This suggests that the structural order of gallium in the germanium lattice creates a narrow band that facilitates superconductivity in germanium, and that this superconductivity arises intrinsically in the germanium, rather than being governed by defects and gallium clusters.

The researchers tested trilayer heterostructures – Ge:Ga/Si/Ge:Ga and Ge:Ga/Ge/Ge:Ga – as proof-of-principle designs for vertical Josephson junction device architectures. In the future, they hope to develop these into fully fledged Josephson junction devices.

Liam Critchley

Environment

Heat engine captures energy as Earth cools at night

A new heat engine driven by the temperature difference between Earth's surface and outer space has been developed by researchers at the University of California, Davis. In an outdoor trial, the team showed how their engine could offer a reliable source of renewable energy at night (*Sci. Adv.* **11** eadw6833).

The technique exploits the fact that the Earth's surface absorbs heat from the Sun during the day and then radiates some of that energy into space at night. While space is about −270 °C, the average temperature of Earth's surface is a balmy 15 °C. Together, these two heat reservoirs provide the essential ingredients of a heat engine, which is a device that extracts mechanical work as thermal energy flows from a heat source to a heat sink.

For the concept to work, however, the engine must radiate the energy it extracts from the Earth within the atmospheric transparency window. This is a narrow band of infrared wavelengths that pass directly into outer space without being absorbed by the atmosphere. To demonstrate this concept, Tristan Deppe and Jeremy Munday created a Stirling engine, which operates through the cyclical expansion and contraction of an enclosed gas as it moves between hot and cold ends. In their set-up, the ends were aligned vertically, with a pair of plates connecting each end to the corresponding heat reservoir.

Mario Rodriguez/UC Davis

Taking the heat Jeremy Munday from the University of California, Davis with a prototype Stirling engine.

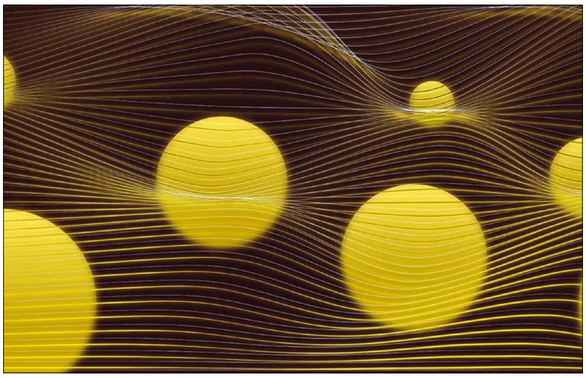
For the hot end, an aluminium mount was pressed into soil, transferring the Earth's ambient heat to the engine's bottom plate. At the cold end, the researchers attached a black-coated plate that emitted an upward stream of infrared radiation within the transparency window. In a series of outdoor experiments performed throughout the year, this set-up maintained a temperature difference greater than 10 °C between the two plates during most months. This was enough to extract more than 400 mW per square metre of mechanical power throughout the night – enough power to run a mechanical fan.

The researchers predict that future improvements could enable the system to extract as much as 6 W per square metre under the same conditions.

Sam Jarman

Theoretical physics

Classical gravity may entangle matter, new study claims


iStock/Denis Pobytov

Defying gravity
The new work considers whether classical gravity could entangle particles.

Gravity might be able to quantum-entangle particles even if the gravitational field itself is classical. That is the conclusion of a new study by Joseph Aziz and Richard Howl at Royal Holloway University of London, which challenges the idea that such entanglement means gravity must be quantized. This could be important in the ongoing attempt to develop a theory of quantum gravity that unites quantum mechanics with Einstein's general theory of relativity (*Nature* **646** 813).

Quantum entanglement occurs when two particles share linked quantum states even when separated. While it has become a powerful probe of the gravitational field, the central question is whether gravity can mediate entanglement only if it is itself quantum in nature. "It has generally been considered that the gravitational interaction can only entangle matter if the gravitational field is quantum," Howl says. "We have argued that even if the field is classical, you could in principle entangle matter."

Quantum field theory postulates that entanglement between masses arises through the exchange of virtual gravitons. These are hypothetical, transient quantum excitations of the gravitational field. Aziz and Howl propose that even if the field remains classical, virtual-matter processes can still generate entanglement indirectly. These processes, he says, "will persist even when the gravitational field is considered classical and could in principle allow for entanglement".

The idea of probing the quantum nature of gravity through entanglement goes back to Richard Feynman in the 1950s. He envisioned placing a tiny mass in a superposition of two locations and checking whether its gravitational field was also superposed. Though elegant, the idea seemed untestable at the time and more recent experimental proposals include levitated diamonds, metallic spheres, or cold atoms, where both position and gravitational effects can be precisely controlled.

Aziz and Howl's work, however, considers whether such entanglement could arise even if gravity is not quantum. They find that certain classical-gravity processes can in principle entangle particles, though the predicted effects are extremely small. "These classical-gravity entangling effects are likely to be very small in near-future experiments," Howl says. "This though is actually a good thing: it means that if we see entanglement…we can be confident that this means that gravity is quantized."

Howl says that experiments capable of detecting gravitationally induced entanglement would be transformative. "We see our work as strengthening the case for these proposed experiments," he says.

Andrey Feldman

'Patchy' nanoparticles emerge from new atomic stencilling technique


University of Illinois/Illustration by Maayan Harel

Researchers in the US and Korea have created nanoparticles with carefully designed "patches" on their surfaces using a new atomic stencilling technique (*Nature* **646** 592). The first step in the stencilling process is to create a mask on the surface of gold nanoparticles. This mask prevents a "paint" made from grafted-on polymers from attaching to certain areas of the nanoparticles. Iodide ions are then used as a stencil that stick to the surface of the nanoparticles in specific patterns that depend on the shape and atomic arrangement of the nanoparticles' facets. This allows the team to tailor the surface chemistry of these tiny patchy nanoparticles in a very controlled way. The researchers, led by Qian Chen at the University of Illinois at Urbana-Champaign, US, will now examine different nanoparticles and substrates. Such patches could be used for drug delivery, catalysis, microelectronics and tissue engineering.

Isabelle Dumé

Opinion

physicsworld

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What 2026 has in store

Predicting the future is hard, but here's a flavour of what's hot in physics right now

I used to set myself the challenge every December of predicting what might happen in physics over the following year. Gazing into my imaginary crystal ball, I tried to speculate on the potential discoveries, the likely trends, and the people who might make the news over the coming year. It soon dawned on me that making predictions in physics is a difficult, if not futile, task


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Apart from space missions pencilled in for launch on set dates, or particle colliders or light sources due to open, so much in science is simply unknown. That uncertainty of science is, of course, also its beauty; if you knew what was out there, looking for it wouldn't be quite as much fun. So if you're wondering what's in store for 2026, I don't know – you'll just have to read *Physics World* to find out.

But this year's Physics World Live series will give you a sense of what's hot in physics right now. The first online panel discussion will be on quantum metrology – a burgeoning field that seeks to ensure companies and academics can test, validate and commercialize new quantum tech.

You can also look forward to an online event on nuclear fusion, which offers a path to limitless energy and a potential solution to the climate crisis. But it's a complex challenge and the route to commercialization is uncertain, despite lots of private firms being active in the area. Among them is Tokamak Energy, which this year won a Business Award from the Institute of Physics (IOP) (see p6).

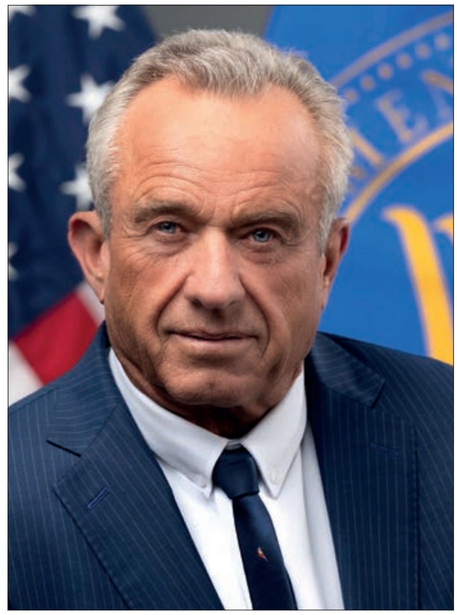
Another of our online panels will be on medical physics, bringing together the current and two past editors-in-chief of *Physics in Medicine & Biology*. Published by IOP Publishing on behalf of the Institute of Physics and Engineering in Medicine, the journal turns 70 this year. The speakers will be reflecting on the vital role of medical-physics research to medicine and biology and examining how the field's evolved since the journal was set up.

Medical physics will also be the focus of a new "impact project" in 2026 from the IOP, which will be starting another on artificial intelligence (AI) as well. The IOP will in addition be continuing its existing impact work on metamaterials, which were of course pioneered by – among others – the Imperial College theorist John Pendry. I wonder if a Nobel prize could be in store for him this year? That's one prediction I'll make that would be great if it came true.

Matin Durrani, editor-in-chief, *Physics World*

Critical Point Lysenko 2.0

US health secretary Robert F Kennedy Jr has led the attacks on US science. But can he really, as **Robert P Crease** wonders, be compared to Stalin's feared science administrator Trofim Lysenko?



Shocking comparison Is it fair to regard Robert F Kennedy Jr (right) as a modern-day Trofim Lysenko (left)?

The US has turned Trofim Lysenko into a hero.

Born in 1898, Lysenko was a Ukrainian plant breeder, who in 1927 found he could make pea and grain plants develop at different rates by applying the right temperatures to their seeds. The Soviet news organ *Pravda* was enthusiastic, saying his discovery could make crops grow in winter, turn barren fields green, feed starving cattle and end famine.

Despite having trained as a horticulturist, Lysenko rejected the then-emerging science of genetics in favour of Lamarckism, according to which organisms can pass on acquired traits to offspring. This meshed well with the Soviet philosophy of "dialectical materialism", which sees both the natural and human worlds as evolving not through mechanisms but environment.

Stalin took note of Lysenko's activities and had him installed as head of key Soviet science agencies. Once in power, Lysenko dismissed scientists who opposed his views, cancelled their meetings, funded studies of discredited theories, and stocked committees with loyalists. Although Lysenko had lost his influence by the time Stalin died in 1953 – with even *Pravda* having turned against him – Soviet agricultural science had been destroyed.

A modern parallel

Lysenko's views and actions have a resonance today when considering the activities of Robert F Kennedy Jr, who was appointed by Donald Trump as secretary of the US Department of Health and Human Services in February 2025. Of course, Trump has repeatedly sought to impose his own agenda on US science, with his destructive impact outlined in a detailed report published by the Union of Concerned Scientists in July 2025.

Last May Trump signed executive order 14303, "Restoring Gold Standard Science", which blasts scientists for not acting "in the best interests of the public". He has withdrawn the US from the World Health Organization (WHO), ordered that Federal-sponsored research fund his own priorities, redefined the hazards of global warming, and cancelled the US National Climate Assessment (NSA), which had been running since 2000.

But after Trump appointed Kennedy, the assault on science continued into US medicine, health and human services. In what might be called a philosophy of "political materialism", Kennedy fired all 17 members of the Advisory Committee on Immunization Practices of the US Centers for Disease Control and Prevention (CDC), cancelled nearly $500m in mRNA vaccine contracts, hired a vaccine sceptic to study its connection with autism despite numerous studies that show no connection, and ordered the CDC to revise its website to reflect his own views on the cause of autism.

In his 2021 book *The Real Anthony Fauci: Bill Gates, Big Pharma, and the Global War on Democracy and Public Health*, Kennedy promotes not germ theory but what he calls "miasma theory", according to which diseases are prevented by nutrition and lifestyle.

Divergent stories

Of course, there are fundamental differences between the 1930s Soviet Union and the 2020s United States. Stalin murdered and imprisoned his opponents, while the US administration only defunds and fires them. Stalin and Lysenko were not voted in, while Trump came democratically to power, with elected representatives confirming Kennedy. Kennedy has also apologized for his most inflammatory remarks, though Stalin and Lysenko never did (nor does Trump for that matter).

What's more, Stalin's and Lysenko's actions were more grounded in apparent scientific realities and social vision than Trump's or Kennedy's. Stalin substantially built up much of the Soviet science and technology infrastructure, whose dramatic successes include launching the first Earth satellite Sputnik in 1957. Though it strains credulity to praise Stalin, his vision to expand Soviet agricultural production during a famine was at least plausible and its intention could be portrayed as humanitarian. Lysenko was a scientist, Kennedy is not.

As for Lysenko, his findings seemed to carry on those of his scientific predecessors. Experimentally, he expanded the work of Russian botanist Ivan Michurin, who bred new kinds of plants able to grow in different regions. Theoretically, his work connected not only with dialectical materialism but also with that of the French naturalist Jean-Baptiste Lamarck, who claimed that acquired traits can be inherited.

Trump and Kennedy are off-the-wall by comparison. Trump has called climate change a con job and hoax and seeks to stop research that says otherwise. In 2019 he falsely stated that Hurricane Dorian was predicted to hit Alabama, then ordered the National Oceanic and Atmospheric Administration to issue a statement supporting him. Trump has said he wants the US birth rate to rise and that he will be the "fertilization president", but later fired fertility and IVF researchers at the CDC.

As for Kennedy, he has said that COVID-19 "is targeted to attack Caucasians and Black people" and that Ashkenazi Jews and Chinese are the most immune (he disputed the remark, but it's on video). He has also sought to retract a 2025 vaccine study from the *Annals of Internal Medicine* (**178** 1369) that directly refuted his views on autism.


Shutterstock/kwest

Strange change The Trump administration has been skewing funding away from research into climate science.

The critical point

US Presidents often have pet scientific projects. Harry Truman created the National Science Foundation, Dwight D Eisenhower set up NASA, John F Kennedy started the Apollo programme, while Richard Nixon launched the Environmental Protection Agency (EPA) and the War on Cancer. But it's one thing to support science that might promote a political agenda and another to quash science that will not.

One ought to be able to take comfort in the fact that if you fight nature, you lose – except that the rest of us lose as well. Thanks to Lysenko's actions, the Soviet Union lost millions of tons of grain and hundreds of herds of cattle. The promise of his work evaporated and Stalin's dreams vanished.

Lysenko, at least, was motivated by seeming scientific promise and social vision; the US has none. Trump has damaged the most important US scientific agencies, destroyed databases and eliminated the EPA's research arm, while Kennedy has replaced health advisory committees with party loyalists.

While Kennedy may not last his term – most Trump Cabinet officials don't – the paths he has sent science policy on surely will. For Trump and Kennedy, the policy seems to consist only of supporting pet projects. Meanwhile, cases of measles in the US have reached their highest level in three decades, the seas continue to rise and the climate is changing. It is hard to imagine how enemy agents could damage US science more effectively.

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)

A call for global responsibility

Alireza Qaiumzadeh says that science can only exist if scientists are recognized and protected as civilians – a principle that is increasingly under threat

The deliberate targeting of scientists in recent years has become one of the most disturbing, and overlooked, developments in modern conflict. In particular, Iranian physicists and engineers have been singled out for almost two decades, with sometimes fatal consequences. In 2007 Ardeshir Hosseinpour, a nuclear physicist at Shiraz University, died in mysterious circumstances that were widely attributed to poisoning or radioactive exposure.

Over the following years, at least five more Iranian researchers have been killed. They include particle physicist Masoud Ali-Mohammadi, who was Iran's representative at the Synchrotron-light for Experimental Science and Applications in the Middle East project. Known as SESAME, it is the only scientific project in the Middle East where Iran and Israel collaborate.

Others to have died include nuclear engineer Majid Shahriari, another Iranian representative at SESAME, and nuclear physicist Mohsen Fakhrizadeh, who were both killed by bombing or gunfire in Tehran. These attacks were never formally acknowledged, nor were they condemned by international scientific institutions. The message, however, was implicit: scientists in politically sensitive fields could be treated as strategic targets, even far from battlefields.

What began as covert killings of individual researchers has now escalated, dangerously, into open military strikes on academic communities. Israeli air strikes on residential areas in Tehran and Isfahan during the 12-day conflict between the two countries in June led to at least 14 Iranian scientists and engineers and members of their family being killed. The scientists worked in areas such as materials science, aerospace engineering and laser physics. I believe this shift, from covert assassinations to mass casualties, crossed a line. It treats scientists as enemy combatants simply because of their expertise.

The assassinations of scientists are not just isolated tragedies; they are a direct assault on the global commons of knowledge, corroding both international law and international science. Unless the world responds, I believe the precedent being set will endanger scientists everywhere and undermine the principle that knowledge belongs to humanity, not the battlefield.

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Vital principle Science is built on openness and the free exchange of ideas – but those values can only be upheld if scientists are recognized and protected as civilians without borders.

Drawing a red line

International humanitarian law is clear: civilians, including academics, must be protected. Targeting scientists based solely on their professional expertise undermines the Geneva Convention and erodes the civilian–military distinction at the heart of international law.

Iran, whatever its politics, remains a member of the Nuclear Non-Proliferation Treaty and the International Atomic Energy Agency. Its scientists are entitled under international law to conduct peaceful research in medicine, energy and industry. Their work is no more inherently criminal than research that other countries carry out in artificial intelligence (AI), quantum technology or genetics.

If we normalize the preemptive assassination of scientists, what stops global rivals from targeting, say, AI researchers in Silicon Valley, quantum physicists in Beijing or geneticists in Berlin? Once knowledge itself becomes a liability, no researcher is safe. Equally troubling is the silence of the international scientific community with organizations such as the UN, UNESCO and the European Research Council as well as leading national academies having not condemned these killings, past or present.

Silence is not neutral. It legitimizes the treatment of scientists as military assets. It discourages international collaboration in sensitive but essential research and it creates fear among younger researchers, who may abandon high-impact fields to avoid risk. Science is built on openness and exchange, and when researchers are murdered for their expertise, the very idea of science as a shared human enterprise is undermined.

The assassinations are not solely Iran's loss. The scientists killed were part of a global community; collaborators and colleagues in the pursuit of knowledge. Their deaths should alarm every nation and every institution that depends on research to confront global challenges, from climate change to pandemics.

I believe that international scientific organizations should act. At a minimum, they should publicly condemn the assassination of scientists and their families; support independent investigations under international law; as well as advocate for explicit protections for scientists and academic facilities in conflict zones.

Importantly, voices within Israel's own scientific community can play a critical role too. Israeli academics, deeply committed to collaboration and academic freedom, understand the costs of blurring the boundary between science and war. Solidarity cannot be selective.

Recent events are a test case for the future of global science. If the international community tolerates the targeting of scientists, it sets a dangerous precedent that others will follow. What appears today as a regional assault on scientists from the Global South could tomorrow endanger researchers in China, Europe, Russia or the US.

Science without borders can only exist if scientists are recognized and protected as civilians without borders. That principle is now under direct threat and the world must draw a red line – killing scientists for their expertise is unacceptable. To ignore these attacks is to invite a future in which knowledge itself becomes a weapon, and the people who create it expendable. That is a world no-one should accept.

Alireza Qaiumzadeh is a quantum physicist at the Norwegian University of Science and Technology in Trondheim

Three Minute Wonder

Science Communication Competition

Three Minute Wonder is IOP's UK and Ireland-wide science communication competition.

It challenges researchers or project team members to explain their work to the public in just three minutes.

Participants work in physics or physics-related fields in **academia**, **business** and/or **industry**.

The aim is to bring cutting edge physics-related activity to life for the general public.

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Who will take part?

The competition is open to anybody from academia, industry or business who is working in a physics-related field. Entrants do not need to be a member of the IOP.

How can you enter?

Regional heats are being run across the UK and Ireland from now until April 2026. The winner from each heat will compete in the grand final in May 2026 as well as being featured in Physics World.

"Three minutes! What can you do?"

More information about heats, competition criteria and entry details can be found at **https://www.iop.org/3mw**

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Transactions Is it good enough?

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That'll do nicely Physicists always want to strive for excellence, but sometimes good enough will do.

We're often to told to aim for perfection in everything we do, but sometimes striving for the best can be futile. **Honor Powrie** extols the virtue of being "good enough" in life

Whether you're running a business project, carrying out scientific research, or doing a spot of DIY around the house, knowing when something is "good enough" can be a tough question to answer. To me, "good enough" means something that is fit for purpose. It's about striking a balance between the effort required to achieve perfection and the cost of not moving forward. It's an essential mindset when perfection is either not needed or – as is often the case – not attainable.

When striving for good enough, the important thing to focus on is that your outcome should meet expectations, but not massively exceed them. Sounds simple, but how often have we heard people say things like they're "polishing coal", striving for "gold plated" or "trying to make a silk purse out of a sow's ear". It basically means they haven't understood, defined or even accepted the requirements of the end goal.

Trouble is, as we go through school, college and university, we're brought up to believe that we should strive for the best in whatever we study. Those with the highest grades, we're told, will probably get the best opportunities and career openings. Unfortunately, this approach means we think we need to aim for perfection in everything in life, which is not always a good thing.

How to be good enough

So why is aiming for "good enough" a good thing to do? First, there's the notion of "diminishing returns". It takes a disproportionate amount of effort to achieve the final, small improvements that most people won't even notice. Put simply, time can be wasted on unnecessary refinements, as embodied by the 80/20 rule (see box).

Good enough also helps us to focus efforts. When a consumer or customer doesn't know exactly what they want, or a product development route is uncertain, it can be better to deliver things in small chunks. Providing something basic but usable can be used to solicit feedback to help clarify requirements or make improvements or additions that can be incorporated into the next chunk. This is broadly along the lines of a "minimum viable product".

Not seeking perfection reminds us too that solutions to problems are often uncertain. If it's not clear how, or even if, something might work, a proof of concept (PoC) can instead be a good way to try something out. Progress can be made by solving a specific technical challenge, whether via a basic experiment, demonstration or short piece of research. A PoC should help avoid committing significant time and resource to something that will never work.

Aiming for "good enough" naturally leads us to the notion of "continuous improvement". It's a personal favourite of mine because it allows for things to be improved incrementally as we learn or get feedback, rather than producing something in one go and then forgetting about it. It helps keep things current and relevant and encourages a culture of constantly looking for a better way to do things.

Finally, when searching for good enough, don't forget the idea of ballpark estimates. Making approximations sounds too simple to be effective, but sometimes a rough estimate is really all you need. If an approximate guess can inform and guide your next steps or determine whether further action will be necessary then go for it.

The 80/20 rule: the guiding principle of "good enough"

Also known as the Pareto principle – in honour of the Italian economist Vilfredo Pareto who first came up with the idea – the 80/20 rule states that for many outcomes, 80% of consequences or results come from 20% of the causes or effort. The principle helps to identify where to prioritize activities to boost productivity and get better results. It is a guideline, and the ratios can vary, but it can be applied to many things in both our professional and personal lives.

Examples from the world of business include the following:

- Business sales: 80% of a company's revenue might come from 20% of its customers.
- Company productivity: 80% of your results may come from 20% of your daily tasks.
- Software development: 80% of bugs could be caused by 20% of the code.
- Quality control: 20% of defects may cause 80% of customer complaints.

The benefits of good enough

Being good enough doesn't just lead to practical outcomes, it can benefit our personal well-being too. Our time, after all, is a precious commodity and we can't magically increase this resource. The pursuit of perfection can lead to stagnation, and ultimately burnout, whereas achieving good enough allows us to move on in a timely fashion.

A good-enough approach will even make you less stressed. By getting things done sooner and achieving more, you'll feel freer and happier about your work even if it means accepting imperfection. Mistakes and errors are inevitable in life, so don't be afraid to make them; use them as learning opportunities, rather than seeing them as something bad. Remember – the person who never made a mistake never got out of bed.

Recognizing that you've done the best you can for now is also crucial for starting new projects and making progress. By accepting good enough you can build momentum, get more things done, and consistently take actions toward achieving your goals.

Finally, good enough is also about shared ownership. By inviting someone else to look at what you've done, you can significantly speed up the process. In my own career I've often found myself agonising over some obscure detail or feeling something is missing, only to have my quandary solved almost instantly simply by getting someone else involved – making me wish I'd asked them sooner.

Caveats and conclusions

Good enough comes with some caveats. Regulatory or legislative requirements mean there will always be projects that have to reach a minimum standard, which will be your top priority. The precise nature of good enough will also depend on whether you're making stuff (be it cars or computers) or dealing with intangible commodities such as software or services.

So what's the conclusion? Well, in the interests of my own time, I've decided to apply the 80/20 rule and leave it to you to draw your own conclusion. As far as I'm concerned, I think this article has been good enough, but I'm sure you'll let me know if it hasn't. Consider it as a minimally viable product that I can update in a future column.

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

Reviews

Gravity comes down to Earth

Emma Chapman reviews *Crush: Close Encounters with Gravity* by James Riordon

Crush: Close Encounters with Gravity
James Riordon
2025 MIT Press
288pp £27hb

iStock/Svitanola

Windfall lesson
We intuitively learn the basics of gravity from observing things falling, like apples from trees. But there is a lot more to the subject than Isaac Newton and black holes.

When I was five years old, my family moved into a 1930s semi-detached house with a long strip of garden. At the end of the garden was a miniature orchard of eight apple trees the previous owners had planted – and it was there that I, much like another significantly more famous physicist, learned an important lesson about gravity.

As I read in the shade of the trees, an apple would sometimes fall with a satisfying thunk into the soft grass beside me. Less satisfyingly, they sometimes landed on my legs, or even my head – and the big cooking apples really hurt. I soon took to sitting on old wooden pallets crudely wedged among the higher branches. It was not comfortable, but at least I could return indoors without bruises.

The effects of gravity become common sense so early in life that we rarely stop to think about them past childhood. In his new book *Crush: Close Encounters with Gravity,* James Riordon has decided to take us back to the basics of this most fundamental of forces. Indeed, he explores an impressively wide range of topics – from why we dream of falling and why giraffes should not exist (but do), to how black holes form and the existence of "Planet 9".

Riordon, a physicist turned science writer, makes for a deeply engaging author. He is not afraid to put himself into the story, introducing difficult concepts through personal experience and explaining them with the help of everything including the kitchen sink, which in his hands becomes an analogue for a black hole.

Gravity as a subject can easily be both too familiar and too challenging. In Riordon's words, "Things with mass attract each other. That's really all there is to Newtonian gravity." While Albert Einstein's theory of general relativity, by contrast, is so intricate that it takes years of university-level study to truly master. Riordon avoids both pitfalls: he manages to make the simple fascinating again, and the complex understandable.

He provides captivating insights into how gravity has shaped the animal kingdom, a perspective I had never much considered. Did you know that tree snakes have their hearts positioned closer to their heads than their land-based cousins? I certainly didn't. The higher placement ensures a steady blood flow to the brain, even when the snake is climbing vertically. It is one of many examples that make you look again at the natural world with fresh eyes.

Riordon's treatment of gravity in Einstein's abstract space–time is equally impressive, perhaps unsurprisingly, as his previous books include *Very Easy Relativity* and *Relatively Easy Relativity*. Riordon takes a careful, patient approach – though I have never before heard general relativity reduced to "space–time is squishy". But why not? The phrase sticks and gives us a handhold as we scale the complications of the theory. For those who want to extend the challenge, a mathematical background to the theory is provided in an appendix, and every chapter is well referenced and accompanied with suggestions for further reading.

If anything, I found myself wanting more examples of gravity as experienced by humans and animals on Earth, as opposed to in the context of the astronomical realm. I found these down-to-earth chapters the most fascinating: they formed a bridge between the vast and the local, reminding us that the same force that governs the orbits of galaxies also brings an apple to the ground. This may be a reaction only felt by astronomers like me, who already spend their days looking upward. I can easily see how the balance Riordon chose is necessary for someone without that background, and Einstein's gravity does require galactic scales to appreciate, after all.

Crush is a generally uncomplicated and pleasurable read. The anecdotes can sometimes be a little long-winded and there are parts of the book that are not without challenge. But it is pitched perfectly for the curious general reader and even for those dipping their toes into popular science for the first time. I can imagine an enthusiastic A-level student devouring it; it is exactly the kind of book I would have loved at that age. Even if some of it would have gone over my head, Riordon's enthusiasm and gift for storytelling would have kept me more than interested, as I sat up on that pallet in my favourite apple tree.

> *Crush* is pitched perfectly for the curious general reader

I left that house, and that tree, a long time ago, but just a few miles down the road from where I live now stands another, far more famous apple tree. In the garden of Woolsthorpe Manor near Grantham, Newton is said to have watched an apple fall. From that small event, he began to ask the questions that reshaped his and our understanding of the universe. Whether or not the story is true hardly matters – Newton was constantly inspired by the natural world, so it isn't improbable, and that apple tree remains a potent symbol of curiosity and insight.

"[Newton] could tell us that an apple falls, and how quickly it will do it. As for the question of why it falls, that took Einstein to answer," writes Riordon. *Crush* is a crisp and fresh tour through a continuum from orchards to observatories, showing that every planetary orbit, pulse of starlight and even every apple fall is part of the same wondrous story.

Emma Chapman is an astrophysicist at the University of Nottingham, UK, and author of *First Light: Switching on Stars at the Dawn of Time*


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Feedback

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Please send us your feedback by e-mail to pwld@ioppublishing.org

Environmental focus

In response to the Forum article by Peter Hughes (November 2025 p19), which called for environmental physics to be included in all undergraduate physics courses.

I could not agree more with Hughes. Climate change is a priority problem of the 21st century. Yet many undergraduate courses do not teach students that understanding climate change or making climate predictions are physics problems. Whether it is solving the Navier–Stokes equations for the fluid flow of the atmosphere and ocean, representing the wavelength-dependent transfer of radiation, or computer modelling the microphysics of clouds – global warming is first and foremost a physics problem.

Summer 2022 brought a taste of the future with the first UK heatwave to exceed 40 °C. The likelihood of such unprecedented events is increasing exponentially and the impacts now in store are only just beginning to be understood. It is physicists, with their knowledge of physical processes and their quantitative skills, who are best equipped to understand the mechanisms and quantify the impacts of these events.

We urgently need to evolve undergraduate courses to address these needs if physics and physicists are to play their full part in society.

Adam Scaife
Met Office and University of Exeter, UK

Practical success

In response to the Forum article by Neil Downie (December 2025 pp21–22), which underlined the importance of practical projects for pupils and students to enthuse them about physics.

At the University of Exeter, we are adopting just the kind of approach that Downie advocates through our lab sessions for first-year undergraduate students. I and several other members of staff have spent the past year designing low-cost, flexible and open-source sets of apparatus to let students explore fundamental concepts such as harmonic motion, the ideal gas laws, free-fall kinematics and the motion of pendula. Each piece of apparatus, which costs no more than about £250, is controlled by a simple Python script running on a Raspberry Pi. Students can see data acquired digitally and plotted in real time.

Being relatively cheap, we have been able to buy and assemble enough copies of the kit so that all students can work on the same experiment at the same time. This is great as it lets us synchronize lab sessions with lectures to avoid students being confronted with practicals based on bits of physics they haven't learnt about yet. What's more, since we have designed and built every part of the apparatus, each practical session has an open-ended element in which students can pursue their own investigations.

We are really excited about the potential of this approach in building critical experimental skills that are so vital to students as they embark on their physics careers.

Ben Sherlock
University of Exeter, UK

Nobel consequences

In response to the feature article by Margaret Harris about the award of the Nobel Prize for Physics to Gabriel Lippmann in 1908 and Gustaf Dalén in 1912 (November 2025 pp28–32).

As Harris rightly points, both prizes were awarded for inventions that were less important than many other advances in physics at the time and she is surely correct that the prizes may have been affected by issues such as nationalism and personal bias.

However, what I find truly surprising is that such instances did not happen more often.

Most physicists would agree that, apart from the two cases above, there are remarkably few cases where the Nobel committee demonstrably got it wrong – in the sense of awarding a Nobel Prize for Physics that was later viewed to be highly questionable. All this in a century that saw our understanding of physics completely up-ended by theories such as quantum mechanics and relativity.

As Karl Grandin, director of the Center for History of Science at the Royal Swedish Academy of Sciences, point outs out in the article, it is an extraordinary task for the physicists and chemists of one small country to select a suitable prize winner each year. It seems to me that the committee has done a remarkably fine job so far.

Cormac O'Raifeartaigh
South East Technological University, Waterford, Ireland

While Lippmann photography was a commercial failure at the time, it can be seen as a forerunner to the white-light holograms now used as security features on credit and debit cards, and on current English banknotes (although these are produced using an embossing process rather than holographically). The holograms are also used to aid the understanding of the vivid interference colours in some insects and birds produced by photonic crystals in their skin or feathers. Thus, the principle underlying Lippmann photography has had a continuing commercial and scientific value.

Laurence Cox
Stanmore, Middlesex, UK

Roman achievements

In response to the *Physics World Weekly* podcast of 20 November 2025, in which Daniel Whiteson spoke about his new book (with artist Andy Warner) *Do Aliens Speak Physics*?

Whiteson suggests the possibility of there being an alien civilization that might have developed highly advanced engineering without understanding the physics. While this sounds outlandish, there is a real example of a culture where something like this happened.

The Romans were legendary engineers, whose work was not surpassed for nearly 1500 years, but their interest in mathematics was minimal. They used a lot of basic geometry but it appears anything above a modern GCSE syllabus was treated with disdain.

This is reflected in their number system being completely unsuitable for advanced tasks such as calculus. While they never went to space, they were remarkably close to inventing the steam engine and their reliance on slaves – rather than disdain for mathematical sciences – seems the generally accepted explanation as to why they never innovated further.

Penny Jackson
Derby, UK

Cosmic dawn: the search for the 21 cm signal

Astronomers around the world are on the hunt for an elusive 21 cm signal from the earliest hydrogen atoms, to better understand our cosmic history. **Sarah Wild** investigates

Sarah Wild is a science journalist based in the UK

"This is one of the big remaining frontiers in astronomy," says Phil Bull, a cosmologist at the Jodrell Bank Centre for Astrophysics at the University of Manchester. "It's quite a pivotal era of cosmic history that, it turns out, we don't actually understand."

Bull is referring to the vital but baffling period in the early universe – from 380 000 years to one billion years after the Big Bang – when its structure went from simple to complex. To lift the veil on this epoch, experiments around the world – from Australia to the Arctic – are racing to find a specific but elusive signal from the earliest hydrogen atoms. This signal could confirm or disprove scientists' theories of how the universe evolved and the physics that governs it.

Hydrogen is the most abundant element in the universe. As neutral hydrogen atoms change states, they can emit or absorb photons. This spectral transition, which can be stimulated by radiation, produces an emission or absorption radio wave signal with a wavelength of 21 cm. To find out what happened during that early universe, astronomers are searching for these 21 cm photons that were emitted by primordial hydrogen atoms.

But despite more teams joining the hunt every year, no-one has yet had a confirmed detection of this radiation. So who will win the race to find this signal and how is the hunt being carried out?

A blank spot

Let's first return to about 380 000 years after the Big Bang, when the universe had expanded and cooled to below 3000 K. At this stage, neutral atoms, including atomic hydrogen, could form. Thanks to the absence of free electrons, ordinary matter particles could decouple from light, allowing it to travel freely across the universe. This ancient radiation that permeates the sky is known as the cosmic microwave background (CMB).

But after that we don't know much about what happened for the next few hundred million years. Meanwhile, the oldest known galaxy MoM-z14 – which existed about 280 million years after the Big Bang – was observed in April 2025 by the James Webb Space Telescope. So there is currently a gap of just under 280 million years in our observations of the early universe. "It's one of the last blank spots," says Anastasia Fialkov, an astrophysicist at the Institute of Astronomy of the University of Cambridge.

This "blank spot" is a bridge between the early, simple universe and today's complex structured cosmos. During this early epoch, the universe went from being filled with a thick cloud of neutral hydrogen, to being diversely populated with stars, black holes and everything in between. It covers the end of the cosmic dark ages, the cosmic dawn, and the epoch of reionization – and is arguably one of the most exciting periods in our universe's evolution.

During the cosmic dark ages, after the CMB flooded the universe, the only "ordinary" matter (made up of protons, neutrons and electrons) was neutral hydrogen (75% by mass) and neutral helium (25%), and there were no stellar structures to provide light. It is thought that gravity then magnified any slight fluctuations in density, causing some of this primordial gas to clump and eventually form the first stars and galaxies – a time called the cosmic dawn. Next came the epoch of reionization, when ultraviolet and X-ray emissions from those first celestial objects heated and ionized the hydrogen atoms, turning the neutral gas into a charged plasma of electrons and protons.

Stellar imprint

The 21 cm signal astronomers are searching for was produced when the spectral transition was excited by collisions in the hydrogen gas during the dark ages and then by the first photons from the first stars during the cosmic dawn. However, the intensity of the 21 cm signal can only be measured against the CMB, which acts as a steady background source of 21 cm photons.

When the hydrogen was colder than the background radiation, there were few collisions, and the atoms would have absorbed slightly more 21 cm photons from the CMB than they emitted themselves. The 21 cm signal would appear as a deficit, or absorption signal, against the CMB. But when the neutral gas was hotter than the CMB, the atoms would emit more photons than they absorbed, causing the 21 cm signal to be seen as a brighter emission against the CMB. These absorption and emission rates depend on the density and temperature of the gas, and the timing and intensity of radiation from the first cosmic sources. Essentially, the 21 cm signal became imprinted with how those early sources transformed the young universe.

One way scientists are trying to observe this imprint is to measure the average – or "global" – signal across the sky, looking at how it shifts from absorption to emission compared to the CMB. Normally, a 21 cm radio wave signal has a frequency of about 1420 MHz. But this ancient signal, according to theory, has been emitted and absorbed at different intensities throughout this cosmic

Rigel Cappallo, MIT Haystack Observatory

Radio quiet
In 2024 an EDGES system was deployed to Adak Island, in the middle of the Aleutian island chain off Alaska. The site is hundreds of miles from any FM radio transmitters, making it an ideal location for the system, which is a collaboration between MIT Haystack Observatory and Arizona State University.

"blank spot", depending on the universe's evolutionary processes at the time. The expanding universe has also stretched and distorted the signal as it travelled to Earth. Theories predict that it would now be in the 1 to 200 MHz frequency range – with lower frequencies corresponding to older eras – and would have a wavelength of metres rather than centimetres.

Importantly, the shape of the global 21 cm signal over time could confirm the lambda-cold dark matter (ΛCDM) model, which is the most widely accepted theory of the cosmos; or it could upend it. Many astronomers have dedicated their careers to finding this radiation, but it is challenging for a number of reasons.

Unfortunately, the signal is incredibly faint. Its brightness temperature, which is measured as the change in the CMB's black body temperature (2.7 K), will only be in the region of 0.1 K.

There is also no single source of this emission, so, like the CMB, it permeates the universe. "If it was the only signal in the sky, we would have found it by now," says Eloy de Lera Acedo, head of Cavendish Radio Astronomy and Cosmology at the University of Cambridge. But the universe is full of contamination, with the Milky Way being a major culprit. Scientists are searching for 0.1 K in an environment "that's a million times brighter", he explains.

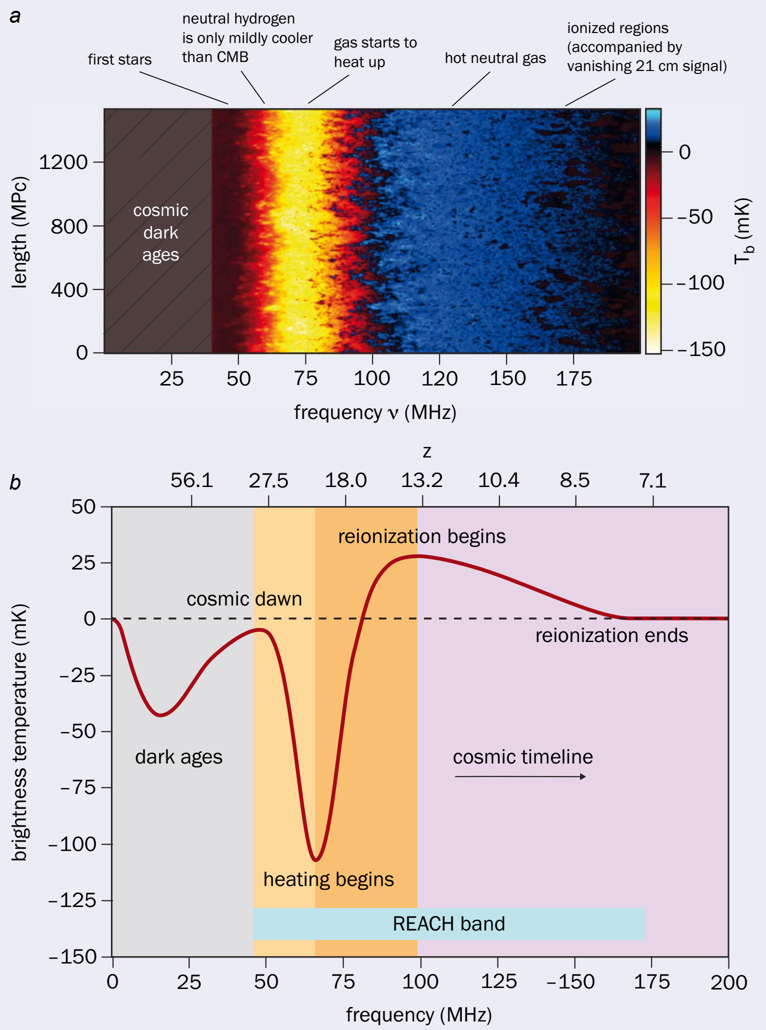
And even before this signal reaches the radio-noisy Earth, it has to travel through the atmosphere, which further distorts and contaminates it. "It's a very difficult measurement," says Rigel Cappallo, a research scientist at the MIT Haystack Observatory. "It takes a really, really well calibrated instrument that you understand really well, plus really good modelling."

Seen but not confirmed

In 2018 the Experiment to Detect the Global EoR Signature (EDGES) – a collaboration between Arizona State University and MIT Haystack Observatory – hit the headlines when it claimed to have detected the global 21 cm signal (*Nature* **555** 67).

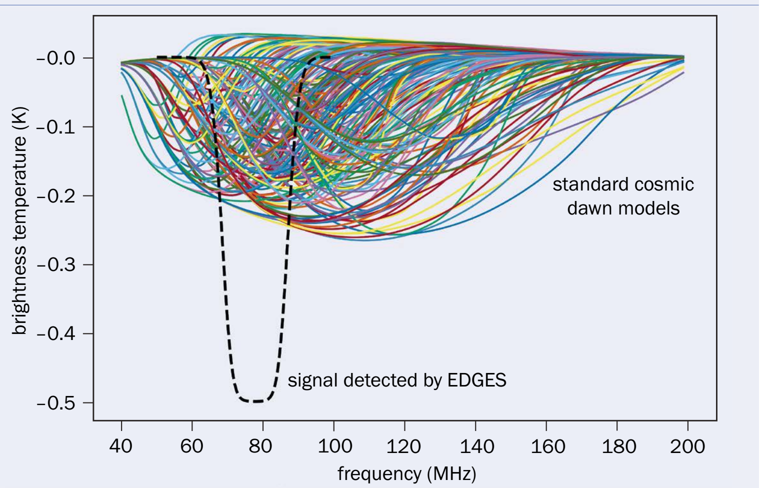
The EDGES instrument is a dipole antenna, which resembles a ping-pong table with a gap in the middle (see photo at top of article for the 2024 set-up). It is mounted

1 The 21 cm signal across cosmic time



a A simulation of the sky-averaged (global) signal as a function of time (horizontal) and space (vertical). *b* A typical model of the global 21 cm line with the main cosmic events highlighted. Each experiment searching for the global 21 cm signal focuses on a particular frequency band. For example, the Radio Experiment for the Analysis of Cosmic Hydrogen (REACH) is looking at the 50–170 MHz range (blue).

2 Weird signal



The 21 cm signals predicted by current cosmology models (coloured lines) and the detection by the EDGES experiment (dashed black line).

on a large metal groundsheet, which is about 30 × 30 m. Its ground-breaking observation was made at a remote site in western Australia, far from radio frequency interference.

But in the intervening seven years, no-one else has been able to replicate the EDGES results.

The spectrum dip that EDGES detected was very different from what theorists had expected. "There is a whole family of models that are predicted by the different cosmological scenarios," explains Ravi Subrahmanyan, a research scientist at Australia's national science agency CSIRO. "When we take measurements, we compare them with the models, so that we can rule those models in or out."

In general, the current models predict a very specific envelope of signal possibilities (see figure 1). First, they anticipate an absorption dip in brightness temperature of around 0.1 to 0.2 K, caused by the temperature difference between the cold hydrogen gas (in an expanding universe) and the warmer CMB. Then, a speedy rise and photon emission is predicted as the gas starts to warm when the first stars form, and the signal should spike dramatically when the first X-ray binary stars fire up and heat up the surrounding gas. The signal is then expected to fade as the epoch of reionization begins, because ionized particles cannot undergo the spectral transition. With models, scientists theorize when this happened, how many stars there were, and how the cosmos unfurled.

"It's just one line, but it packs in so many physical phenomena," says Fialkov, referring to the shape of the 21 cm signal's brightness temperature over time. The timing of the dip, its gradient and magnitude all represent different milestones in cosmic history, which affect how it evolved.

The EDGES team, however, reported a dip of more than double the predicted size, at about 78 MHz (see figure 2). While the frequency was consistent with predictions, the very wide and deep dip of the signal took the community by surprise.

"It would be a revolution in physics, because that signal will call for very, very exotic physics to explain it," says de Lera Acedo. "Of course, the first thing we need to do is to make sure that that is actually the signal."

A spanner in the works

The EDGES claim has galvanized the cosmology community. "It set a cat among the pigeons," says Bull. "People realized that, actually, there's some very exciting science to be done here." Some groups are trying to replicate the EDGES observation, while others are trying new approaches to detect the signal that the models promise.

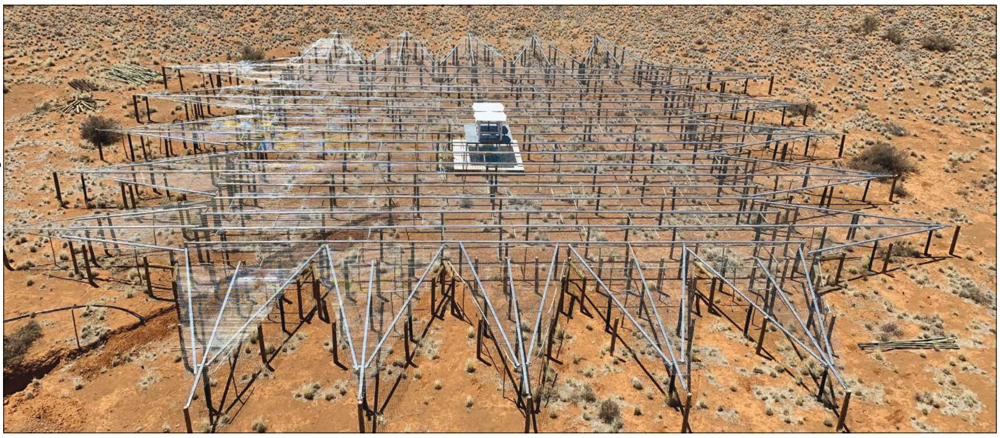
The Radio Experiment for the Analysis of Cosmic Hydrogen (REACH) – a collaboration between the University of Cambridge and Stellenbosch University in South Africa – focuses on the 50–170 MHz frequency range. Sitting on the dry and empty plains of South Africa's Northern Cape, it is targeting the EDGES observation (*Nature Astronomy* **6** 984).

In this radio-quiet environment, REACH has set up two antennas: one looks like EDGES' dipole ping-pong table, while the other is a spiral cone. They sit on top of a giant metallic mesh – the ground plate – in the shape of a many-pointed star, which aims to minimize reflections from the ground.

Hunting for this signal "requires precision cosmology and engineering", says de Lera Acedo, the principal

SARAS Team

Saurabh Pegwal, REACH collaboration



The race to replicate
(Above) Evolution of the SARAS experiment and sites up to 2020. The third edition of the telescope, SARAS 3, was deployed on lakes to further reduce radio interference. (Left) REACH went online in the Karoo region of South Africa in December 2023. (Below) MIST conducts measurements of the sky-averaged radio spectrum at frequencies below 200 MHz. Its monopole and dipole variants are highly portable and have been deployed in some of the most remote sites on Earth, including the Arctic and the Nevada desert.

Raul Monsalve

investigator on REACH. Reflections from the ground or mesh, calibration errors, and signals from the soil, are the kryptonite of cosmic dawn measurements. "You need to reduce your systemic noise, do better analysis, better calibration, better cleaning [to remove other sources from observations]," he says.

Desert, water, snow

Another radio telescope, dubbed the Shaped Antenna measurement of the background Radio Spectrum (SARAS) – which was established in the late 2000s by the Raman Research Institute (RRI) in Bengaluru, India – has undergone a number of transformations to reduce noise and limit other sources of radiation. Over time, it has morphed from a dipole on the ground to a metallic cone floating on a raft. It is looking at 40 to 200 MHz (*Exp. Astron.* **51** 193).

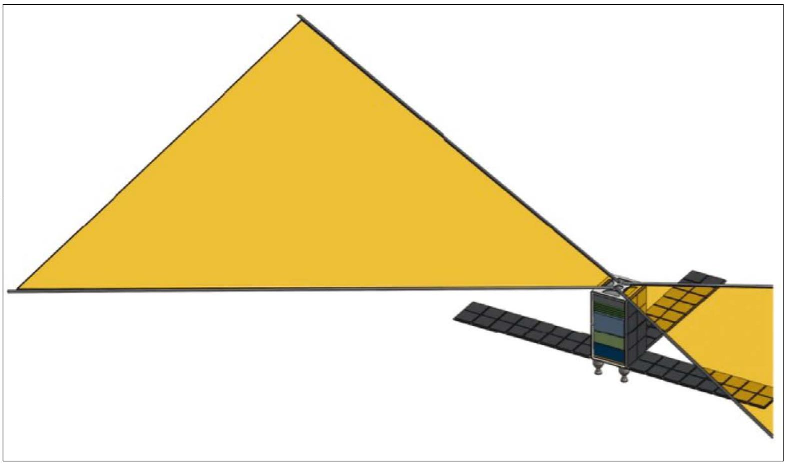
After the EDGES claim, SARAS pivoted its attention to verifying the detection, explains Saurabh Singh, a research scientist at the RRI. "Initially, we were not able to get down to the required sensitivity to be able to say anything about their detection," he explains. "That's why we started floating our radiometer on water." Buoying the experiment reduces ground contamination and creates a more predictable surface to include in calculations.

Using data from their floating radiometer, in 2022 Singh and colleagues disfavoured EDGES' claim (*Nature Astronomy* **6** 607), but for many groups the detection still remains a target for observations.

While SARAS has yet to detect a cosmic-dawn signal of its own, Singh says that non-detection is also an important element of finding the global 21 cm signal. "Non-detection gives us an opportunity to rule out a lot of these models, and that has helped us to reject a lot of properties of these stars and galaxies," he says.

Raul Monsalve Jara – a cosmologist at the University of California, Berkeley – has been part of the EDGES collaboration since 2012, but decided to also explore other ways to detect the signal. "My view is that we need several experiments doing different things and taking different approaches," he says.

The Mapper of the IGM Spin Temperature (MIST)



Taking the hunt to space Provisional illustration of the CosmoCube with its antenna deployed for the 21 cm signal detection, i.e. in operational mode in space. This nanosatellite would travel to the far side of the Moon to get away from the Earth's ionosphere, which introduces substantial distortions and absorption effects to any radio signal detection.

experiment, of which Monsalve is co-principal investigator, is a collaboration between Chilean, Canadian, Australian and American researchers. These instruments are looking at 25 to 105 MHz (*MNRAS* **530** 4125). "Our approach was to simplify the instrument, get rid of the metal ground plate, and to take small, portable instruments to remote locations," he explains. These locations have to fulfil very specific requirements – everything around the instrument, from mountains to the soil, can impact the instrument's performance. "If the soil itself is irregular, that will be very difficult to characterize and its impact will be difficult to remove [from observations]," Monsalve says.

So far, the MIST instrument, which is also a dipole ping-pong table, has visited a desert in California, another in Nevada, and even the Arctic. Each time, the researchers spend a few weeks at the site collecting data, and it is portable and easy to set up, Monsalve explains. The team is planning more observations in Chile. "If you suspect that your environment could be doing something to your measurements, then you need to be able to move around," continues Monsalve. "And we are contributing to the field by doing that."

Aaron Parsons, also from the University of California, Berkeley, decided that the best way to detect this elusive signal would be to try and eliminate the ground entirely – by suspending a rotating antenna over a giant canyon with 100 m empty space in every direction.

His Electromagnetically Isolated Global Signal Estimation Platform (EIGSEP) includes an antenna hanging four storeys above the ground, attached to Kevlar cable strung across a canyon in Utah. It's observing at 50 to 250 MHz. "It continuously rotates around and twists every which way," Parsons explains. Hopefully, that will allow them to calibrate the instrument very accurately. Two antennas on the ground cross-correlate observations. EIGSEP began making observations last year.

More experiments are expected to come online in the next year. The Remote HI eNvironment Observer (RHINO), an initiative of the University of Manchester, will have a horn-shaped receiver made of a metal mesh that is usually used to construct skyscrapers. Horn shapes are particularly good for calibration, allowing for very precise measurements. The most famous horn-shaped antenna is Bell Laboratories' Holmdel Horn Antenna in the US, with which two scientists accidentally discovered the CMB in 1965.

Initially, RHINO will be based at Jodrell Bank Observatory in the UK, but like other experiments, it could travel to other remote locations to hunt for the 21 cm signal.

Similarly, Subrahmanyan – who established the SARAS experiment in India and is now with CSIRO in Australia – is working to design a new radiometer from scratch. The instrument, which will focus on 40–160 MHz, is called Global Imprints from Nascent Atoms to Now (GINAN). He says that it will feature a recently patented self-calibrating antenna. "It gives a much more authentic measurement of the sky signal as measured by the antenna," he explains.

In the meanwhile, the EDGES collaboration has not been idle. MIT Haystack Observatory's Cappallo project manages EDGES, which is currently in its third iteration. It is still the size of a desk, but its top now looks like a box, with closed sides and its electronics tucked inside, and an even larger metal ground plate. The team has now made observations from islands in the Canadian archipelago and in Alaska's Aleutian island chain (see photo at top of article).

"The 2018 EDGES result is not going to be accepted by the community until somebody completely independently verifies it," Cappallo explains. "But just for our own sanity and also to try to improve on what we can do, we want to see it from as many places as possible and as many conditions as possible." The EDGES team has replicated its results using the same data analysis pipeline, but no-one else has been able to reproduce the unusual signal.

All the astronomers interviewed welcomed the introduction of new experiments. "I think it's good to have a rich field of people trying to do this experiment because nobody is going to trust any one measurement," says Parsons. "We need to build consensus here."

Taking off

Some astronomers have decided to avoid the struggles of trying to detect the global 21 cm signal from Earth – instead, they have their sights set on the Moon. Earth's atmosphere is one of the reasons why the 21 cm signal is so difficult to measure. The ionosphere, a charged region of the atmosphere, distorts and contaminates this incredibly faint signal. On the far side of the Moon, any antenna would also be shielded from the cacophony of radio-frequency interference from Earth.

"This is why some experiments are going to the Moon," says Parsons, adding that he is involved in NASA's LuSEE-Night experiment. LuSEE-Night, or the Lunar Surface Electromagnetics Experiment, aims to land a low-frequency experiment on the Moon next year.

In July, at the National Astronomical Meeting in Durham, the University of Cambridge's de Lera Acedo presented a proposal to put a miniature radiometer into lunar orbit. Dubbed "Cosmocube", it will be a nanosatellite that will orbit the Moon searching for this 21 cm signal.

"It is just in the making," says de Lera Acedo, adding that it will not be in operation for at least a decade. "But it is the next step."

In the meanwhile, groups here on Earth are in a race to detect this elusive signal. The instruments are getting more sensitive, the modelling is improving, and the unknowns are reducing. "If we do the experiments right, we will find the signal," Monsalve believes. The big question is who, of the many groups with their hat in the ring, is doing the experiment "right". ■

A sensitive approach to the brain

UK start-up Crainio won the Lee Lucas award from the Institute of Physics in 2024 for developing a sensor that can non-invasively measure intracranial pressure. The firm's chief scientist **Panicos Kyriacou** tells Tami Freeman how it could help diagnose traumatic brain injury

Traumatic brain injury (TBI), caused by a sudden impact to the head, is a leading cause of death and disability. After such an injury, the most important indicator of how severe the injury is intracranial pressure – the pressure inside the skull. But currently, the only way to assess this is by inserting a pressure sensor into the patient's brain. UK-based start-up Crainio aims to change this by developing a non-invasive method to measure intracranial pressure using a simple optical probe attached to the patient's forehead. Tami Freeman recently caught up with the company's chief scientist Panicos Kyriacou to find out more.

Crainio

Powerful mind Based at City St George's, University of London, Panicos Kyriacou is also chief scientist at Crainio, which is developing a brain-pressure sensor that he thinks could be widely used.

AUDIO Listen to our full podcast interview with Panicos Kyriacou

Why is diagnosing TBI such an important clinical challenge?

Every three minutes in the UK, someone is admitted to hospital with a head injury, it's a very common problem. But when someone has a blow to the head, nobody knows how bad it is until they actually reach the hospital. TBI is something that, at the moment, cannot be assessed at the point of injury.

From the time of impact to the time that the patient receives an assessment by a neurosurgical expert is known as the golden hour. And nobody knows what's happening to the brain during this time – you don't know how best to manage the patient, whether they have a severe TBI with intracranial pressure rising in the head, or just a concussion or a medium TBI.

Once at the hospital, the neurosurgeons have to assess the patient's intracranial pressure, to determine whether it is above the threshold that classifies the injury as severe. And to do that, they have to drill a hole in the head – literally – and place an electrical probe into the brain. This really is one of the most invasive non-therapeutic procedures, and you obviously can't do this to every patient that comes with a blow in the head. It has its risks, there is a risk of haemorrhage or of infection.

Therefore, there's a need to develop technologies that can measure intracranial pressure more effectively, earlier and in a non-invasive manner. For many years, this was almost like a dream: "How can you access the brain and see if the pressure is rising in the brain, just by placing an optical sensor on the forehead?"

Crainio has now created such a non-invasive sensor; what led to this breakthrough?

The research goes back to 2016, at the Research Centre for Biomedical Engineering at City, University of London (now City St George's, University of London), when the National Institute for Health Research (NIHR) gave us our first grant to investigate the feasibility of a non-invasive intracranial sensor based on light technologies. We developed a prototype, secured the intellectual property and conducted a feasibility study on TBI patients at the Royal London Hospital, the biggest trauma hospital in the UK.

It was back in 2021, before Crainio was established, that we first discovered that after we shone certain frequencies of light, like near-infrared, into the brain through the forehead, the optical signals coming back – known as the photoplethysmogram, or PPG – contained information about the physiology or the haemodynamics of the brain.

When the pressure in the brain rises, the brain swells up, but it cannot go anywhere because the skull is like concrete. Therefore, the arteries and vessels in the brain are compressed by that pressure. PPG measures changes in blood volume as it pulses through the arteries during the cardiac cycle. If you have a viscoelastic artery that is opening and closing, the volume of blood changes and this is captured by the PPG. Now, if you have an artery that is compromised, pushed down because of pressure in the brain, that viscoelastic property is impacted and that will impact the PPG.

Changes in the PPG signal due to changes arising from compression of the vessels in the brain, can give us information about the intracranial pressure. And we developed algorithms to interrogate this optical signal and machine-learning models to estimate intracranial pressure.

How did the establishment of Crainio help to progress the sensor technology?

Following our research within the university, Crainio was set up in 2022. It brought together a team of experts in medical devices and optical sensors to lead the further development and commercialization of this device. And this small team worked tirelessly over the last few years to generate funding to progress the development of the optical sensor technology and bring it to a level that is ready for further clinical trials.

The primary motivation of Crainio is to create solutions for healthcare, developing a technology that can help clinicians to diagnose traumatic brain injury effectively, faster, accurately and earlier

In 2023, Crainio was successful with an Innovate UK biomedical catalyst grant, which will enable the company to engage in a clinical feasibility study, optimize the probe technology and further develop the algorithms. The company was later awarded another NIHR grant to move into a validation study.

The interest in this project has been overwhelming. We've had a very positive feedback from the neurocritical care community. But we also see a lot of interest from communities where injury to the brain is significant, such as rugby associations, for example.

Could the device be used in the field, at the site of an accident?

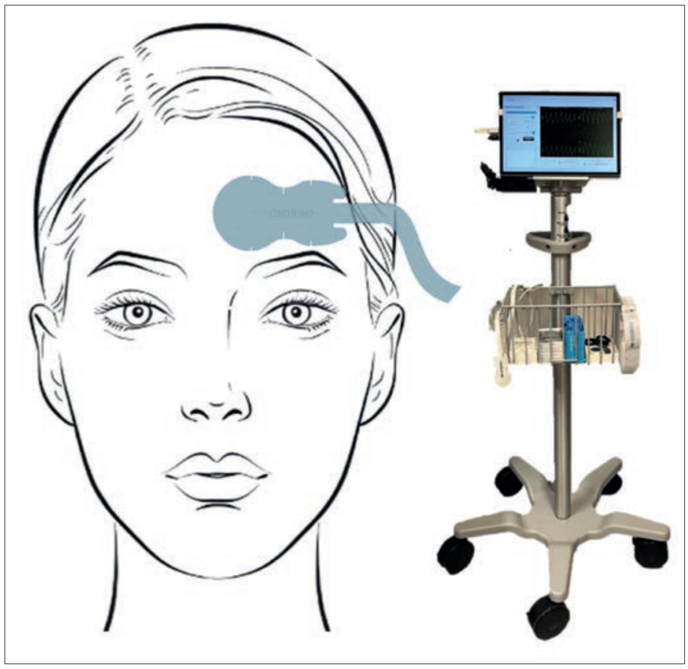
While Crainio's primary focus is to deliver a technology for use in critical care, the system could also be used in ambulances, in helicopters, in transfer patients and beyond. The device is non-invasive, the sensor is just like a sticking plaster on the forehead and the backend is a small box containing all the electronics. In the past few years, working in a research environment, the technology was connected into a laptop computer. But we are now transferring everything into a graphical interface, with a monitor to be able to see the signals and the intracranial pressure values in a portable device.

Following preliminary tests on patients, Crainio is now starting a new clinical trial. What do you hope to achieve with the next measurements?

The first study, a feasibility study on the sensor technology, was done during the time when the project was within the university. The second round is led by Crainio using a more optimized probe. Learning from the technical challenges we had in the first study, we tried to mitigate them with a new probe design. We've also learned more about the challenges associated with the acquisition of signals, the type of patients, how long we should monitor.

We are now at the stage where Crainio has redeveloped the sensor and it looks amazing. The technology has received approval by MHRA, the UK regulator, for clinical studies and ethical approvals have been secured. This will be an opportunity to work with the new probe, which has more advanced electronics that enable more detailed acquisition of signals from TBI patients.

We are again partnering with the Royal London Hospital, as well as collaborators from the traumatic brain injury team at Cambridge and we're expecting to enter clinical trials soon. These are patients admitted into neurocritical trauma units and they all have an invasive intracranial pressure bolt. This will allow us to compare the physiological signal coming from our intracranial pressure sensor with the gold standard.



Crainio

Easy does it Crainio has found a non-invasive way to measure brain pressure using a sensor that can be placed like a sticking plaster on the forehead and the backend being a small box containing all the electronics.

The signals will be analysed by Crainio's data science team, with machine-learning algorithms used to look at changes in the PPG signal, extract morphological features and build models to develop the technology further. So we're enriching the study with a more advanced technology, and this should lead to more accurate machine-learning models for correctly capturing dynamic changes in intracranial pressure.

This time around, we will also record more information from the patients. We will look at CT scans to see whether scalp density and thickness have an impact. We will also collect data from commercial medical monitors within neurocritical care to see the relation between intracranial pressure and other physiological data acquired in the patients. We aim to expand our knowledge of what happens when a patient's intracranial pressure rises – what happens to their blood pressures? What happens to other physiological measurements?

How far away is the system from being used as a standard clinical tool?

Crainio is very ambitious. We're hoping that within the next couple of years we will progress adequately in order to achieve CE marking and meet the standards that are necessary to launch a medical device.

The primary motivation of Crainio is to create solutions for healthcare, developing a technology that can help clinicians to diagnose TBI effectively, faster, accurately and earlier. This can only yield better outcomes and improve patients' quality of life.

Of course, as a company we're interested in being successful commercially. But the ambition here is, first of all, to keep the cost affordable. We live in a world where medical technologies need to be affordable, not only for Western nations, but for nations that cannot afford state-of-the-art technologies. So this is another of Crainio's primary aims, to create a technology that could be used widely, because there is a massive need, but also because it's affordable.

Tami Freeman is an online editor of *Physics World*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The forgotten pioneers of computational physics

In the early years of computational physics, starting during the Second World War, the discipline and its practitioners did not yet have a name. **Iulia Georgescu** tells the story of these forgotten figures and calls for a wider appreciation of research software engineers

Iulia Georgescu is science manager at the Institute of Physics, but writes this in a personal capacity

When you look back at the early days of computing, some familiar names pop up, including John von Neumann, Nicholas Metropolis and Richard Feynman. But they were not lonely pioneers – they were part of a much larger group, using mechanical and then electronic computers to do calculations that had never been possible before.

These people, many of whom were women, were the first scientific programmers and computational scientists. Skilled in the complicated operation of early computing devices, they often had degrees in maths or science, and were an integral part of research efforts. And yet, their fundamental contributions are mostly forgotten.

This was in part because of their gender – it was an age when sexism was rife, and it was standard for women to be fired from their job after getting married. However, there is another important factor that is often overlooked, even in today's scientific community – people in technical roles are often underappreciated and underacknowledged, even though they are the ones who make research possible.

Human and mechanical computers

Originally, a "computer" was a human being who did calculations by hand or with the help of a mechanical calculator. It is thought that the world's first computational lab was set up in 1937 at Columbia University. But it wasn't until the Second World War that the demand for computation really exploded; with the need for artillery calculations, new technologies and code breaking.

In the US, the development of the atomic bomb during the Manhattan Project (established in 1943) required huge computational efforts, so it wasn't long before the New Mexico site had a hand-computing group. Called the T-5 group of the Theoretical Division, it initially consisted of about 20 people. Most were women, including the spouses of other scientific staff. Among them was Mary Frankel, a mathematician married to physicist Stan Frankel; mathematician Augusta "Mici" Teller who was married to Edward Teller, the "father of the hydrogen bomb"; and Jean Bacher, the wife of physicist Robert Bacher.

As the war continued, the T-5 group expanded to include civilian recruits from the nearby towns and members of the Women's Army Corps. Its staff worked around the clock, using printed mathematical tables and desk calculators in four-hour shifts – but that was not enough to keep up with the computational needs for bomb development. In the early spring of 1944, IBM punch-card machines were brought in to supplement the human power. They became so effective that the machines were

LANL/Science Source/Science Picture Library

soon being used for all large calculations, 24 hours a day, in three shifts.

The computational group continued to grow, and among the new recruits were Naomi Livesay and Eleonor Ewing. Livesay held an advanced degree in mathematics and had done a course in operating and programming IBM electric calculating machines, making her an ideal candidate for the T-5 division. She in turn recruited Ewing, a fellow mathematician who was a former colleague. The two young women supervised the running of the IBM machines around the clock.

The frantic pace of the T-5 group continued until the end of the war in September 1945. The development of the atomic bomb required an immense computational effort, which was made possible through hand and punch-card calculations.

Electronic computers

Shortly after the war ended, the first fully electronic, general-purpose computer – the Electronic Numerical Integrator and Computer (ENIAC) – became operational at the University of Pennsylvania, following two years of development. The project had been led by physicist John Mauchly and electrical engineer J Presper Eckert. The machine was operated and coded by six women – mathematicians Betty Jean Jennings (later Bartik); Kathleen, or Kay, McNulty (later Mauchly, then Antonelli); Frances Bilas (Spence); Marlyn Wescoff (Meltzer) and Ruth Lichterman (Teitelbaum); as well as Betty Snyder (Holberton) who had studied journalism.

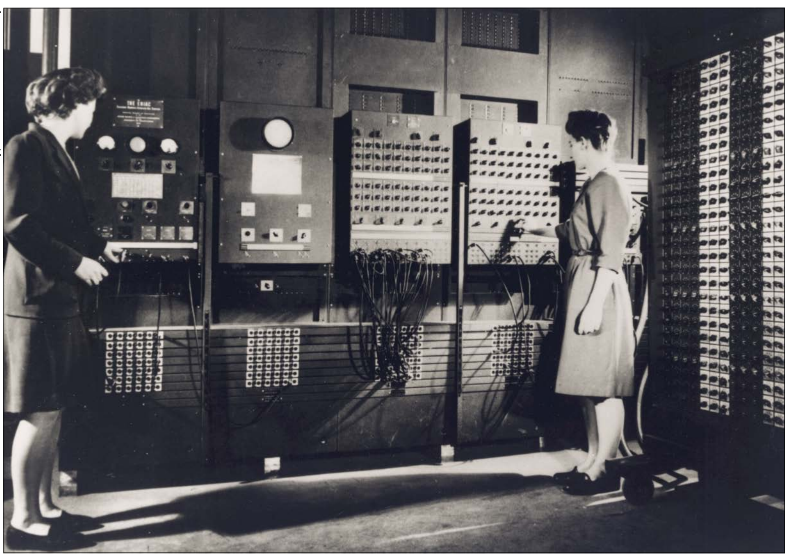
Polymath John von Neumann also got involved when looking for more computing power for projects at the new Los Alamos Laboratory, established in New Mexico

Out of the picture
The MANIAC was a programmable computer built and operated at Los Alamos from 1952 to 1958. It was run by a large team of scientists, mathematicians and engineers, but the latter two groups – many of whom were women – tend to be omitted from accounts of this important project.

US government

Human computers The term “computer” originally referred to people who performed calculations by hand. Here, Kay McNulty, Alyse Snyder and Sis Stump operate the differential analyser in the basement of the Moore School of Electrical Engineering, University of Pennsylvania, circa 1942–1945.

US Army/ ARL Technical Library



World first The ENIAC was the first programmable, electronic, general-purpose digital computer. It was built at the US Army’s Ballistic Research Laboratory in 1945, then moved to the University of Pennsylvania in 1946. Its initial team of six coders and operators were all women, including Betty Jean Jennings (later Bartik – left of photo) and Frances Bilas (later Spence – right of photo). They are shown preparing the computer for Demonstration Day in February 1946.

in 1947. In fact, although originally designed to solve ballistic trajectory problems, the first problem to be run on the ENIAC was “the Los Alamos problem” – a thermonuclear feasibility calculation for Teller’s group studying the H-bomb.

Like in the Manhattan Project, several husband-and-wife teams worked on the ENIAC, the most famous being von Neumann and his wife Klara Dán, and mathematicians Adele and Herman Goldstine. Dán von Neumann in particular worked closely with Nicholas Metropolis, who alongside mathematician Stanislaw Ulam had coined the term Monte Carlo to describe numerical methods based on random sampling. Indeed, between 1948 and 1949 Dán von Neumann and Metropolis ran the first series of Monte Carlo simulations on an electronic computer.

Work began on a new machine at Los Alamos in 1948 – the Mathematical Analyzer Numerical Integrator and Automatic Computer (MANIAC) – which ran its first large-scale hydrodynamic calculation in March 1952. Many of its users were physicists, and its operators and coders included mathematicians Mary Tsingou (later Tsingou-Menzel), Marjorie Jones (Devaney) and Elaine Felix (Alei); plus Verna Ellingson (later Gardiner) and Lois Cook (Leurgans).

Early algorithms

The Los Alamos scientists tried all sorts of problems on the MANIAC, including a chess-playing program – the first documented case of a machine defeating a human at the game. However, two of these projects stand out because they had profound implications on computational science.

In 1953 the Tellers, together with Metropolis and physicists Arianna and Marshall Rosenbluth, published the seminal article “Equation of state calculations by fast computing machines” (*J. Chem. Phys.* **21** 1087). The work introduced the ideas behind the “Metropolis (later renamed Metropolis–Hastings) algorithm”, which is a Monte Carlo method that is based on the concept of “importance sampling”. (While Metropolis was involved in the development of Monte Carlo methods, it appears that he did not contribute directly to the article, but provided access to the MANIAC nightshift.) This is the progenitor of the Markov Chain Monte Carlo methods, which are widely used today throughout science and engineering.

Marshall later recalled how the research came about when he and Arianna had proposed using the MANIAC to study how solids melt (*AIP Conf. Proc.* **690** 22).

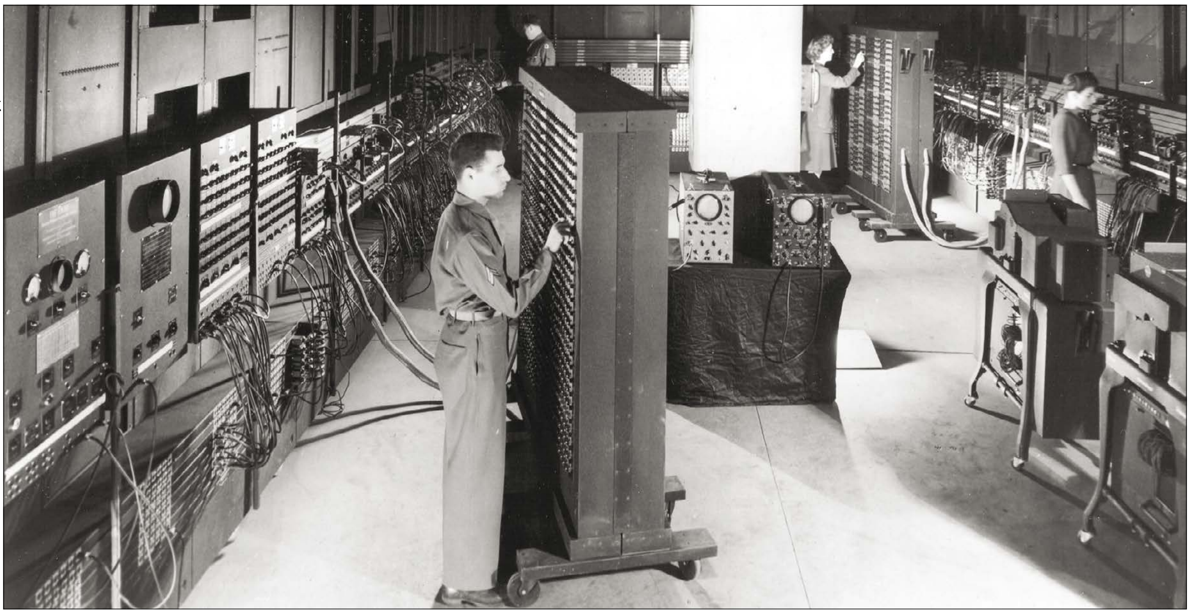
Edward Teller meanwhile had the idea of using statistical mechanics and taking ensemble averages instead of following detailed kinematics for each individual disk, and Mici helped with programming during the initial stages. However, the Rosenbluths did most of the work, with Arianna translating and programming the concepts into an algorithm.

The 1953 article is remarkable, not only because it led to the Metropolis algorithm, but also as one of the earliest examples of using a digital computer to simulate a physical system. The main innovation of this work was in developing “importance sampling”. Instead of sampling from random configurations, it samples with a bias toward physically important configurations which contribute more towards the integral.

Furthermore, the article also introduced another computational trick, known as “periodic boundary conditions” (PBCs): a set of conditions which are often used to approximate an infinitely large system by using a small part known as a “unit cell”. Both importance sampling and PBCs went on to become workhorse methods in computational physics.

In the summer of 1953, physicist Enrico Fermi, Ulam, Tsingou and physicist John Pasta also made a significant breakthrough using the MANIAC. They ran a “numerical experiment” as part of a series meant to illustrate possible uses of electronic computers in studying various physical phenomena.

US Army / Harold Breaux



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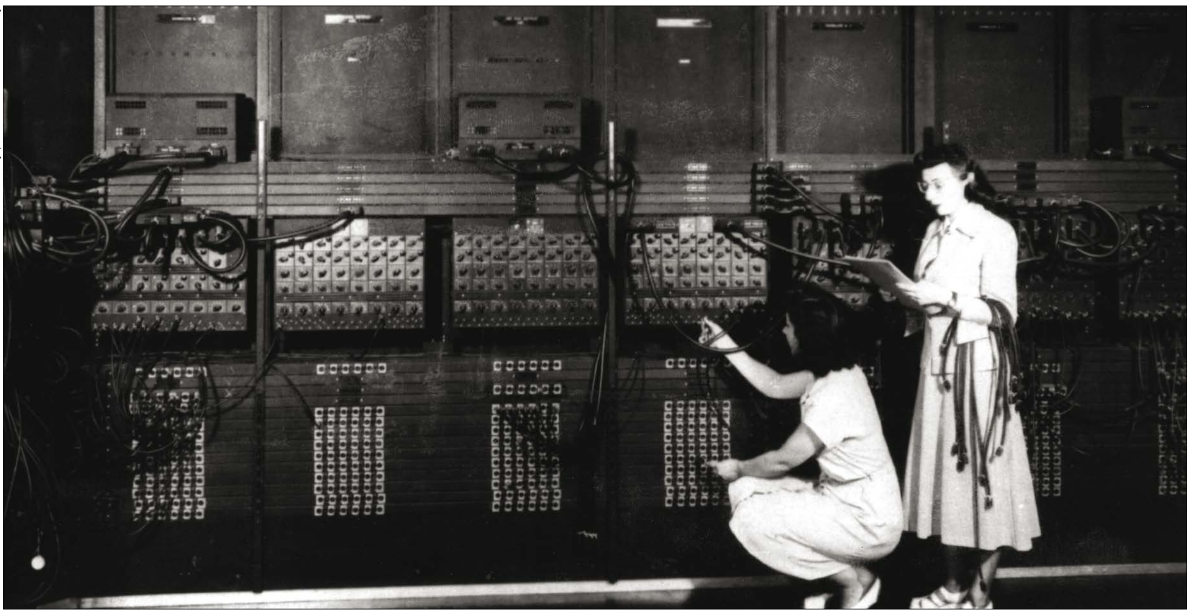

Skilled role
Operating the ENIAC required an analytical mind as well as technical skills. (Top) Irwin Goldstein setting the switches on one of the ENIAC's function tables at the Moore School of Electrical Engineering in 1946. (Bottom) Gloria Gordon (later Bolotsky – crouching) and Ester Gerston (standing) wiring the right side of the ENIAC with a new program, c. 1946.

The team modelled a 1D chain of oscillators with a small nonlinearity to see if it would behave as hypothesized, reaching an equilibrium with the energy redistributed equally across the modes (doi.org/10.2172/4376203). However, their work showed that this was not guaranteed for small perturbations – a non-trivial and non-intuitive observation that would not have been apparent without the simulations. It is the first example of a physics discovery made not by theoretical or experimental means, but through a computational approach. It would later lead to the discovery of solitons and integrable models, the development of chaos theory, and a deeper understanding of ergodic limits.

Although the paper says the work was done by all four scientists, Tsingou's role was forgotten, and the results became known as the Fermi–Pasta–Ulam problem. It was not until 2008, when French physicist Thierry Dauxois advocated for giving her credit in a *Physics Today* article, that Tsingou's contribution was properly acknowledged. Today the finding is called the Fermi–Pasta–Ulam–Tsingou problem.

The year 1953 also saw IBM's first commercial, fully electronic computer – an IBM 701 – arrive at Los Alamos. Soon the theoretical division had two of these machines, which, alongside the MANIAC, gave the scientists unprecedented computing power. Among those to take advantage of the new devices were Martha Evans (whom very little is known about) and theoretical physicist Francis Harlow, who began to tackle the largely unexplored subject of computational fluid dynamics.

The idea was to use a mesh of cells through which the fluid, represented as particles, would move. This computational method made it possible to solve complex hydrodynamics problems (involving large distortions and compressions of the fluid) in 2D and 3D. Indeed, the method proved so effective that it became a standard tool in plasma physics where it has been applied to every conceivable topic from astrophysical plasmas to fusion energy.

The resulting internal Los Alamos report – *The Particle-in-cell Method for Hydrodynamic Calculations*, published in 1955 – showed Evans as first author and acknowledged eight people (including Evans) for the machine calculations. However, while Harlow is remem-

An evolving identity

In the 1950s there was no computational physics or computer science, therefore it's unsurprising that the practitioners of these disciplines went by different names, and their identity has evolved over the decades since.

1930s–1940s
Originally a "computer" was a person doing calculations by hand or with the help of a mechanical calculator.

Late 1940s – early 1950s
A "coder" was a person who translated mathematical concepts into a set of instructions in machine language. John von Neumann and Herman Goldstine distinguished between "coding" and "planning", with the former being the lower-level work of turning flow diagrams into machine language (and doing the physical configuration) while the latter did the mathematical analysis of the problem.

Meanwhile, an "operator" would physically handle the computer (replacing punch cards, doing the rewiring, etc). In the late-1940s coders were also operators.

As historians note in the book *ENIAC in Action* this was an age where "It was hard to devise the mathematical treatment without a good knowledge of the processes of mechanical computation…It was also hard to operate the ENIAC without understanding something about the mathematical task it was undertaking."

For the ENIAC a "programmer" was not a person but "a unit combining different sequences in a coherent computation". The term would later shift and eventually overlap with the meaning of coder as a person's job.

1960s
Computer scientist Margaret Hamilton, who led the development of the on-board flight software for NASA's Apollo programme, coined the term "software engineering" to distinguish the practice of designing, developing, testing and maintaining software from the engineering tasks associated with the hardware.

1980s – early 2000s
Using the term "programmer" for someone who coded computers peaked in popularity in the 1980s, but by the 2000s was replaced in favour of other job titles such as various flavours of "developer" or "software architect".

Early 2010s
A "research software engineer" is a person who combines professional software engineering expertise with an intimate understanding of scientific research.


US government / Los Alamos National Laboratory

A mind for chess Paul Stein (left) and Nicholas Metropolis play "Los Alamos" chess against the MANIAC. "Los Alamos" chess was a simplified version of the game, with the bishops removed to reduce the MANIAC's processing time between moves. The computer still needed about 20 minutes between moves. The MANIAC became the first computer to beat a human opponent at chess in 1956.

bered as one of the pioneers of computational fluid dynamics, Evans was forgotten.

A clear-cut division of labour?

In an age where women had very limited access to the frontlines of research, the computational war effort brought many female researchers and technical staff in. As their contributions come more into the light, it becomes clearer that their role was not a simple clerical one.

There is a view that the coders' work was "the vital link between the physicist's concepts (about which the coders more often than not didn't have a clue) and their translation into a set of instructions that the computer was able to perform, in a language about which, more often than not, the physicists didn't have a clue either", as physicists Giovanni Battimelli and Giovanni Ciccotti wrote in 2018 (*Eur. Phys. J. H* **43** 303). But the examples we have seen show that some of the coders had a solid grasp of the physics, and some of the physicists had a good understanding of the machine operation. Rather than a skilled–non-skilled/men–women separation, the division of labour was blurred. Indeed, it was more of an effective collaboration between physicists, mathematicians and engineers.

Even in the early days of the T-5 division before electronic computers existed, Livesay and Ewing, for example, attended maths lectures from von Neumann, and introduced him to punch-card operations. As has been documented in books including *Their Day in the Sun* by Ruth Howes and Caroline Herzenberg, they also took part in the weekly colloquia held by J Robert Oppenheimer and other project leaders. This shows they should not be dismissed as mere human calculators and machine operators who supposedly "didn't have a clue" about physics.

Verna Ellingson (Gardiner) is another forgotten coder who worked at Los Alamos. While little information about her can be found, she appears as the last author on a 1955 paper (*Science* **122** 465) written with Metropolis and physicist Joseph Hoffman – "Study of tumor cell populations by Monte Carlo methods". The next year she was first author of "On certain sequences of integers defined by sieves" with mathematical physicist Roger Lazarus, Metropolis and Ulam (*Mathematics Magazine* **29** 117). She also worked with physicist George Gamow on attempts to discover the code for DNA selection of amino acids, which just shows the breadth of projects she was involved in.

Evans not only worked with Harlow but took part in a 1959 conference on self-organizing systems, where she queried AI pioneer Frank Rosenblatt on his ideas about human and machine learning. Her attendance at such a meeting, in an age when women were not common attendees, implies we should not view her as "just a coder".

With their many and wide-ranging contributions, it is more than likely that Evans, Gardiner, Tsingou and many others were full-fledged researchers, and were perhaps even the first computational scientists. "These women were doing work that modern computational physicists in the [Los Alamos] lab's XCP [Weapons Computational Physics] Division do," says Nicholas Lewis, a historian at Los Alamos. "They needed a deep understanding of both the physics being studied, and of how to map the problem to the particular architecture of the machine being used."


US government / Los Alamos National Laboratory

What's in a name Marjory Jones (later Devaney), a mathematician, shown in 1952 punching a program onto paper tape to be loaded into the MANIAC.

Overlooked then, overlooked now

Credited or not, these pioneering women and their contributions have been mostly forgotten, and only in recent decades have their roles come to light again. But why were they obscured by history in the first place?

Secrecy and sexism seem to be the main factors at play. For example, Livesay was not allowed to pursue a PhD in mathematics because she was a woman, and in the cases of the many married couples, the team contributions were attributed exclusively to the husband. The existence of the Manhattan Project was publicly announced in 1945, but documents that contain certain nuclear-weapons-related information remain classified today. Because these are likely to remain secret, we will never know the full extent of these pioneers' contributions.

But another often overlooked reason is the widespread underappreciation of the key role of computational scientists and research software engineers, a term that was only coined just over a decade ago. Even today, these non-traditional research roles end up being undervalued. A 2022 survey by the UK Software Sustainability Institute, for example, showed that only 59% of research software engineers were named as authors, with barely a quarter (24%) mentioned in the acknowledgements or main text, while a sixth (16%) were not mentioned at all.

The separation between those who understand the physics and those who write the code, understand and operate the hardware goes back to the early days of computing (see box opposite), but it wasn't entirely accurate even then. People who implement complex scientific computations are not just coders or skilled operators of supercomputers, but truly multidisciplinary scientists who have a deep understanding of the scientific problems, mathematics, computational methods and hardware.

Such people – whatever their gender – play a key role in advancing science and yet remain the unsung heroes of the discoveries their work enables. Perhaps what this story of the forgotten pioneers of computational physics tells us is that some views rooted in the 1950s are still influencing us today. It's high time we moved on. ■

● The author thanks Nicholas Lewis and Thomas Haigh for the very useful discussions

People who implement complex scientific computations are truly multi-disciplinary scientists who have a deep understanding of the scientific problems, mathematics, computational methods and hardware


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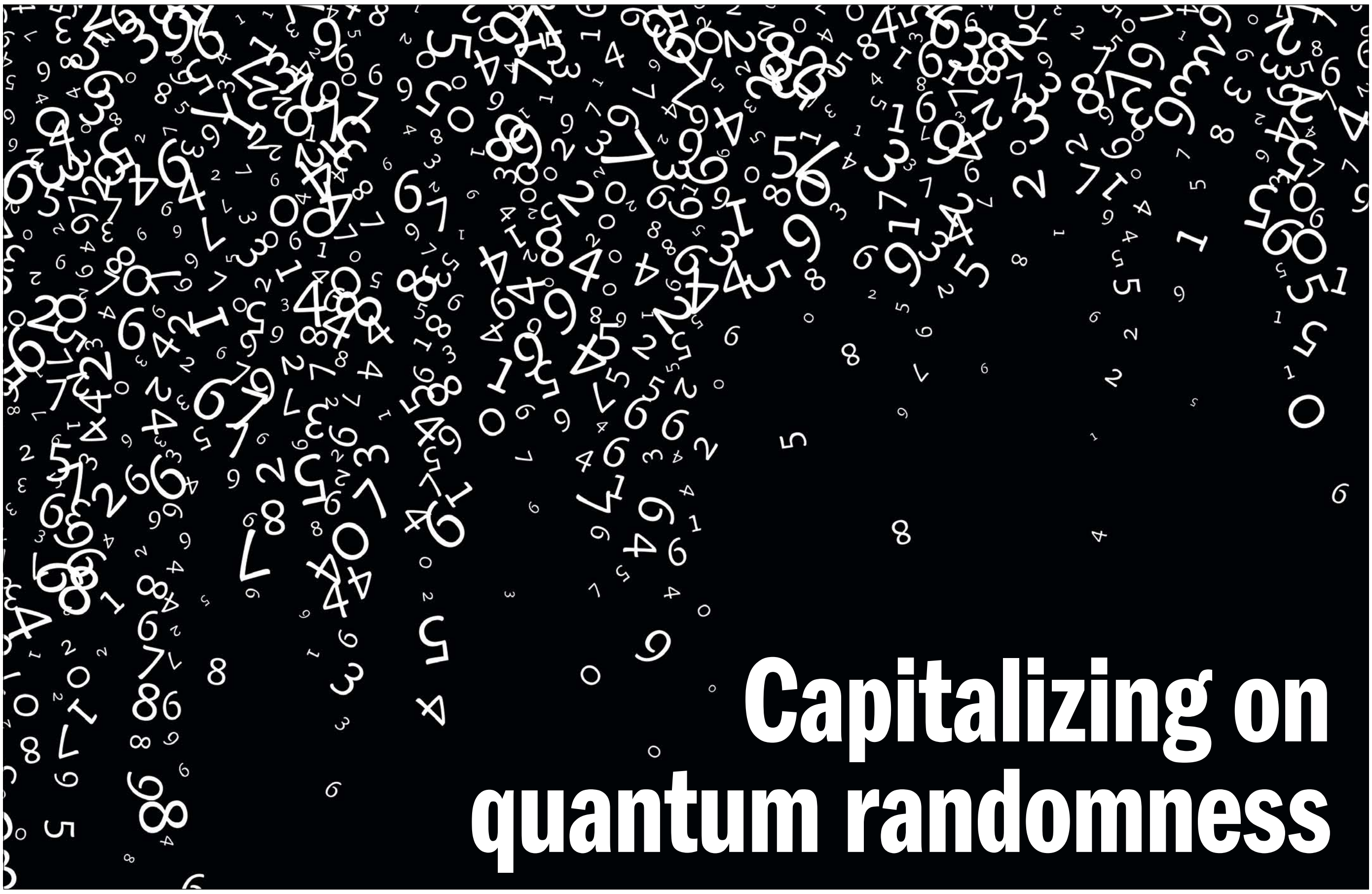

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Capitalizing on quantum randomness

Roll of the dice Quantum Dice is generating truly random numbers by taking advantage of the inherent randomness of certain quantum properties.

Ramy Shelbaya – co-founder and chief executive of UK firm Quantum Dice – talks to **Anna Demming** about how the company is using quantum mechanics to generate random numbers, and the challenges and rewards of persuading clients, staff and hardware to work together

Ramy Shelbaya has been hooked on physics ever since he was a 12-year-old living in Egypt and read about the Joint European Torus (JET) fusion experiment in the UK. Biology and chemistry were interesting to him but never quite as "satisfying", especially as they often seemed to boil down to physics in the end. "So I thought, maybe that's where I need to go," Shelbaya recalls.

His instincts seem to have led him in the right direction. Shelbaya is now chief executive of Quantum Dice, an Oxford-based start-up he co-founded in 2020 to develop quantum hardware for exploiting the inherent randomness in quantum mechanics. It closed its first funding round in 2021 with a seven-figure investment from a consortium of European investors, while also securing grant funding on the same scale.

Now providing cybersecurity hardware systems for clients such as BT, Quantum Dice is launching a piece of hardware for probabilistic computing, based on the same core innovation. Full of joy and zeal for his work, Shelbaya admits that his original decision to pursue physics was "scary". Back then, he didn't know anyone who had studied the subject and was not sure where it might lead.

The journey to a start-up

Fortunately, Shelbaya's parents were on board from the start and their encouragement proved "incredibly helpful". His teachers also supported him to explore physics in his extracurricular reading, instilling a confidence in the subject that eventually led Shelbaya to do undergraduate and master's degrees in physics at École normale supérieure PSL in France.

He then moved to the UK to do a PhD in atomic and laser physics at the University of Oxford. Just as he was wrapping up his PhD, Oxford University Innovation (OUI) – which manages its technology transfer and consulting activities – launched a new initiative that proved pivotal to Shelbaya's career.

OUI had noted that the university generated a lot of intellectual property and research results that could be commercialized but that the academics producing it often favoured academic work over progressing the technology transfer themselves. On the other hand, lots of students were interested in entering the world of business.

To encourage those who might be business-minded to found their own firms, while also fostering more spin-outs from the university's patents and research, OUI launched the Student Entrepreneurs' Programme (StEP). A kind of talent show to match budding entrepreneurs with technology ready for development, StEP invited participants to team up, choose commercially promising research from the university, and pitch for support and mentoring to set up a company.

As part of Oxford's atomic and laser physics department, Shelbaya was aware that it had been developing a quantum random number generator. So when the competition was launched, he collaborated with other competition participants to pitch the device. "My team won, and this is how Quantum Dice was born."

Random value

The initial technology was geared towards quantum random number generation, for particular use in cybersecurity. Random numbers are at the heart of all encryption algorithms, but generating truly random numbers has been a stumbling block, with the "pseudorandom" numbers people make do with being prone to prediction and hence security violation.

Quantum mechanics provides a potential solution because there is inherent randomness in the values of certain quantum properties. Although for a long time this randomness was "a bane to quantum physicists", as Shelbaya puts it, Quantum Dice and other companies producing quantum random number generators are now harnessing it for useful technologies.

Where Quantum Dice sees itself as having an edge over its competitors is in its real-time quality assurance of the true quantum randomness of the device's output. This means it should be able to spot any corruption to the output due to environmental noise or someone tampering with the device, which is an issue with current technologies.

Quantum Dice already offers Quantum Random Number Generator (QRNG) products in a range of form factors that integrate directly within servers, PCs and hardware security systems. Clients can also access the company's cloud-based solution – Quantum Entropy-as-a-Service – which, powered by its QRNG hardware, integrates into the Internet of Things and cloud infrastructure.

Recently Quantum Dice has also launched a probabilistic computing processor based on its QRNG for use in algorithms centred on probabilities. These are often geared towards optimization problems that apply in a number of sectors, including supply chains and logistics, finance, telecommunications and energy, as well as simulating quantum systems, and Boltzmann machines – a type of energy-based machine-learning model for which Shelbaya says researchers "have long sought efficient hardware".

Quantum Dice

From PhD student to CEO Ramy Shelbaya transformed a research idea into a commercial product after winning a competition for budding entrepreneurs.

Stress testing

After winning the start-up competition in 2019 things got trickier when Quantum Dice was ready to be incorporated, which occurred just at the start of the first COVID-19 lockdown. Shelbaya moved the prototype device into his living room because it was the only place they could ensure access to it, but it turned out the real challenges lay elsewhere.

"One of the first things we needed was investments, and really, at that stage of the company, what investors are investing in is you," explains Shelbaya, highlighting how difficult this is when you cannot meet in person. On the plus side, since all his meetings were remote, he could speak to investors in Asia in the morning, Europe in the afternoon and the US in the evening, all within the same day.

Another challenge was how to present the technology simply enough so that people would understand and trust it, while not making it seem so simple that anyone could be doing it. "There's that sweet spot in the middle," says Shelbaya. "That is something that took time, because it's a muscle that I had never worked."

Due rewards

The company performed well for its size and sector in terms of securing investments when their first round of funding closed in 2021. Shelbaya is shy of attributing the success to his or even the team's abilities alone, suggesting this would "underplay a lot of other factors". These include the rising interest in quantum technologies, and the advantages of securing government grant funding programmes at the same time, which he feels serves as "an additional layer of certification".

For Shelbaya every day is different and so are the challenges. Quantum Dice is a small new company, where many of the 17 staff are still fresh from university, so nurturing trust among clients, particularly in the high-stakes world of cybersecurity is no small feat. Managing a group of ambitious, energetic and driven young people can be complicated too.

But there are many rewards, ranging from seeing a piece of hardware finally work as intended and closing a deal with a client, to simply seeing a team "you have been working to develop, working together without you".

For others hoping to follow a similar career path, Shelbaya's advice is to do what you enjoy – not just because you will have fun but because you will be good at it too. "Do what you enjoy," he says, "because you will likely be great at it."

Anna Demming is a science journalist based in the UK

Ask me anything: Jason Palmer

Jason Palmer did a PhD in chemical physics at Imperial College London and a postdoc at the European Laboratory for Non-linear Spectroscopy (LENS) in Italy, before leaving research to become a science journalist. Having worked as a science writer for the BBC, *New Scientist* and the *Economist*, he now co-hosts the daily global news and analysis podcast the *Intelligence* at the *Economist*.


Economist

AUDIO Listen to an extended version of this interview with Jason Palmer

What skills do you use every day in your job?

One thing I can say for sure that I got from working in academia is the ability to quickly read, summarize and internalize information from a bunch of sources. Journalism requires a lot of that. Being able to skim through papers – reading the abstract, reading the conclusion, picking the right bits from the middle and so on – that is a life skill.

In terms of other skills, I'm always considering who's consuming what I'm doing rather than just thinking about how I'd like to say something. You have to think about how it's going to be received – what's the person on the street going to hear? Is this clear enough? If I were hearing this for the first time, would I understand it? Putting yourself in someone else's shoes – be it the listener, reader or viewer – is a skill I employ every day.

What do you like best and least about your job?

The best thing is the variety. I ended up in this business and not in scientific research because of a desire for a greater breadth of experience. And boy, does this job have it. I get to talk to people around the world about what they're up to, what they see, what it's like, and how to understand it. And I think that makes me a much more informed person than I would be had I chosen to remain a scientist.

When I did research – and even when I was a science journalist – I thought "I don't need to think about what's going on in that part of the world so much because that's not my area of expertise." Now I have to, because I'm in this chair every day. I need to know about lots of stuff, and I like that feeling of being more informed.

I suppose what I like the least about my job is the relentlessness of it. It is a newsy time. It's the flip side of being well informed, you're forced to confront lots of bad things – the horrors that are going on in the world, the fact that in a lot of places the bad guys are winning.

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

When I started in science journalism, I wasn't a journalist – I was a scientist pretending to be one. So I was always trying to show off what I already knew as a sort of badge of legitimacy. I would call some professor on a topic that I wasn't an expert in yet just to have a chat to get up to speed, and I would spend a bunch of time showing off, rabbiting on about what papers I'd read and what I knew, just to feel like I belonged in the room or on that call. And it's a waste of time. You have to swallow your ego and embrace the idea that you may sound like you don't know stuff even if you do. You might sound dumber, but that's okay – you'll learn more and faster, and you'll probably annoy people less.

In journalism in particular, you don't want to preload the question with all of the things that you already know because then the person you're speaking to can fill in those blanks – and they're probably going to talk about things you didn't know you didn't know, and take your conversation in a different direction.

It's one of the interesting things about science in general. If you go into a situation with experts, and are open and comfortable about not knowing it all, you're showing that you understand that nobody can know everything and that science is a learning process.

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Wind turbines by bike

Janina Moereke joins a cycle tour in Munich to discover more about the practical challenges facing a community-led project to install wind turbines in her local forest

As a physicist in industry, I spend my days developing new types of photovoltaic (PV) panels. But I'm also keen to do something for the transition to green energy outside work, which is why I recently installed two PV panels on the balcony of my flat in Munich. Fitting them was great fun – and I can now enjoy sunny days even more knowing that each panel is generating electricity.

However, the panels, which each have a peak power of 440 W, don't cover all my electricity needs, which prompted me to take an interest in a plan to build six wind turbines in a forest near me on the outskirts of Munich. Curious about the project, I particularly wanted to find out when the turbines will start generating electricity for the grid. So when I heard that a weekend cycle tour of the site was being organized to showcase it to local residents, I grabbed my bike and joined in.

As we cycle, I discover that the project – located in Forstenrieder Park – is the joint effort of four local councils and two "citizen-energy" groups, who've worked together for the last five years to plan and start building the six turbines. Each tower will be 166 m high and the rotor blades will be 80 m long, with the plan being for them to start operating in 2027.

I've never thought of Munich as a particularly windy city. But tour leader Dieter Maier, who's a climate adviser to Neuried council, explains that at the height at which the blades operate, there's always a steady, reliable flow of wind. In fact, each turbine has a designed power output of 6.5 MW and will deliver a total of 10 GWh in energy over the course of a year.

Janina Moereke

Green interest Janina Moereke went on a cycle tour of Forstenrieder Park near Munich, where six new community-led wind turbines are to be built.

Practical questions

Cycling around, I'm excited to think that a single turbine could end up providing the entire electricity demand for Neuried. But installing wind turbines involves much more than just the technicalities of generating electricity. How do you connect the turbines to the grid? How do you ensure planes don't fly into the turbines? What about wildlife conservation and biodiversity?

At one point of our tour, we cycle round a 90-degree bend in the forest and I wonder how a huge, 80 m-long blade will be transported round that kind of tight angle? Trees will almost certainly have to be felled to get the blade in place, which sounds questionable for a supposedly green project. Fortunately, project leaders have been working with the local forest manager and conservationists, finding ways to help improve the local biodiversity despite the loss of trees.

I've never thought of Munich as a particularly windy city, but at the height at which the blades operate, there's always a steady, reliable flow of wind

As a representative of BUND (one of Germany's biggest conservation charities) explains on the tour, a natural, or "unmanaged", forest consists of a mix of areas with a higher or lower density of trees. But Forstenrieder Park has been a managed forest for well over a century and is mostly thick with trees. Clearing trees for the turbines will therefore allow conservationists to grow more of the bushes and plants that currently struggle to find space to flourish.

To avoid endangering birds and bats native to this forest, meanwhile, the turbines will be turned off when the animals are most active, which coincidentally corresponds to low wind periods in Munich. Insurance costs have to be factored in too. Thankfully, it's quite unlikely that a turbine will burn down or get ice all over its blades, which means liability insurance costs are low. But vandalism is an ever-present worry.

In fact, at the end of our bike tour, we're taken to a local wind turbine that is already up and running about 13 km further south of Forstenrieder Park. This turbine, I'm disappointed to discover, was vandalized back in 2024, which led to it being fenced off and video surveillance cameras being installed.

But for all the difficulties, I'm excited by the prospect of the wind turbines supporting the local energy needs. I can't wait for the day when I'm on my balcony, solar panels at my side, sipping a cup of tea made with water boiled by electricity generated by the rotor blades I can see turning round and round on the horizon.

Janina Moereke is an engineer in photovoltaic research and development in Munich, Germany