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July 2025

Medical marvels

Five ways quantum physics is boosting healthcare

Insider insights Nick Stone on the use of optics in medicine

Storage solution Could biomass burial tackle climate change?

Earworm answer Why catchy music can help students learn

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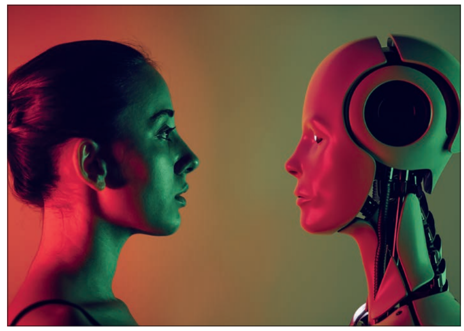

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News & Analysis

US astronomy faces 'extinction'

US president Trump sets out his budget request for 2026, which if passed, will see science hit like never before, as **Peter Gwynne** reports

Under threat
The budget, if passed by Congress, could mean the closure of one of the twin Laser Interferometer Gravitational-Wave Observatory facilities.

Caltech/MIT/LIGO Lab

The administration of US president Donald Trump has proposed drastic cuts to science that would have severe consequence for physics and astronomy if passed by the US Congress. The proposal could involve the cancellation of one of the twin US-based gravitational-wave detectors as well as the axing of a proposed next-generation ground-based telescope and a suite of planned NASA mission. Scientific societies, groups of scientists and individuals have expressed their shock over the scale of the reductions.

In the budget request, which represents the start of the budgeting procedure for the year from 1 October, the National Science Foundation(NSF) would see its funding plummet from $9bn to just $3.9bn – imperilling several significant projects. While the NSF had hoped to support both next-generation ground-based telescopes planned by the agency – the Giant Magellan Telescope (GMT) and the Thirty Meter Telescope (TMT) – the new budget would only allow one to be supported.

On 12 June the GMT, which is already 40% completed thanks to private funds, received NSF approval confirming that the observatory will advance into its "major facilities final design phase", one of the final steps before becoming eligible for federal construction funding. The TMT, meanwhile, which is set to be built in Hawaii, has been hit with delays following protests over adding more telescopes to Mauna Kea. In a statement from the TMT International Observatory, it said it was "disappointed that the NSF's current budget proposal does not include TMT".

It is also possible that one of the twin Laser Interferometer Gravitational-Wave Observatory (LIGO) facilities – one in Hanford, Washington and the other in Livingston, Louisiana – would have to close down after the budget proposes a 39.6% cut to LIGO operations. Having one LIGO facility would significantly cut its ability to identify and localize events that produce gravitational waves.

"This level of cut, if enacted, would drastically reduce the science coming out of LIGO and have long-term negative consequences for gravitational-wave astrophysics," notes LIGO executive director David Reitze. LIGO officials told *Physics World* that the cuts would be "extremely punishing to US gravitational wave science" and would mean "layoffs to staff, reduced scientific output, and the loss of scientific leadership in a field that made first detections just under 10 years ago".

NASA's science funding, meanwhile, would reduce by 47% year on year, and the agency as a whole would see more than 5500 staff lose their jobs as its workforce gets slashed from 17 391 to just 11 853. NASA would also lose planned missions to Venus, Mars, Jupiter and the asteroid Apophis that will pass close to Earth in 2029. Several scientific missions focusing on planet Earth, meanwhile, would also be axed.

The American Astronomical Society expressed "grave concern" that the cuts to NASA and the NSF "would result in an historic decline of American investment in basic scientific research". The Planetary Society called the proposed NASA budget "an extinction-level event for the space agency's most productive, successful and broadly supported activity". Before the cuts were announced, the Trump administration pulled its nomination of billionaire industrialist Jared Isaacman for NASA administrator after his supporter Elon Musk left his post as head of the "Department of Government Efficiency."

The Department of Energy, meanwhile, will receive a slight increase in its defence-related budget, from the current $33.0bn to next year's proposed $33.8bn. But its non-defence budget will fall by 26% from $16.83bn to $12.48bn. Michael Kratsios, Trump's science adviser and head of the White House Office of Science and Technology Policy, sought to justify the administration's planned cuts in a meeting at the National Academy of Sciences (NAS) on 19 May.

"Spending more money on the wrong things is far worse than spending less money on the right things," Kratsios noted, adding that the country had received "diminishing returns" on its investments in science over the past four decades and that it now requires "new methods and approaches to supporting research". He also suggested that research now undertaken at US universities falls short of what he called "gold standard science", citing "political biases [that] have displaced the vital search for truth". Universities, he stated, have lost public trust because they have "promoted diversity, equity and inclusion".

The US science community, however, is unconvinced. “The elephant in the room right now is whether the drastic reductions in research budgets and new research policies across the federal agencies will allow us to remain a research and development powerhouse,” says Marcia McNutt, president of the National Academy of Sciences. “Thus, we are embarking on a radical new experiment in what conditions promote science leadership – with the US being the ‘treatment’ group, and China as the control.”

Former presidential science adviser Neal Lane, now at Rice University, told *Physics World* that while the US administration appears to value some aspects of scientific research such as AI, quantum, nuclear and biotechnologies, it “doesn’t seem to understand or acknowledge that technological advances and innovation often come from basic research in unlikely fields of science“. He expects the science community to “continue to push back” by writing and visiting members of Congress, many of whom support science, and “by speaking out to the public and encouraging various organizations to do that same”.

Indeed, an open letter by the group Stand Up for Science dated 26 May calls the administration’s stated commitment to “gold standard science” an approach “that will actually undermine scientific rigor and the transparent progress of science”. It would “introduce stifling limits on intellectual freedom in our nation’s laboratories and federal funding agencies”, the letter adds.

US scientists are gearing up for a difficult summer of speculation about financial support

As of 13 June, the letter had more than 9250 signatures. Another letter, sent to Jay Bhattachayra, director of the National Institutes of Health (NIH), from some 350 NIH members, almost 100 of whom identified themselves, asserted that they “remain pressured to implement harmful measures” such as halting clinical trials midstream. In the budget request, the NIH would lose about 40%, leaving it with $27.5bn next year. The administration also plans to consolidate the NIH’s 27 institutes into just eight.

A political divide

On the day that the budget was announced, 16 states run by Democratic governors called on a federal court to block cuts in programmes and funding for the NSF. They point out that universities in their states could lose significant income if the cuts go ahead. In fact, the administration’s budget proposal is just that: a proposal. Congress will almost certainly make changes to it before presenting it to Trump for his signature. And while Republicans in the Senate and House of Representatives find it difficult to oppose the administration, science has historically enjoyed support by both Democrats and Republicans.

Despite that, scientists are gearing up for a difficult summer of speculation about financial support. “We are gaming matters at the moment because we are looking at the next budget cycle,” says Peter Littlewood, chair of the University of Chicago’s physics department. “The principal issues now are to bridge postdocs and graduating PhD students, who are in limbo because offers are drying up.” Littlewood says that, while alternative sources of funding such as philanthropic contributions can help, if the proposed government cuts are approved then philanthropy can’t replace federal support. “I’m less worried about whether this or that piece of research gets done than in stabilizing the pipeline, so all our discussions centre around that,” adds Littlewood.

Lane fears the cuts will put people off from careers in science, even in the unlikely event that all the cuts get reversed. “The combination of statements by the president and other administrative officials do considerable harm by discouraging young people born in the US and other parts of the world from pursuing their education and careers in [science] in America,” he says. “That’s a loss for all Americans.”

Peter Gwynne is *Physics World*’s North America correspondent

Awards

Richard Bond and George Efstathiou win Shaw Prize in Astronomy

The 2025 Shaw Prize in Astronomy has been awarded to Richard Bond and George Efstathiou “for their pioneering research in cosmology, in particular for their studies of fluctuations in the cosmic microwave background”. Their predictions, the citation continues, “have been verified by an armada of ground-, balloon- and space-based instruments, leading to precise determinations of the age, geometry and mass–energy content of the universe”.

Efstathiou is an astrophysicist at the University of Cambridge in the UK, while Bond is based at the Canadian Institute for Theoretical Astrophysics (CITA) and the University of Toronto in Canada. They share the $1.2m prize money equally.

The Gruber Foundation, Yale University/University of Cambridge

Astro pioneers Richard Bond (left) and George Efstathiou have won the 2025 Shaw Prize in Astronomy.

The annual award is given by the Shaw Prize Foundation, which was founded in 2002 by the Hong Kong-based filmmaker, television executive and philanthropist Run Run Shaw (1907–2014). It will be presented at a ceremony in Hong Kong on 21 October. There are also Shaw Prizes for life sciences and medicine; and mathematical sciences.

AUDIO Listen to Bond and Efstathiou discuss their work

Bond studied mathematics and physics at Toronto. In 1979 he completed a PhD in theoretical physics at the California Institute of Technology (Caltech). He directed CITA from 1996 to 2006. Efstathiou studied physics at Oxford before completing a PhD in astronomy at the UK’s Durham University in 1979. He is currently director of the Institute of Astronomy in Cambridge.

Matin Durrani

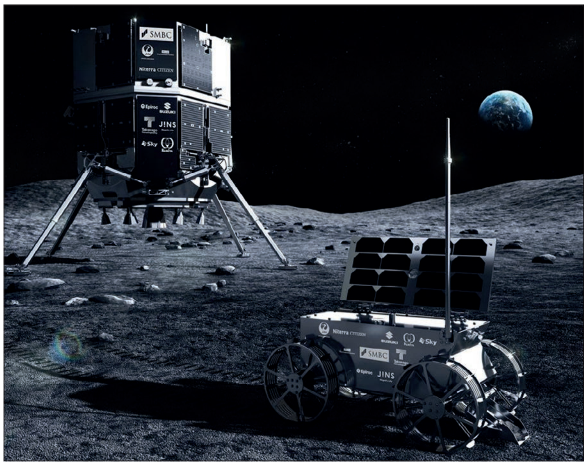
Space

Japan's ispace suffers second lunar landing failure

The Japanese firm ispace has suffered another setback after its second attempt to land on the Moon ended in failure last month. The Hakuto-R Mission 2, also known as Resilience, failed to touch down near the centre of Mare Frigoris (sea of cold) in the far north of the Moon after a sensor malfunctioned during descent.

Launched on 15 January from the Kennedy Space Center, Florida, aboard a SpaceX Falcon 9 rocket, the craft spent four months travelling to the Moon before it entered lunar orbit on 7 May. During the descent phase, the 2.3 m-high lander began a landing sequence that involved firing its main propulsion system to gradually decelerate and adjust its attitude. ispace says that the lander was confirmed to be nearly vertical but then the company lost communication with the craft.

The firm concludes that the laser rangefinder experienced delays attempting to measure the distance to the lunar surface during descent, meaning that it was unable to decelerate sufficiently to carry out a soft landing. "Given that there is currently no prospect of a successful lunar landing, our top priority is to swiftly analyse the telemetry data we have obtained thus far and work diligently to identify the cause," said ispace founder and chief executive officer Takeshi Hakamada in a statement. "We strive to restore trust by providing a report of the findings."



ispace

Lunar loss
ispace's Hakuto-R Mission 2 – dubbed Resilience – failed to land on the Moon during an attempt last month.

The mission was planned to operate for about two weeks. Resilience featured several commercial payloads, worth $16m, including a food-production experiment and a deep-space radiation probe. It also carried a rover, dubbed Tenacious, which was about the size of a microwave oven and would have collected and analysed lunar regolith. The rover would have also delivered a Swedish artwork called *The Moonhouse* – a small red cottage with white corners – and placed it at a "symbolically meaningful" site on the Moon.

The company's first attempt to land on the Moon also ended in failure in 2023 when the Hakuto-R Mission 1 crash landed despite being in a vertical position as it carried out the final approach to the lunar surface. The issue was put down to a software problem that incorrectly assessed the craft's altitude during descent. If the latest attempt was a success, ispace would have joined the US firms Intuitive Machines and Firefly Aerospace, which both successfully landed on the Moon last year and in March, respectively. This second lunar loss casts doubt on ispace's plans for further lunar landings and its grand aim of establishing a lunar colony of 1000 inhabitants by the 2040s.

Michael Banks

Astronomy

China launches Tianwen-2 asteroid sample-return mission

China has launched its first mission to retrieve samples from an asteroid. The Tianwen-2 mission launched on 28 May from the Xichang satellite launch centre in south-west China, aboard a Long March B rocket. Tianwen-2's target is a small near-Earth asteroid called 469219 Kamo'oalewa, which is 15–39 million km away and is known as a "quasi-satellite" of Earth.

The mission is set to reach the body, which is 40–100 m wide, in July 2026. It will first study it up close using a suite of 11 instruments including cameras, spectrometers and radar, before aiming to collect about 100 g of material. This will be achieved via three possible methods. One is via hovering close to the asteroid; another is using a robotic arm to collect samples from the body; while a third dubbed "touch and go" involves gently landing on the asteroid and using drills at the end of each leg to retrieve material.

Addy Graham/University of Arizona

Heavenly questions
An artist's impression of Earth quasi-satellite Kamo'oalewa near the Earth–Moon system.

The collected samples will then be stored in a module that is released and returned to Earth in November 2027. If successful, it will make China the third nation to retrieve asteroid material behind the US and Japan. The second part of the 10-year mission involves using Earth for a gravitational swing-by to spend six years travelling to another target – 311P/PanSTARRS. The body lies in the main asteroid belt between Mars and Jupiter and at its closest distance is about 140 million km away from Earth.

The 480 m-wide object, which was discovered in 2013, has six dust tails and has characteristics of both asteroids and comets. Tianwen-2 will not land on 311P/PanSTARRS but instead use its instruments to study the "active asteroid" from a distance. Tianwen-2's predecessor, Tianwen-1, was China's first mission to Mars, successfully landing on Utopia Planitia following a six-month journey.

China's third interplanetary mission, Tianwen-3, will aim to retrieve samples from Mars and could launch as soon as 2028.

Michael Banks

Philanthropy

Leinweber Foundation ploughs $90m into US physics

The Leinweber Foundation has awarded five US institutions $90m to create their own theoretical research institutes. The investment, which the foundation says is the largest ever for theoretical physics research, will be used to fund graduate students and postdocs at each institute as well as several Leinweber Physics Fellows.

The Leinweber Foundation was set up in 2015 by the software entrepreneur Larry Leinweber. In 1982 he founded the software company New World Systems Corporation, which provided software to the emergency services, before selling it in 2015 to Tyler Technologies for $670m. Based in Michigan, the Leinweber Foundation supports research, education and community endeavours where it has provided Leinweber Software Scholarships to undergraduates at Michigan's universities.

A Leinweber Institute for Theoretical Physics (LITP) will now be created at the universities of California, Berkeley, Chicago and Michigan as well as at the Massachusetts Institute of Technology (MIT) and at Princeton's Institute for Advanced Study (IAS), where the institute will instead be named the Leinweber Forum for Theoretical and Quantum Physics.

University of Chicago

New investment The University of Chicago is one of five US institutions to get money to create a Leinweber Institute for Theoretical Physics.

The MIT LITP, initially led by Washington Taylor before physicist Tracy Slatyer takes over later this year, will receive $20m from the foundation and will provide support for six postdocs, six graduate students as well as visitors, seminars and "other scholarly activities". "This landmark endowment from the Leinweber Foundation will enable us to support the best graduate students and postdoctoral researchers to develop their own independent research programmes and to connect with other researchers in the Leinweber Institute network," says Taylor.

UC Berkeley, meanwhile, will receive $14.4m from the foundation in return for which the existing Berkeley Center for Theoretical Physics (BITP) will be renamed LITP at Berkeley and led by physicist Yasunori Nomura. The money will be used for four postdoc positions to join the existing 15 at the BITP as well as to support graduate students and visitors.

Chicago will receive $18.4m where the existing Kadanoff Center for Theoretical Physics will be merged into a new LITP at the University of Chicago and led by physicist Dam Thanh Son. The remaining $37.2m will be split between the Leinweber Forum for Theoretical and Quantum Physics at the IAS and at Michigan, in which the existing Leinweber Center for Theoretical Physics will expand and become an institute. "Theoretical physics may seem abstract to many, but it is the tip of the spear for innovation. It fuels our understanding of how the world works and opens the door to new technologies that can shape society for generations," says Leinweber in a statement.

Michael Banks

Metrology

Symposium in Paris celebrates 150 years of the metric system

The 150th anniversary of the Metre Convention was celebrated at a symposium arranged by the Bureau International des Poids et Mesures (BIPM) and the United Nations Educational, Scientific and Cultural Organisation (UNESCO) at UNESCO headquarters on 20 May, World Metrology Day. The event included talks from the Nobel-prize-winning physicist William Phillips of the US National Institute of Standards and Technology (NIST) and the BIPM director Martin Milton, as well as panel discussions on the future of metrology featuring representatives of other national metrology institutes and metrology professionals from around the globe.

The Metre Convention was signed in 1875 in Paris by representatives of all 17 nations that belonged to the BIPM at the time, making it one of the first truly international agreements, and kick-starting the construction of new length and mass standards. The new International Prototype of the Metre and International Prototype of the Kilogram were manufactured in 1879 and officially adopted as replacements for the old metre and kilogram in 1889.

Isabelle Dumé

Made to measure William Phillips gave the keynote address at the Metre Convention's 150th anniversary symposium in Paris at the end of May.

From the 1960s onwards, the BIPM decided to replace its expanded metric system with a framework encompassing the entire field of metrology. This new framework consisted of six basic units – the metre, kilogram, second, ampere, degree Kelvin (later simply the kelvin), candela and mole – plus a set of "derived" units (the Newton, Hertz, Joule and Watt) built from the six basic ones. Thus was born the International System of Units, or SI after the French initials for Système International d'unités.

The next major step – a "brilliant choice", in Phillips' words – came in 1983, when the BIPM decided to redefine the metre in terms of the speed of light. This decision set the stage for defining the rest of the seven base units in terms of natural fundamental constants.

Isabelle Dumé
Paris

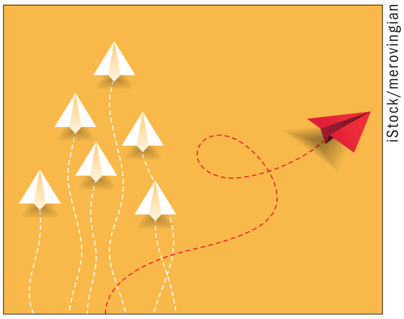
Publishing

Switching research fields? Beware the 'pivot penalty'

Scientists who switch research fields suffer a drop in the impact of their new work – a so-called "pivot penalty". That is according to a new analysis of scientific papers and patents, which finds that the pivot penalty increases the further away a researcher shifts from their previous topic of research (*Nature* 10.1038/s41586-025-09048-1).

The analysis has been carried out by a team led by Dashun Wang and Benjamin Jones of Northwestern University in Illinois. They analysed more than 25 million scientific papers published between 1970 and 2015 across 154 fields as well as 1.7 million US patents across 127 technology classes granted between 1985 and 2020. To identify pivots and quantify how far a scientist moves from their existing work, the team looked at the scientific journals referenced in a paper and compared them with those cited by previous work. The more the set of journals referenced in the main work diverged from those usually cited, the larger the pivot. For patents, the researchers used "technological field codes" to measure pivots.

Larger pivots are associated with fewer citations and a lower propensity for high-impact papers, defined as those in the top 5% of citations received in their field and publication year. Low-pivot work – moving only slightly away from the typical field of research – led to a high-impact paper 7.4% of the time. The highest-pivot shift resulted in a high-impact paper only 2.2% of the time. A similar trend was seen for patents. When looking at the output of an individual researcher, low-pivot work is 2.1% more likely to have a high-impact paper, while high-pivot work is 1.8% less likely to do so. The study finds the pivot penalty to be almost universal across scientific fields and it persists regardless of a scientist's career stage, productivity and collaborations.



iStock/merovingian

Change of direction Your citation rate will drop if you switch field and the "pivot penalty" increases the further away you move from your previous topic of research.

The researchers also studied the impact of COVID-19, when many researchers pivoted to research linked to the pandemic. After analysing 83 000 COVID-19 papers and 2.63 million non-COVID papers published in 2020, they found that COVID-19 research was not immune to the pivot penalty. Such research had a higher impact than average, but the further a scientist shifted from their previous work to study COVID-19 the less impact the research had.

Wang told *Physics World* that researchers should not avoid change but rather "approach it strategically". Researchers should, for example, try anchoring their new work in the conventions of their prior field or the one they are entering. To help researchers pivot, Wang says research institutions should "acknowledge the friction" and not "assume that a promising researcher will thrive automatically after a pivot". Instead, he says, institutions need to design support systems, such as funding or protected time to explore new ideas, or pairing researchers with established scholars in the new field.

Michael Allen

People

Former IOP president Cyril Hilsum celebrates 100th birthday

Cyril Hilsum, a former president of the Institute of Physics (IOP), celebrated his 100th birthday in late May at a special event held at the Royal Society of Chemistry. Born on 17 May 1925, Hilsum completed a degree in physics at University College London in 1945. During his career he worked at the Services Electronics Research Laboratory and the Royal Radar Establishment and in 1983 was appointed chief scientist of GEC Hirst Research Centre, where he later became research director before retiring aged 70.

Hilsum helped develop commercial applications for the semiconductor gallium arsenide and is responsible for creating the UK's first semiconductor laser as well as developments that led to modern liquid crystal display technologies. Between 1988 and 1990 he was president of the IOP and in 1990 was appointed a Commander of the Order of the British Empire (CBE) for "services to the electrical and electronics industry".

Hilsum was honoured by many prizes during his career, including IOP awards such as the Max Born Prize in 1987, the Faraday Medal in 1988 as well as the Richard Glazebrook Medal and Prize in 1998. In 2007 he was awarded the Royal Society's Royal Medal "for his many outstanding contributions and for continuing to use his prodigious talents on behalf of industry, government and academe to this day". Despite now being a centenarian, Hilsum still works part-time as chief science officer for Infi-tex, which produces force sensors for use in textiles. Hilsum says that while the IOP gives much support to applied physics, there is still a great need for physicists "to give critical contributions to the lives of society as a whole". He adds: "As scientists, we may welcome progress in the subject, but all can get pleasure in seeing the results in their home, on their iPhone, or especially in their hospital."

Lindsey Hilsum

100 not out Cyril Hilsum at a special event held at the Royal Society of Chemistry on 17 May.

Michael Banks

Research updates

CERN takes protons on lorry ride

Researchers at CERN show that trapped protons can be transported by truck, which could pave the way for antimatter particles to go on the move, as **Isabelle Dumé** reports

Physicists at the CERN particle-physics lab have completed a "test run" for taking antimatter out of the laboratory and transporting it across the lab's campus. Although the test was instead carried out with protons, the researchers say that antiprotons could soon get the same treatment. The goal is to study antimatter in places other than the labs that create it, enabling more precise measurements of the differences between matter and antimatter (*Nature* **641** 871).

According to the Standard Model of particle physics, particles such as protons and electrons should have a corresponding antiparticle that is identical in every way apart from its charge and magnetic properties (which are reversed). Yet the Big Bang that formed our universe nearly 14 billion years ago should have generated equal amounts of antimatter and matter. If that were the case, however, there shouldn't be any matter left, because whenever pairs of antimatter and matter particles collide, they annihilate each other in a burst of energy.

Physicists therefore suspect that there are other, more subtle differences between matter particles and their antimatter counterparts – differences that could explain why the former prevailed while the latter all but disappeared. By searching for these differences, they hope to shed more light on antimatter–matter asymmetry – and perhaps even reveal physics beyond the Standard Model.

At CERN's Baryon-Antibaryon Symmetry Experiment (BASE) experiment, the search for matter–antimatter differences focuses on measuring the magnetic moment (or charge-to-mass ratio) of protons and antiprotons. These measurements need to be extremely precise, but that is difficult at CERN's "Antimatter Factory" (AMF), which manufactures the necessary low-energy antiprotons in profusion. This is because essential nearby equipment – including the Antiproton Decelerator and ELENA, which reduce the energy of incoming antiprotons from GeV to MeV – produces magnetic field fluctuations that blur the signal.

BASE/Julia Jäger

Road trip
A Penning-trap system containing protons has been successfully transported by lorry across CERN's Meyrin campus.

To carry out more precise measurements, the team therefore needs a way of transporting the antiprotons to other, better-shielded, laboratories. This is easier said than done, however, given that antimatter needs to be carefully isolated from its environment to prevent it from annihilating with the walls of its container or with ambient gas molecules. The BASE team's solution was to develop a device that can transport trapped antiprotons on a truck for substantial distances. This device, known as BASE-STEP (for Symmetry Tests in Experiments with Portable Antiprotons), has now been field-tested for the first time.

If we can transport protons, we should also be able to transport antiprotons

Protons on the go

During the test, the team successfully transported a cloud of about 10^5 trapped protons out of the AMF and across CERN's Meyrin campus over four hours. Although protons are not the same as antiprotons, BASE-STEP team leader Christian Smorra says they are just as sensitive to disturbances in their environment caused by, say, driving them around. "They are therefore ideal stand-ins for initial tests, because if we can transport protons, we should also be able to transport antiprotons," he says.

The BASE-STEP device is mounted on an aluminium frame and measures 1.95 × 0.85 × 1.65 m. At 850–900 kg, it is light enough to be transported using standard forklifts and cranes. Like BASE, it traps particles in a Penning trap composed of gold-plated cylindrical electrode stacks made from oxygen-free copper. To further confine the protons and prevent them from colliding with the trap's walls, this trap is surrounded by a superconducting magnet bore operated at cryogenic temperatures. The second electrode stack is also kept at ultralow pressures of 10^{-19} bar, which Smorra says is low enough to keep antiparticles from annihilating with residual gas molecules. To transport antiprotons instead of protons, Smorra adds, they would just need to switch the polarity of the electrodes.

The transportable trap system is designed to remain operational on the road. It uses a carbon-steel vacuum chamber to shield the particles from stray magnetic fields, and its frame can handle accelerations of up to 1*g* (9.81 m/s^2) in all directions over and above the usual (vertical) force of gravity. This means it can travel up and down slopes with a gradient of up to 10%, or approximately 6°. Once the BASE-STEP device is re-configured to transport antiprotons, the first destination on the team's list is a new Penning-trap system currently being constructed at the Heinrich Heine University in Düsseldorf, Germany. Here, physicists hope to search for charge-parity-time violations in protons and antiprotons with a precision at least 100 times higher than is possible at CERN's AMF.

Astronomy

Andromeda might not collide with the Milky Way after all

Astrophysicists say that there is a 50/50 chance that the Andromeda galaxy will collide with our own Milky Way within the next 10 billion years. The researchers, led by Till Sawala of the University of Helsinki, Finland, reached this conclusion by using the latest data from the European Space Agency's Gaia astrometric mission (*Nat. Astron.* doi:10.1038/s41550-025-02563-1).

The Andromeda galaxy, which is 2.5 million light–years away, is racing towards our own Milky Way at about 110 kilometres per second. In 2012, astrophysicists at the Space Telescope Science Institute in Maryland, US, concluded that the collision would happen in four billion years. To update such conclusions, Sawala and colleagues took into account the gravitational effect of an additional galaxy, the Large Magellanic Cloud (LMC), alongside the Milky Way, Andromeda and the nearby Triangulum spiral galaxy, M33.

While M33's gravity, in effect, adds to Andromeda's motion towards us, the team found that the LMC's gravity tends to pull the Milky Way out of Andromeda's path. While the LMC contains only around 10% of the Milky Way's mass, Sawala and colleagues' work indicates that it may nevertheless be massive enough to turn a head-on collision into a near miss. Even with more detailed simulations, though, uncertainties in the motion and masses of the galaxies leave room for a range of possible outcomes. According to Sawala, the uncertainty with the greatest effect on merger probability lies in the so-called "proper motion" of Andromeda, which is its motion as it appears on our night sky. This motion is a mixture of Andromeda's radial motion towards the centre of the Milky Way and the two galaxies' transverse motion perpendicular to one another.


NASA / ESA

Uncertain future Three scenarios for a future encounter between the Milky Way and Andromeda galaxies: bypass each other (top left), a close encounter (top right) and a collision (bottom).

If the combined transverse motion is large enough, Andromeda will pass the Milky Way at a distance greater than 200 kiloparsecs (652,000 light–years). This would avert a collision in the next 10 billion years. Conversely, a smaller transverse motion would limit the distance at closest approach to less than 200 kiloparsecs. If that happens, Sawala says the two galaxies are "almost certain to merge" because of the dynamical friction effect, which arises from the diffuse halo of old stars and dark matter around galaxies. "I would expect that there is a very high probability that they will eventually merge, but that could take tens of billions of years," Sawala says.

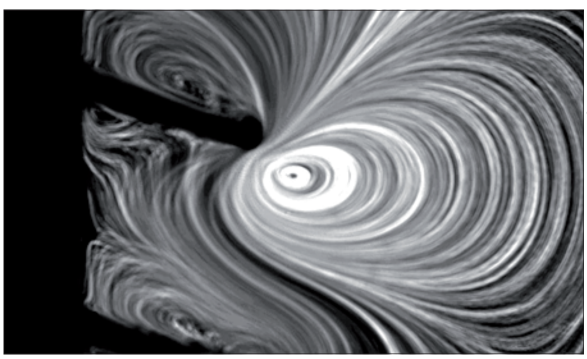
Keith Cooper

Biomedical devices

Ultrasound-activated structures clear biofilms from medical implants

Researchers at the University of Bern and ETH Zurich, Switzerland, have developed a way to remove biofilms from implanted medical devices without the need to remove and replace them. The method works by incorporating ultrasound-activated moving structures into a prototype "stent-on-a-chip" device. If translated into clinical practice, the technology could increase the safe lifespan of implants, saving money and avoiding operations that are uncomfortable and sometimes hazardous for patients (*Proc. Natl. Acad. Sci.* 122 e2418938122).

Biofilms are mechanically robust and resistant to standard antibacterial treatment. If not removed from implanted devices, such films can cause infections, obstructions and other complications. To combat this, researchers created a new coating made from microscopic hair-like structures known as cilia. Under the influence of an acoustic field, which is applied externally via a piezoelectric transducer, these cilia begin to move. This movement produces intense, steady fluid flows with velocities of up to 10 mm/s – enough to break apart encrusted deposits and flush away biofilms from the inner and outer surfaces of implanted urological devices.


Pedro Amado and Cornel Dillinger

Sounds good "Acoustic streaming" generated by ultrasound-activated cilia has been used to clean stents and catheters.

"Our polymeric cilia in fact amplify the effects of ultrasound by allowing for an effect known as acoustic streaming at frequencies of 20 to 100 kHz," says ETH Zurich's Daniel Ahmed. "This frequency is lower than that possible with previous microresonator devices developed to work in a similar way that had to operate in the MHz-frequency range." Ahmed adds that the lower frequency achieves the desired therapeutic effects while minimizing the risk of tissue damage.

Future versions of the technology could involve applying the ultrasound probe directly to a patient's skin. "This technology has potential applications beyond urology, including fields like visceral surgery and veterinary medicine, where keeping implanted medical devices clean is also essential," says Bern's Francesco Clavica.

Isabelle Dumé

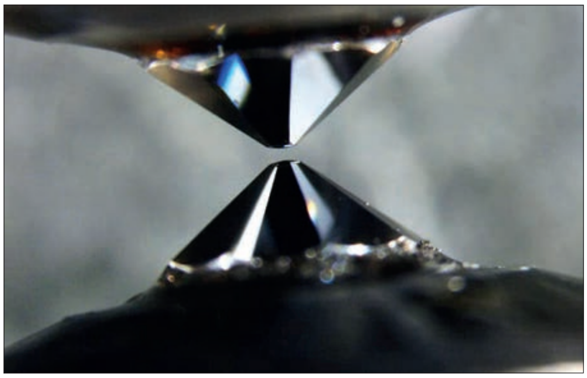
Condensed matter

Evidence for superconducting gap emerges in hydrogen sulphides

Researchers in Germany have directly measured a superconducting gap in a hydride sulphide material for the first time. The new finding represents "smoking gun" evidence for superconductivity in these materials, while also confirming that the electron pairing that causes it is mediated by phonons (*Nature* 641 619).

Superconductors conduct electricity without resistance below a certain temperature known as T_c. In 2015, researchers discovered that a sulphide material, H_3S, has a T_c of 203 K when compressed to pressures of 150 GPa and in 2019, the record was broken again, this time by lanthanum decahydride, which was found to have a T_c of 250–260 K, again at very high pressures. A further advance occurred in 2021 with the discovery of high-temperature superconductivity in cerium hydrides. These novel phases of CeH_9 and another newly-synthesized material, CeH_{10}, are stable and superconduct at lower pressures (about 80 GPa) than the other so-called "superhydrides".

One unanswered question concerns the mechanism for superhydride superconductivity. According to the Bardeen–Cooper–Schrieffer theory of "conventional" superconductivity, it occurs when electrons overcome their mutual electrical repulsion to form Cooper pairs, which can then travel unhindered through the material as a supercurrent without scattering off phonons or other impurities. Cooper pairing is characterized by a tell-tale energy gap near the Fermi level. This gap is equivalent to the maximum energy required to break up a Cooper pair of electrons and spotting it is regarded as unambiguous proof of that material's superconducting nature.


Feng Du, MPIC

Mind the gap
A new experimental technique, known as planar electron tunnelling spectroscopy, has found that H_3S and D_3S have fully open superconducting gaps.

For the superhydrides, however, measuring such a gap requires instruments that can withstand the extremely high pressures required for superhydrides to exist and behave as superconductors. A team led by researchers at Germany's Max Planck Institute for Chemistry has now developed a form of spectroscopy that can operate under extreme pressures. The technique, known as planar electron tunnelling spectroscopy, required the researchers to synthesize highly pure planar tunnel junctions of H_3S and its deuterated equivalent D_3S under pressures of over 100 GPa. Using a technique called laser heating, they created junctions with three parts: a metal, tantalum; a barrier made of tantalum pentoxide, Ta_2O_5; and the H_3S or D_3S superconductors. By measuring the differential conductance across the junctions, they determined the density of electron states in H_3S and D_3S near the Fermi level.

The tunnelling spectra revealed that both H_3S and D_3S have fully open superconducting gaps of 60 meV and 44 meV, respectively. According to team member Feng Du, the smaller gap in D_3S confirms that the superconductivity in H_3S comes about thanks to interactions between electrons and phonons.

Isabelle Dumé

Optics

New contact lenses allow wearers to see in the near-infrared

A new contact lens lets humans see near-infrared light without night vision goggles or other bulky equipment. The lens, which incorporates metallic nanoparticles that "upconvert" normally-invisible wavelengths into visible ones, could have applications for rescue workers operating in conditions with poor visibility (*Cell* doi: 10.1016/j.cell.2025.04.019).

The infrared part of the electromagnetic spectrum encompasses light between 700 nm and 1 mm. Human eyes cannot normally detect these wavelengths because opsins, the light-sensitive protein molecules that allow us to see, do not have the required thermodynamic properties. This means we see only a small fraction of the electromagnetic spectrum, typically between 400–700 nm. While night vision goggles and infrared-visible converters can extend this range, they require external power sources. They also cannot distinguish between different wavelengths of infrared light.


Yuqian Ma, Yunuo Chen, Hang Zhao

Seeing is believing
A contact lens that incorporates metallic nanoparticles allows wearers to see near-infrared.

Neuroscientist Tian Xue of the University of Science and Technology of China and colleagues integrated nanoparticles into biocompatible polymeric materials similar to those used in standard soft contact lenses. The nanoparticles in the lenses are made from $Au/NaGdF_4$: Yb^{3+}, Er^{3+} and are each about 45 nm in diameter. They work by capturing photons with lower energies and re-emitting them as photons with higher energies.

After testing the upconverting contact lenses (UCLs) on mice, the team moved on to human volunteers. "In humans, the near-infrared UCLs enabled participants to accurately detect flashing Morse code-like signals and perceive the incoming direction of near-infrared light," Xue says. Importantly, Xue notes that wearing the lenses did not affect participants' normal vision.

Isabelle Dumé

Biophysics

Wireless e-tattoos could help manage mental workload

For those performing safety-critical tasks monitoring how hard their brain is working is important. But how can a person's mental workload be assessed? A team at the University of Texas at Austin has now proposed temporary face tattoos that can track when a person's brain is working too hard (*Device* **3** 100781).

The traditional approach for monitoring mental workload is electroencephalography (EEG), which analyses the brain's electrical activity. But EEG devices are wired, bulky and uncomfortable, making them impractical for real-world situations. One alternative for assessing mental workload is to measure eye movements using electrooculography (EOG). Nanshu Lu and colleagues have now developed an ultrathin wireless e-tattoo that records high-fidelity EEG and EOG signals from the forehead. The e-tattoo combines a disposable sticker-like electrode layer and a reusable battery-powered flexible printed circuit (FPC) for data acquisition and wireless transmission.

Device/Huh et al.

Skin deep The e-tattoo can carry out electro-encephalography and electro-oculography via adhesive electrodes with a flexible printed circuit module.

The serpentine-shaped electrodes and interconnects are made from cheap, conductive graphite-deposited polyurethane, coated with an adhesive polymer composite to reduce contact impedance and improve skin attachment. The e-tattoo stretches and conforms to the skin, providing reliable signal acquisition, even during dynamic activities such as walking and running. To assess the e-tattoo's ability to record basic neural activities, the team used it to measure alpha brainwaves as a volunteer opened and closed their eyes. The e-tattoo captured equivalent neural spectra to that recorded by a commercial gel electrode-based EEG system with comparable signal fidelity.

The researchers next tested the e-tattoo on six participants while they performed a visuospatial memory task that gradually increased in difficulty. They analysed the signals collected by the e-tattoo during the tasks, extracting EEG band powers for delta, theta, alpha, beta and gamma brainwaves, plus various EOG features. As the task got harder, the participants showed higher activity in the theta and delta bands, a feature associated with increased cognitive demand. Meanwhile, activity in the alpha and beta bands decreased, indicating mental fatigue.

The researchers built a machine-learning model to predict the level of mental workload experienced during the tasks, training it on forehead EEG and EOG features recorded by the e-tattoo. The model could reliably estimate mental workload in each of the six subjects, demonstrating the feasibility of real-time cognitive state decoding.

Tami Freeman

Medical physics

Proton arc therapy eliminates hard-to-treat cancer with minimal side effects

Researchers from Corewell Health William Beaumont University Hospital have used a new proton-therapy technique called "step-and-shoot" proton arc therapy to treat head-and-neck cancer in a human patient – the first person in the US to receive this highly accurate treatment (*International Journal of Particle Therapy* 16 100749).

Traditional proton therapies, such as intensity-modulated proton therapy (IMPT), are manual in nature and require a lot of monitoring. Step-and-shoot technology, however, delivers radiation directly to a tumour in a more continuous and automated fashion, with less lag time between radiation dosages. During treatment delivery, the gantry rotates to each beam angle and stops to deliver the treatment irradiation.

"Step-and-shoot proton arc therapy uses more beam angles per plan compared to the current clinical practice using IMPT and optimizes the spot and energy layers sparsity level," explains Xuanfeng Ding. The extra beam angles provide a greater degree-of-freedom to optimize the treatment plan and provide a better dose conformity.

Emily Rose Bennett, Corewell Health

On target Physicians and scientists at Corewell Health William Beaumont University Hospital in Royal Oak, Michigan have used a new step-and-shoot proton-arc therapy technique.

The team trialled the new technique on a patient with adenoid cystic carcinoma in her salivary gland – a rare and highly invasive cancer, which is difficult to treat as it targets the nerves in the body. This tendency to target nerves also means that fighting such tumours typically causes a lot of side effects. Using step-and-shoot proton arc therapy, however, the patient experienced minimal side effects and no radiation toxicity to other areas of her body (including the brain) after 33 treatments. Since finishing her treatment in August 2024, she continues to be cancer-free.

"Radiation to the head-and-neck typically results in dryness of the mouth, pain and difficulty swallowing, abnormal taste, fatigue and difficulty with concentration," says Rohan Deraniyagala, a Corewell Health radiation oncologist. "Our patient had minor skin irritation but did not have any issues with eating or performing at her job during treatment and for the last year since she was diagnosed."

Liam Critchley

Opinion

physicsworld

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Quantum island

Why Helgoland was a great spot for fundamental thinking

Jack Harris, a quantum physicist at Yale University in the US, has a fascination with islands. Having grown up on Martha's Vineyard, an island just south of Cape Cod on the east coast of America, he believes that islands shape a person's thinking. "Your world view has a border – you're on or you're off," Harris said on a recent episode of the *Physics World Stories* podcast.

Harris was one of the main organizers of a five-day conference that took place last month on Helgoland, where Werner Heisenberg discovered quantum mechanics exactly a century ago. Heisenberg had come to the tiny, windy, pollen-free island, which lies 50 km off the coast of Germany, in June 1925, to seek respite from the hay fever he was suffering from in Göttingen.


Matin Durrani

According to Heisenberg's 1971 book *Physics and Beyond*, he supposedly made his breakthrough early one morning that month. Unable to sleep, Heisenberg left his guest house just before daybreak and climbed to the top of the island's southern headland. As the Sun rose, Heisenberg pieced together the curious observations of frequencies of light that materials had been seen to absorb and emit.

While admitting that the development of quantum mechanics isn't as simple as Heisenberg made out, Harris believes it's nevertheless a "very compelling" story. "It has a place and a time: an actual, clearly defined, quantized discrete place – an island," Harris says. "This is a cool story to have as part of the fabric of [the physics] community." Hardly surprising, then, that more than 300 physicists, myself included, travelled to Helgoland to take part in the centenary meeting.

Much time was spent discussing the fundamentals of quantum mechanics, which might seem self-indulgent given the burgeoning (and financially lucrative) applications of the subject. Should one really worry about non-locality, the meaning of measurement, or the nature of particles, information and randomness?

But these fundamental questions are fascinating in their own right. What's more, building, say, a quantum computer is not just a technical and engineering endeavour. "To make it work you have to absorb a lot of the foundational topics of quantum mechanics," Harris points out.

As one of the main events of the International Year of Quantum Science and Technology, Helgoland 2025 also underlined the importance of global collaboration in science. Tiny it might be, but Helgoland had a very high concentration of bright minds.

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

Critical Point How I was terminated

Robert P Crease reports on how his grant was axed because it appeared to threaten the priorities of US President Donald Trump

iStock/sesame

Axed in error A grant given to Robert P Crease by the US National Science Foundation to study lab-community relations was terminated and then reinstated.

Late on Friday 18 April, the provost of Stony Brook University, where I teach, received a standard letter from the National Science Foundation (NSF), the body that funds much academic research in the US. "Termination of certain awards is necessary," the e-mail ran, "because they are not in alignment with current NSF priorities". The e-mail mentioned "NSF Award Id 2318247". Mine.

The termination notice, forwarded to me a few minutes later, was the same one that 400 other researchers all over the US received the same day, in which the agency, following a directive from the Trump administration, grabbed back \$233m in grant money. According to the NSF website, projects terminated were "including but not limited to those on diversity, equity, and inclusion (DEI) and misinformation/disinformation".

Losing grant money is disastrous for research and for the faculty, postdocs, graduate students and support staff who depend on that support. A friend of mine tried to console me by saying that I had earned a badge of honour for being among the 400 people who threatened the Trump Administration so much that it set out to stop their work. Still, I was baffled. Did I really deserve the axe?

My award, entitled "Social and political dynamics of lab-community relations", was small potatoes. As the sole principal investigator, I'd hired no postdocs or grad students. I'd also finished most of the research and been given a "no-cost extension" to write it up that was due to expire in a few months. In fact, I'd spent all but \$21,432 of the \$263,266 of cash.

That may sound like a lot for a humanities researcher, but it barely covered a year of my salary and included indirect costs (to which my grant was subject like any other), along with travel and so on. What's more, my project's stated aim was to "enhance the effectiveness of national scientific facilities", which was clearly within the NSF's mission.

Such facilities, I had pointed out in my official proposal, are vital if the US is to fulfil its national scientific, technological, medical and educational goals. But friction between a facility and the surrounding community can hamper its work, particularly if the lab's research is seen as threatening – for example, involving chemical, radiological or biological hazards. Some labs, in fact, have had important, yet perfectly safe, facilities permanently closed out of such fear.

"In an age of Big Science," I argued, "understanding the dynamics of lab-community interaction is crucial to advancing national, scientific, and public interests." What's so contentious about that?

"New bad words"

Maybe I had been careless. After all, Ted Cruz, who chairs the Senate's commerce committee, had claimed in February that 3400 NSF awards worth over \$2 billion made during the Biden–Harris administration had promoted DEI and advanced "neo-Marxist class warfare propaganda". I wondered if I might have inadvertently used some trigger word that outed me as an enemy of the state.

I knew, for instance, that the Trump Administration had marked for deletion photos of the Enola Gay aircraft, which had dropped an atomic bomb on Hiroshima, in a Defense Department database because officials had not realized that "Gay" was part of the name of the pilot's mother. Administration officials had made similar misinterpretations in scientific proposals that included the words "biodiversity" and "transgenic".

Had I used one of those "new bad words"? I ran a search on my proposal. Did it mention "equity"? No. "Inclusion"? Also no. The word "diversity" appeared only once, in the subtitle of an article in the bibliography about radiation fallout. "Neo-Marxist"? Again, no. Sure, I'd read Marx's original texts during my graduate training in philosophy, but my NSF documents hadn't tapped him or his followers as essential to my project.

Then I remembered a sentence in my proposal. "Well-established scientific findings," I wrote, "have been rejected by activists and politicians, distorted by lurid headlines, and fuelled partisan agendas." These lead in turn to "conspiracy theories, fake facts, science denial and charges of corruption".

Was that it, I wondered? Had the NSF officials thought that I had meant to refer to the administration's attacks on climate change science, vaccines, green energy and other issues? If so, that was outrageous! There was not a shred of truth to it – no truth at all!

Ructions and retractions

On 23 April – five days after the NSF termination notice – two researchers at Harvard University put together an online "Terminated NSF grant tracker", which contained information based on what they found in the NSF database. Curious, I scrolled down to SUNY at Stony Brook and found mine: "Social and political dynamics of lab-community relations".

I was shocked to discover that almost everything about it in the NSF database was wrong, including the abstract. The abstract given for my grant was apparently that of another NSF award, for a study that touched on DEI themes – a legitimate and useful thing to study under any normal regime, but not this one. At last, I had the reason for my grant termination: an NSF error.

The next day, 24 April, I managed to speak to the beleaguered NSF programme director, who was kind and understanding and said there'd been a mistake in the database. When I asked her if it could be fixed she said, "I don't know". When I asked her if the termination can be reversed, she said, "I don't know". I alerted Stony Brook's grants-management office, which began to press the NSF to reverse its decision. A few hours later I learned that NSF director Sethuraman Panchanathan had resigned.

I briefly wondered if Panchanathan had been fired because my grant had been bungled. No such luck; he was probably disgusted with the administration's treatment of the agency. But while the mistake over my abstract evidently wasn't deliberate, the malice behind my grant's termination certainly was. Further, doesn't one routinely double-check before taking such an unprecedented and monumental step as terminating a grant by a major scientific agency?

I then felt guilty about my anger; who was I to complain? After all, some US agencies have been shockingly incompetent lately. A man was mistakenly sent by the Department of Homeland Security to a dangerous prison in El Salvador and they couldn't (or wouldn't) get him back. The Department of Health and Human Services has downplayed the value of vaccines, fuelling a measles epidemic in Texas, while defence secretary Pete Hegseth used the Signal messaging app to release classified military secrets regarding a war in progress to a journalist.

How narcissistic of me to become livid only when personally affected by termination of an award that's almost over anyway.

A few days later, on 28 April, Stony Brook's provost received another e-mail about my grant from the NSF. Forwarded to me, it said: "the termination notice is retracted; NSF terminated this project in error". Since then, the online documents at the NSF, and the information about my grant in the tracker, have thankfully been corrected.

The critical point

In a few years' time, I'll put together another proposal to study the difference between the way that US government handles science and the needs of its citizens. I'll certainly have a lot more material to draw on. Meanwhile, I'll reluctantly wear my badge of honour. For I deserve it – though not, as I initially thought, because I had threatened the Trump Administration enough that they tried to halt my research.

I got it simply because I'm yet another victim of the Trump Administration's incompetence.

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)

For science or for profit?

Jonte Hance reveals why they stopped reviewing and submitting articles to for-profit publishers

iStock/NuPenDekDee

Stacking up A bottleneck is emerging as the number of papers grows quicker than the number of researchers in academia who can peer review them.

Peer review is a cornerstone of academic publishing. It is how we ensure that published science is valid. Peer review, by which researchers judge the quality of papers submitted to journals, stops pseudoscience from being peddled as equivalent to rigorous research. At the same time, the peer-review system is under considerable strain as the number of journal articles published each year increases, jumping from 1.9 million in 2016 to 2.8 million in 2022, according to Scopus and Web of Science.

All these articles require experienced peer reviewers, with papers typically taking months to go through peer review. This cannot be blamed alone on the time taken to post manuscripts and reviews back and forth between editors and reviewers, but instead is a result of high workloads and, fundamentally, how busy everyone is. Given peer reviewers need to be expert in their field, the pool of potential reviewers is inherently limited. A bottleneck is emerging as the number of papers grows quicker than the number of researchers in academia.

Scientific publishers have long been central to managing the process of peer review. For anyone outside academia, the concept of peer review may seem illogical given that researchers spend their time on it without much acknowledgement. While initiatives are in place to change this such as outstanding-reviewer awards and the Web of Science recording reviewer data, there is no promise that such recognition will be considered when looking for permanent positions or applying for promotion.

The impact of open access

Why, then, do we agree to review? As an active researcher myself in quantum physics, I peer-reviewed more than 40 papers last year and I've always viewed it as a duty. It's a necessary time-sink to make our academic system function, to ensure that published research is valid and to challenge questionable claims. However, like anything people do out of a sense of duty, inevitably there are those who will seek to exploit it for profit.

Many journals today are open access, in which fees, known as article-processing charges, are levied to make the published work freely available online. It makes sense that costs need to be imposed – staff working at publishing companies need paying; articles need editing and typesetting; servers need be maintained and web-hosting fees have to be paid. Recently, publishers have invested heavily in digital technology and developed new ways to disseminate research to a wider audience.

Open access, however, has encouraged some publishers to boost revenues by simply publishing as many papers as possible. At the same time, there has been an increase in retractions, especially of fabricated or manipulated manuscripts sold by "paper mills". The rise of retractions isn't directly linked to the emergence of open access, but it's not a good sign, especially when the academic publishing industry reports profit margins of roughly 40% – higher than many other industries. Elsevier, for instance, publishes nearly 3000 journals and in 2023 its parent company, Relx, recorded a profit of £1.79bn. This is all money that was either paid in open-access fees or by libraries (or private users) for journal subscriptions but ends up going to shareholders rather than science.

It's important to add that not all academic publishers are for-profit. Some, like the American Physical Society (APS), IOP Publishing, Optica, AIP Publishing and the American Association for the Advancement of Science – as well as university presses – are wings of academic societies and universities. Any profit they make is reinvested into research, education or the academic community. Indeed, IOP Publishing, AIP Publishing and the APS have formed a new "purpose-led publishing" coalition, in which the three publishers confirm that they will continue to reinvest the funds generated from publishing back into research and "never" have shareholders that result in putting "profit above purpose".

But many of the largest publishers – the likes of Springer Nature, Elsevier, Taylor and Francis, MDPI and Wiley – are for-profit companies and are making massive sums for their shareholders. Should we just accept that this is how the system is? If not, what can we do about it and what impact can we as individuals have on a multi-billion-dollar industry? I have decided that I will no longer review for, nor submit my articles (when corresponding author) to, any for-profit publishers.

I'm lucky in my field that I have many good alternatives such as the arXiv overlay journal *Quantum*, IOP Publishing's *Quantum Science and Technology*, APS's *Physical Review X Quantum* and *Optica Quantum*. If your field doesn't, then why not push for them to be created? We may not be able to dismantle the entire for-profit publishing industry, but we can stop contributing to it (especially those who have a permanent job in academia and are not as tied down by the need to publish in high impact factor journals). Such actions may seem small, but together can have an effect and push to make academia the environment we want to be contributing to. It may sound radical to take change into your own hands, but it's worth a try. You never know, but it could help more money make its way back into science.

Jonte Hance is a lecturer in applied quantum foundations at Newcastle University, UK, e-mail jonte.hance@newcastle.ac.uk

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Transactions Machine healthcare

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Seeing inside Modern sensors can provide real-time digital data about the health of machines (left) and the human body (right).

Honor Powrie sees intriguing similarities between how we monitor the health of machines and our own human bodies

I began my career in the 1990s at a university spin-out company, working for a business that developed vibration sensors to monitor the condition of helicopter powertrains and rotating machinery. It was a job that led to a career developing technologies and techniques for checking the "health" of machines, such as planes, trains and trucks.

What a difference three decades has made. When I started out, we would deploy bespoke systems that generated limited amounts of data. These days, everything has gone digital and there's almost more information than we can handle. We're also seeing a growing use of machine learning and artificial intelligence (AI) to track how machines operate.

In fact, with AI being increasingly used in medical science – for example to predict a patient's risk of heart attacks – I've noticed intriguing similarities between how we monitor the health of machines and the health of human bodies. Jet engines and hearts are very different objects, but in both cases monitoring devices gives us a set of digitized physical measurements.

Sensors installed on a machine provide various basic physical parameters, such as its temperature, pressure, flow rate or speed. More sophisticated devices can yield information about, say, its vibration, acoustic behaviour, or (for an engine) oil debris or quality. Bespoke sensors might even be added if an important or otherwise unchecked aspect of a machine's performance needs to be monitored – provided the benefits of doing so outweigh the cost.

Generally speaking, the sensors you use in a particular situation depend on what's worked before and whether you can exploit other measurements, such as those controlling the machine. But whatever sensors are used, the raw data then have to be processed and manipulated to extract particular features and characteristics.

Once you've done all that, you can then determine the health of the machine, rather like in medicine. Is it performing normally? Does it seem to be developing a fault? If the machine appears to be going wrong, can you try to diagnose what the problem might be?

Generally, we do this by tracking a range of parameters to look for consistent behaviour, such as a steady increase, or by seeing if a parameter exceeds a pre-defined threshold. With further analysis, we can also try to predict the future state of the machine, work out what its remaining useful life might be, or decide if any maintenance needs scheduling.

A diagnosis typically involves linking various anomalous physical parameters (or symptoms) to a probable cause. As machines obey the laws of physics, a diagnosis can either be based on engineering knowledge or be driven by data – or sometimes the two together. If a concrete diagnosis can't be made, you can still get a sense of where a problem might lie before carrying out further investigation or doing a detailed inspection.

One way of doing this is to use a "borescope" – essentially a long, flexible cable with a camera on the end. Rather like an endoscope in medicine, it allows you to look down narrow or difficult-to-reach cavities. But unlike medical imaging, which generally takes place in the controlled environment of a lab or clinic, machine data are typically acquired "in the field". The resulting images can be tricky to interpret because the light is poor, the measurements are inconsistent, or the equipment hasn't been used in the most effective way.

Even though it can be hard to work out what you're seeing, *in-situ* visual inspections are vital as they provide evidence of a known condition, which can be directly linked to physical sensor measurements. It's a kind of health status calibration. But if you want to get more robust results, it's worth turning to advanced modelling techniques, such as deep neural networks.

One way to predict the wear and tear of a machine's constituent parts is to use what's known as a "digital twin". Essentially a virtual replica of a physical object, a digital twin is created by building a detailed model and then feeding in real-time information from sensors and inspections. The twin basically mirrors the behaviour, characteristics and performance of the real object.

Real-time monitoring

Real-time health data are great because they allow machines to be serviced as and when required, rather than following a rigid maintenance schedule. For example, if a machine has been deployed heavily in a difficult environment, it can be serviced sooner, potentially preventing an unexpected failure. Conversely, if it's been used relatively lightly and not shown any problems, then maintenance could be postponed

> We can work out which parts will need repairing or replacing, when the maintenance will be required and who will do it

or reduced in scope. This saves time and money because the equipment will be out of action less than anticipated.

Having information about a machine's condition at any point in time not only allows this kind of "intelligent maintenance" but also lets us use associated resources wisely. For example, we can work out which parts will need repairing or replacing, when the maintenance will be required and who will do it. Spare parts can therefore be ordered only when required, saving money and optimizing supply chains.

Real-time health-monitoring data are particularly useful for companies owning many machines of one kind, such as airlines with a fleet of planes or haulage companies with a lot of trucks. It gives them a better understanding not just of how machines behave individually – but also collectively to give a "fleet-wide" view. Noticing and diagnosing failures from data becomes an iterative process, helping manufacturers create new or improved machine designs.

This all sounds great, but in some respects, it's harder to understand a machine than a human. People can be taken to hospitals or clinics for a medical scan, but a wind turbine or jet engine, say, can't be readily accessed, switched off or sent for treatment. Machines also can't tell us exactly how they feel.

However, even humans don't always know when there's something wrong. That's why it's worth us taking a leaf from industry's book and consider getting regular health monitoring and checks. There are lots of brilliant apps out there to monitor and track your heart rate, blood pressure, physical activity and sugar levels.

Just as with a machine, you can avoid unexpected failure, reduce your maintenance costs, and make yourself more efficient and reliable. You could, potentially, even live longer too.

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

Harnessing the power of light

Nick Stone from the University of Exeter talks to Tami Freeman about the many ways in which light can be used for diagnostic and therapeutic applications

Matthew Jones Photography

Novel tool Nick Stone demonstrates a prototype Raman needle probe to the audience at the Institute of Physics' Celebration of Physics in Nottingham, UK.

Light has always played a central role in healthcare, enabling a wide range of tools and techniques for diagnosing and treating disease. Nick Stone from the University of Exeter is a pioneer in this field, working with technologies ranging from laser-based cancer therapies to innovative spectroscopy-based diagnostics. Stone was recently awarded the Institute of Physics' Rosalind Franklin Medal and Prize for developing novel Raman spectroscopic tools for rapid *in vivo* cancer diagnosis and monitoring. *Physics World*'s Tami Freeman spoke with Stone about his latest research.

What is Raman spectroscopy and how does it work?

Think about how we see the sky. It is blue due to elastic (specifically Rayleigh) scattering – when an incident photon scatters off a particle without losing any energy. But in about one in a million events, photons interacting with molecules in the atmosphere will be inelastically scattered. This changes the energy of the photon as some of it is taken by the molecule to make it vibrate.

If you shine laser light on a molecule and cause it to vibrate, the photon that is scattered from that molecule will be shifted in energy by a specific amount relating to the molecule's vibrational mode. Measuring the wavelength of this inelastically scattered light reveals which molecule it was scattered from. This is Raman spectroscopy.

Because most of the time we're working at room or body temperatures, most of what we observe is Stokes Raman scattering, in which the laser photons lose energy to the molecules. But if a molecule is already vibrating in an excited state (at higher temperature), it can give up energy and shift the laser photon to a higher energy. This anti-Stokes spectrum is much weaker, but can be very useful – as I'll come back to later.

How are you using Raman spectroscopy for cancer diagnosis?

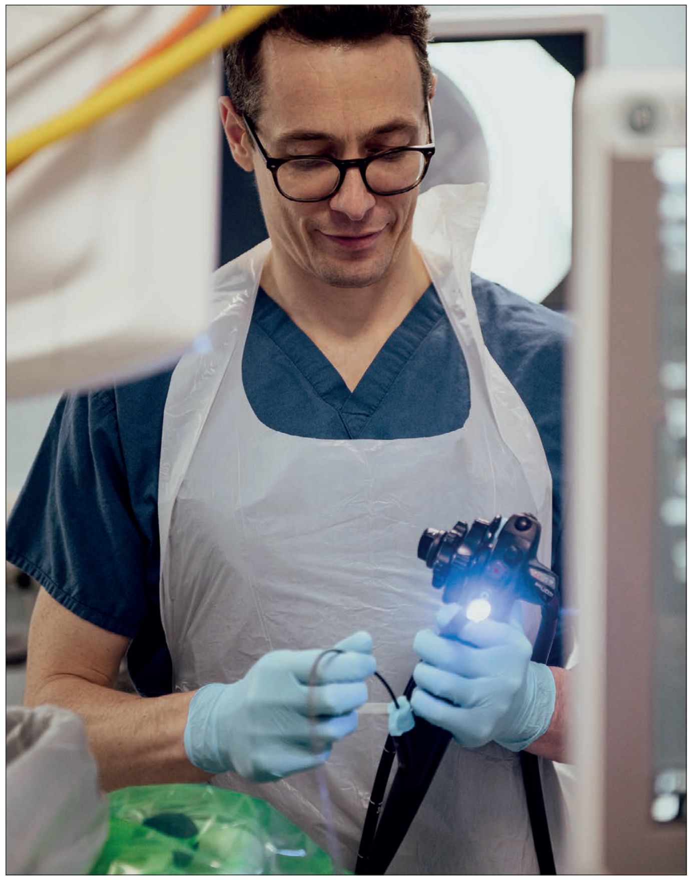
A cell in the body is basically a nucleus: one set of molecules, surrounded by the cytoplasm: another set of molecules. These molecules change subtlety depending on the phenotype [set of observable characteristics] of the particular cell. If you have a genetic mutation, which is what drives cancer, the cell tends to change its relative expression of proteins, nucleic acids, glycogen and so on.

We can probe these molecules with light, and therefore determine their molecular composition. Cancer diagnostics involves identifying minute changes between the different compositions. Most of our work has been in tissues, but it can also be done in biofluids such as tears, blood plasma or sweat. You build up a molecular fingerprint of the tissue or cell of interest, and then you can compare those fingerprints to identify the disease.

We tend to perform measurements under a microscope and, because Raman scattering is a relatively weak effect, this requires good optical systems. We're trying to use a single wavelength of light to probe molecules of interest and look for wavelengths that are shifted from that of the laser illumination. Technology improvements have provided holographic filters that remove the incident laser wavelength readily, and less complex systems that enable rapid measurements.

RaPIDE Team

RaPIDE Team



Tiny but mighty (above) A Raman probe protruding from the instrument channel of an endoscope. (right) Oliver Old, consultant surgeon, passing the probe down an endoscope for a study led by the University of Exeter, with the University of Bristol and Gloucestershire Hospitals NHS Foundation Trust as partners.

Raman spectroscopy can classify tissue samples removed in cancer surgery, for example. But can you use it to detect cancer without having to remove tissue from the patient?

Absolutely, we've developed probes that fit inside an endoscope for diagnosing oesophageal cancer.

Earlier in my career I worked on photodynamic therapy. We would look inside the oesophagus with an endoscope to find disease, then give the patient a phototoxic drug that would target the diseased cells. Shining light on the drug causes it to generate singlet oxygen that kills the cancer cells. But I realized that the light we were using could also be used for diagnosis.

Currently, to find this invisible disease, you have to take many, many biopsies. But our *in vivo* probes allow us to measure the molecular composition of the oesophageal lining using Raman spectroscopy, to be and determine where to take biopsies from. Oesophageal cancer has a really bad outcome once it's diagnosed symptomatically, but if you can find the disease early you can deliver effective treatments. That's what we're trying to do.

The very weak Raman signal, however, causes problems. With a microscope, we can use advanced filters to remove the incident laser wavelength. But sending light down an optical fibre generates unwanted signal, and we also need to remove elastically scattered light from the oesophagus. So we had to put a filter on the end of this tiny 2 mm fibre probe. In addition, we don't want to collect photons that have travelled a long way through the body, so we needed a confocal system. We built a really complex probe, working in collaboration with John Day at the University of Bristol – it took a long time to optimize the optics and the engineering.

Are there options for diagnosing cancer in places that can't be accessed via an endoscope?

Yes, we have also developed a smart needle probe that's currently in trials. We are using this to detect lymphomas – the primary cancer in lymph nodes – in the head and neck, under the armpit and in the groin.

If somebody comes forward with lumps in these areas, they usually have a swollen lymph node, which shows that something is wrong. Most often it's following an infection and the node hasn't gone back down in size.

This situation usually requires surgical removal of the node to decide whether cancer is present or not. Instead, we can just insert our needle probe and send light in. By examining the scattered light and measuring its fingerprint we can identify if it's lymphoma. Indeed, we can actually see what type of cancer it is and where it has come from.

Currently, the prototype probe is quite bulky because we are trying to make it low in cost. It has to have a disposable tip, so we can use a new needle each time, and the filters and optics are all in the handpiece.

Are you working on any other projects at the moment?

As people don't particularly want a needle stuck in them, we are now trying to understand where the photons travel if you just illuminate the body. Red and near-infrared light travel a long way through the body, so we can use near-infrared light to probe photons that have travelled many, many centimetres.

We are doing a study looking at calcifications in a very early breast cancer called ductal carcinoma in situ (DCIS) – it's a Cancer Research UK Grand Challenge called DCIS PRECISION, and we are just moving on to the *in vivo* phase.

Calcifications aren't necessarily a sign of breast cancer – they are mostly benign; but in patients with DCIS, the composition of the calcifications can show how their condition will progress. Mammographic screening is incredibly good at picking up breast cancer, but it's also incredibly good at detecting calcifications that are not necessarily breast cancer yet. The problem is how to treat these patients, so our aim is to determine whether the calcifications are completely fine or if they require biopsy.

We are using Raman spectroscopy to understand the composition of these calcifications, which are different in patients who are likely to progress onto invasive disease. We can do this in biopsies under a microscope and are now trying to see whether it works using transillumination, where we send near-infrared light through the breast. We could use this to significantly reduce the number of biopsies, or monitor individuals with DCIS over many years.

Matthew Jones Photography

In conversation Nick Stone and Tami Freeman discuss optics in medicine at the Institute of Physics' Celebration of Physics in Nottingham, UK.

Light can also be harnessed to treat disease, for example using photodynamic therapy as you mentioned earlier. Another approach is nanoparticle-based photothermal therapy, how does this work?

This is an area I'm really excited about. Nanoscale gold can enhance Raman signals by many orders of magnitude – it's called surface-enhanced Raman spectroscopy. We can also "label" these nanoparticles by adding functional molecules to their surfaces. We've used unlabelled gold nanoparticles to enhance signals from the body and labelled gold to find things.

During that process, we also realized that we can use gold to provide heat. If you shine light on gold at its resonant frequency, it will heat the gold up and can cause cell death. You could easily blow holes in people with a big enough laser and lots of nanoparticles – but we want to do is more subtle. We're decorating the tiny gold nanoparticles with a label that will tell us their temperature.

By measuring the ratio between Stokes and anti-Stokes scattering signals (which are enhanced by the gold nanoparticles), we can measure the temperature of the gold when it is in the tumour. Then, using light, we can keep the temperature at a suitable level for treatment to optimize the outcome for the patient.

Ideally, we want to use 100 nm gold particles, but that is not something you can simply excrete through the kidneys. So we've spent the last five years trying to create nanoconstructs made from 5 nm gold particles that replicate the properties of 100 nm gold, but can be excreted. We haven't demonstrated this excretion yet, but that's the process we're looking at.

This research is part of a project to combine diagnosis and heat treatment into one nanoparticle system – if the Raman spectra indicate cancer, you could then apply light to the nanoparticle to heat and destroy the tumour cells. Can you tell us more about this?

We've just completed a five-year programme called Raman Nanotheranostics. The aim is to label our nanoparticles with appropriate antibodies that will help the nanoparticles target different cancer types. This could provide signals that tell us what is or is not present and help decide how to treat the patient.

We have demonstrated the ability to perform treatments in preclinical models, control the temperature and direct the nanoparticles. We haven't yet achieved a multiplexed approach with all the labels and antibodies that we want. But this is a key step forward and something we're going to pursue further.

We are also trying to put labels on the gold that will enable us to measure and monitor treatment outcomes. We can use molecules that change in response to pH, or the reactive oxygen species that are present, or other factors. If you want personalized medicine, you need ways to see how the patient reacts to the treatment, how their immune system responds. There's a whole range of things that will enable us to go beyond just diagnosis and therapy, to actually monitor the treatment and potentially apply a boost if the gold is still there.

Looking to the future, what do you see as the most promising applications of light within healthcare?

Light has always been used for diagnosis: "you look yellow, you've got something wrong with your liver"; "you've got blue-tinged lips, you must have oxygen depletion". But it's getting more and more advanced. I think what's most encouraging is our ability to measure molecular changes that potentially reveal future outcomes of patients, and individualization of the patient pathway.

But the real breakthrough is what's on our wrists. We are all walking around with devices that shine light in us – to measure heartbeat, blood oxygenation and so on. There are already Raman spectrometers that sort of size. They're not good enough for biological measurements yet, but it doesn't take much of a technology step forward.

I could one day have a chip implanted in my wrist that could do all the things the gold nanoconstructs might do, and my watch could read it out. And this is just Raman – there are a whole host of approaches, such as photoacoustic imaging or optical coherence tomography. Combining different techniques together could provide greater understanding in a much less invasive way than many traditional medical methods. Light will always play a really important role in healthcare. ■

- This article is based on a session at the Institute of Physics' Celebration of Physics in April 2025.

Tami Freeman is an online editor for *Physics World*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Bury it, don't burn it

Waste biomass created by forestry work, crop production and wildfire mitigation is often simply burned, releasing the carbon stored within. But what if we could stop that carbon from entering the atmosphere by burying the biomass instead? **Michael Allen** investigates

Michael Allen is a science writer based in Bristol, UK, www.michaelallen.co.uk

If a tree fell in a forest almost 4000 years ago, did it make a sound? Well, in the case of an Eastern red cedar in what is now Quebec, Canada, it's certainly still making noise today.

That's because in 2013, a team of scientists were digging a trench when they came across the 3775-year-old log. Despite being buried for nearly four millennia, the wood wasn't rotten and useless. In fact, recent analysis unearthed an entirely different story.

The team, led by atmospheric scientist Ning Zeng of the University of Maryland in the US, found that the wood had only lost 5% of its carbon compared with a freshly cut Eastern red cedar log. "The wood is nice and solid – you could probably make a piece of furniture out of it," says Zeng. The log had been preserved in such remarkable shape because the clay soil it was buried in was highly impermeable. That limited the amount of oxygen and water reaching the wood, suppressing the activity of micro-organisms that would otherwise have made it decompose.

This ancient log is a compelling example of "biomass burial". When plants decompose or are burnt, they release

Mark Sherwood

Fortified and ancient Ning Zeng and colleagues discovered this 3775-year-old preserved log while conducting a biomass burial pilot project in Quebec, Canada.

the carbon dioxide (CO_2) they had absorbed from the atmosphere. One idea to prevent this CO_2 being released back into the atmosphere is to bury the waste biomass under conditions that prevent or slow decomposition, thereby trapping the carbon underground for centuries.

In fact, Zeng and his colleagues discovered the cedar log while they were digging a huge trench to bury 35 tonnes of wood to test this very idea. Nine years later, when they dug up some samples, they found that the wood had barely decomposed. Further analysis suggested that if the logs had been left buried for a century, they would still hold 97% of the carbon that was present when they were felled.

Digging holes

To combat climate change, there is often much discussion about how to remove carbon from the atmosphere. As well as conventional techniques like restoring peatland and replanting forests, there are a variety of more technical methods being developed (figure 1). These include direct air capture (DAC) and ocean alkalinity enhancement, which involves tweaking the chemistry of oceans so that they absorb more CO_2. But some scientists – like Sinéad Crotty, a managing director at the Carbon Containment Lab in Connecticut, US – think that biomass burial could be a simpler and cheaper way to sequester carbon.

The 3775-year-old log shows that carbon can be stored for centuries underground, but the wood has to be buried under specific conditions. "People tend to think, 'Who doesn't know how to dig a hole and bury some wood?'" Zeng says. "But think about how many wooden coffins were buried in human history. How many of them survived? For a timescale of hundreds or thousands of years, we need the right conditions."

The key for scientists seeking to test biomass burial is to create dry, low-oxygen environments, similar to those in the Quebec clay soil. Last year, for example, Crotty and her colleagues dug more than 100 pits at a site in Colorado, in the US, filled them with woody material and then covered them up again. In five years' time they plan to dig the biomass back out of the pits to see how much it has decomposed.

The pits vary in depth, and have been refilled and packed in different ways, to test how their build impacts

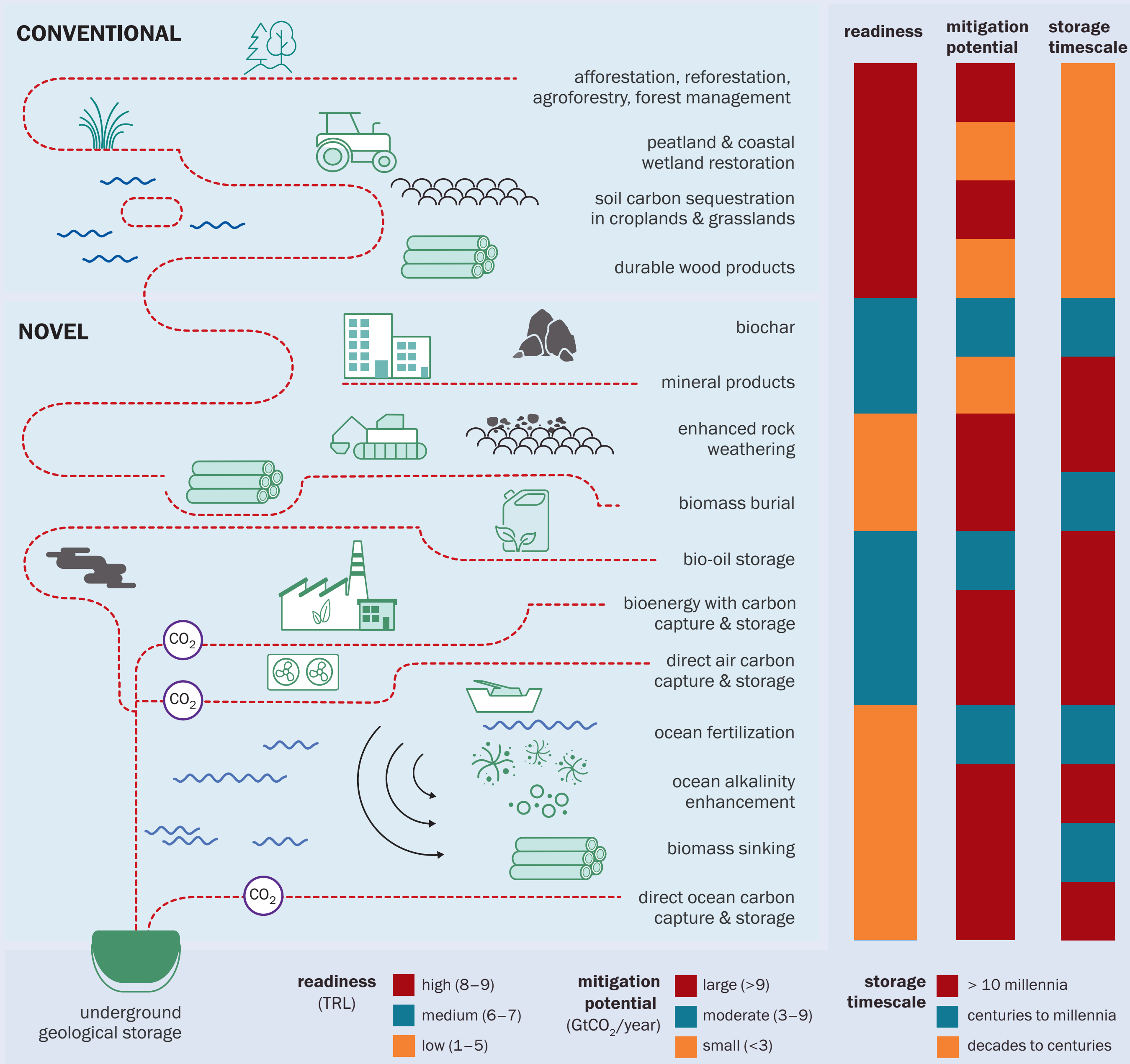
Methods of carbon dioxide storage

The *State of Carbon Dioxide Removal* report defines each technique for carbon-dioxide storage as follows:

- **Afforestation** – Conversion to forest of land that was previously not forest.
- **Reforestation** – Conversion to forest of land that was previously deforested.
- **Agroforestry** – Growing trees on agricultural land while maintaining agricultural production.
- **Forest management** – Stewardship and use of existing forests. To count as carbon dioxide removal (CDR), forest management practices must enhance the long-term average carbon stock in the forest system.
- **Peatland and coastal wetland restoration** – Assisted recovery of inland ecosystems that are permanently or seasonally flooded or saturated by water (such as peatlands) and of coastal ecosystems (such as tidal marshes, mangroves and seagrass meadows). To count as CDR, this recovery must lead to a durable increase in the carbon content of these systems.
- **Durable wood products** – Wood products which meet a given threshold of durability, typically used in construction. These can include sawn wood, wood panels and composite beams, but exclude less durable products such as paper.
- **Biochar** – Relatively stable, carbon-rich material produced by heating biomass in an oxygen-limited environment. Assumed to be applied as a soil amendment unless otherwise stated.
- **Mineral products** – Production of solid carbonate materials for use in products such as aggregates, asphalt, cement and concrete, using CO_2 captured from the atmosphere.
- **Enhanced rock weathering** – Increasing the natural rate of removal of CO_2 from the atmosphere by applying crushed rocks, rich in calcium and magnesium, to soil or beaches.
- **Biomass burial** – Burial of biomass in land sites such as soils or exhausted mines. Excludes storage in the typical geological formations associated with carbon capture and storage (CCS).
- **Bio-oil storage** – Oil made by biomass conversion and placed into geological storage.
- **Bioenergy with carbon capture and storage** – Process by which biogenic CO_2 is captured from a bioenergy facility, with subsequent geological storage.
- **Direct air carbon capture and storage** – Chemical process by which CO_2 is captured from the ambient air, with subsequent geological storage.
- **Ocean fertilization** – Enhancement of nutrient supply to the near-surface ocean with the aim of sequestering additional CO_2 from the atmosphere stimulated through biological production. Methods include direct addition of micro-nutrients or macro-nutrients. To count as CDR, the biomass must reach the deep ocean where the carbon has the potential to be sequestered durably.
- **Ocean alkalinity enhancement** – Spreading of alkaline materials on the ocean surface to increase the alkalinity of the water and thus increase ocean CO_2 uptake.
- **Biomass sinking** – Sinking of terrestrial (e.g. straw) or marine (e.g. macroalgae) biomass in the marine environment. To count as CDR, the biomass must reach the deep ocean where the carbon has the potential to be sequestered durably.
- **Direct ocean carbon capture and storage** – Chemical process by which CO_2 is captured directly from seawater, with subsequent geological storage. To count as CDR, this capture must lead to increased ocean CO_2 uptake.

1 Ready or not

Adapted from Smith et al. (2024) *State of Carbon Dioxide Removal – Edition 2.* DOI:10.17605/OSF.IO/F85QJ



There are multiple methods being developed for capturing, converting and storing carbon dioxide (CO_2), each at different stages of readiness for deployment, with varying removal capabilities and storage durability timescales. This figure – adapted from the *State of Carbon Dioxide Removal* report – shows methods that are already deployed or analysed in research literature. They are categorized as either "conventional", processes that are widely established and deployed at scale; or "novel", those that are at a lower level of readiness and therefore only used on smaller scales. The figure also rates their Technology Readiness Level (TRL), maximum mitigation potential (how many gigatonnes (10^9 tonnes) of CO_2 can be sequestered per year), and storage timescale. Definitions of each method are provided in the box opposite.

carbon storage. The researchers will also be calculating the carbon emissions of processes such as transporting and burying the biomass – including the amount of carbon released from the soil when the pits are dug. "What we are trying to do here is build an understanding of what works and what doesn't, but also how we can measure, report and verify that what we are doing is truly carbon negative," Crotty says.

Over the next five years the team will continuously measure surface CO_2 and methane fluxes from several of the pits, while every pit will have its CO_2 and methane emissions measured monthly. There are also moisture sensors and oxygen probes buried in the pits, plus a full weather station on the site.

Crotty says that all this data will allow them to assess how different depths, packing styles and the local environment alter conditions in the chambers. When the samples are excavated in five years, the researchers will also explore what types of decomposition the burial did and did not suppress. This will include tests to identify different fungal and bacterial signatures, to uncover the micro-organisms involved in any decay.

Josh Goldstein/Coconino National Forest

Cheap but costly Typically, waste biomass from forest management is burnt, like this pile of slash at the edge of Coconino National Forest in Arizona – but doing so releases CO_2.

The big questions

Experiments like Crotty's will help answer one of the key concerns about terrestrial storage of biomass: how long can the carbon be stored?

In 2023 a team led by Lawrence Livermore National Laboratory (LLNL) did a large-scale analysis of the potential for CO_2 removal in the US. The resulting *Road to Removal* report outlined how CO_2 removal could be used to help the US achieve its net zero goals (these have since been revoked by the Trump administration), focusing on techniques like direct air capture (DAC), increasing carbon uptake in forests and agricultural lands, and converting waste biomass into fuels and CO_2.

The report did not, however, look at biomass burial. One of the report authors, Sarah Baker – an expert in decarbonization and CO_2 removal at LLNL – told *Physics World* that this was because of a lack of evidence around the durability of the carbon stored. The report's minimum requirement for carbon storage was at least 100 years, and there were not enough data available to show how much carbon stored in biomass would remain after that period, Baker explains.

The US Department of Energy is also working to address this question. It has funded a set of projects, which Baker is involved with, to bridge some of the knowledge gaps on carbon-removal pathways. This includes one led by the National Renewable Energy Lab, measuring how long carbon in buried biomass remains stored under different conditions.

Bury the problem

Crotty's Colorado experiment is also addressing another question: are all forms of biomass equally appropriate for burial? To test this, Crotty's team filled the pits with a range of woody materials, including different types of wood and wood chip as well as compressed wood, and "slash" – small branches, leaves, bark and other debris created by logging and other forestry work.

Indeed, Crotty and her colleagues see biomass storage as crucial for those managing our forests. The western US states, in particular, have seen an increased risk of wildfires through a mix of climate change and aggressive fire-suppression policies that do not allow smaller fires to burn and thereby produce overgrown forests. "This has led to a build-up of fuels across the landscape," Crotty says. "So, in a forest that would typically have a high number of low-severity fires, it's changed the fire regime into a very high-intensity one."

These concerns led the US Forest Service to announce a 10-year wildfire crisis plan in 2022 that seeks to reduce the risk of fires by thinning and clearing 50 million acres of forest land, in addition to 20 million acres already slated for treatment. But this creates a new problem.

"There are currently very few markets for the types of residues that need to come out of these forests – it is usually small-diameter, low-value timber," explains Crotty. "They typically can't pay their way out of the forests, so business as usual in many areas is to simply put them in a pile and burn them."

A recent study Crotty co-authored suggests that every year "pile burning" in US National Forests emits greenhouse gases equivalent to almost two million tonnes of CO_2, and more than 11 million tonnes of fine particulate matter – air pollution that is linked to a range of health problems. Conservative estimates by the Carbon Containment Lab indicate that the material scheduled for clearance under the Forest Service's 10-year crisis plan will contain around two gigatonnes (Gt) of CO_2 equivalents. This is around 5% of current annual global CO_2 emissions.

There are also cost implications. Crotty's recent analysis found that piling and burning forest residue costs around $700 to $1300 per acre. By adding value to the carbon in the forest residues and keeping it out of the atmosphere, biomass storage may offer a solution to these issues, Crotty says.

As an incentive to remove carbon from the atmosphere, trading mechanisms exist whereby individuals, companies and governments can buy and sell carbon emissions. In essence, carbon has a price attached to it, meaning that someone who has emitted too much, say, can pay someone else to capture and store the equivalent amount of emissions, with an often-touted figure being $100 per tonne of CO_2 stored. For a long time, this has been seen as the price at which carbon capture becomes affordable, enabling scale up to the volumes needed to tackle climate change.

"There is only so much capital that we will ever deploy towards [carbon removal] and thus the cheaper the solution, the more credits we'll be able to generate, the more carbon we will be able to remove from the atmosphere," explains Justin Freiberg, a managing director of the Carbon Containment Lab. "$100 is relatively arbitrary, but it is important to have a target and aim low on pricing for high quality credits."

DAC has not managed to reach this magical price point. Indeed, the Swiss firm Climeworks – which is one of the biggest DAC companies – has stated that its costs might be around $300 per tonne by 2030.

A tomb in a mine

Another carbon-removal company, however, claims it has hit this benchmark using biomass burial. "We're

The need for carbon capture

The Intergovernmental Panel on Climate Change says that carbon capture is essential to limit global warming to 1.5 °C above pre-industrial levels.

To stay within the Paris Agreement's climate targets, the 2024 *State of Carbon Dioxide Removal* report (DOI:10.17605/OSF.IO/F85QJ) estimated that 7–9 gigatonnes (Gt) of CO_2 removal will be needed annually by 2050. According to the report – which was put together by multiple institutions, led by the University of Oxford – currently two billion tonnes of CO_2 are being removed per year, mostly through "conventional" methods like tree planting and wetland restoration. "Novel" methods – such as direct air capture (DAC), bioenergy with carbon capture, and ocean alkalinity enhancement – contribute 1.3 million tonnes of CO_2 removal per year, less than 0.1% of the total.


Graphyte

Big hole in the ground Graphyte is using an old gravel mine 30 km from Pine Bluff in Arkansas to store its compressed biomass bricks.

selling our first credits at $100 per tonne," says Hannah Murnen, chief technology officer at Graphyte – a US firm backed by Bill Gates.

Graphyte is confident that there is significant potential in biomass burial. Based in Pine Bluff, Arkansas, the firm dries and compresses waste biomass into blocks before storage. "We dry it to below a level at which life can exist," says Murnen, which effectively halts decomposition.

The company claims that it will soon be storing 50 000 tonnes of CO_2 per year and is aiming for five million tonnes per year by 2030. Murnen acknowledges that these are "really significant figures", particularly compared with what has been achieved in carbon capture so far. Nevertheless, she adds, if you look at the targets around carbon capture "this is the type of scale we need to get to".

Graphyte is currently working with sawmill residue and rice hulls, but in the future Murnen says it plans to accept all sorts of biomass waste. "One of the great things about biomass for the purpose of carbon removal is that, because we are not doing any sort of chemical transformation on the biomass, we're very flexible to the type of biomass," Murnen adds.

And there appears to be plenty available. Estimates by researchers in the UK and India (*NPJ Climate and Atmospheric Science* **2** 35) suggest that every year around 140 Gt of biomass waste is generated globally from forestry and agriculture. Around two-thirds of the agricultural residues are from cereals, like wheat, rice, barley and oats, while sugarcane stems and leaves are the second largest contributors. The rest is made up of things like leaves, roots, peels and shells from other crops. Like forest residues, much of this waste ends up being burnt or left to rot, releasing its carbon.

Currently, Graphyte has one storage site about 30 km from Pine Bluff, where its compressed biomass blocks are stored underground, enclosed in an impermeable layer that prevents water ingress. "We took what used to be an old gravel mine – so basically a big hole in the ground – and we've created a lined storage tomb where we are placing the biomass and then sealing it closed," says Murnen.

Once sealed, Graphyte monitors the CO_2 and methane concentrations in the headspace of the vaults, to check for any decomposition of the biomass. The company also analyses biomass as it enters the facility, to track how much carbon it is storing. Wood residues, like sawmill waste are generally around 50% carbon, says Murnen, but rice hulls are closer to 35% carbon.

Graphyte is confident that its storage is physically robust and could avoid any re-emission for what Murnen calls "a very long period of time". However, it is also exploring how to prevent accidental disturbance of the biomass in the future – possibly long after the company ceases to exist. One option is to add a conservation easement to the site, a well-established US legal mechanism for adding long-term protection to land.

"We feel pretty strongly that the way we are approaching [carbon removal] is one of the most scalable ways," Murnen says. "In as far as impediments or barriers to scale, we have a much easier permitting pathway, we don't need pipelines, we are pretty flexible on the type of land that we can use for our storage sites, and we have a huge variety of feedstocks that we can take into the process."

A simple solution

Back at LLNL, Baker says that although she hasn't "run the numbers", and there are a lot caveats, she suspects that biomass burial is "true carbon removal because it is so simple".

Once associated upstream and downstream emissions are taken into account, many techniques that people call carbon removal are probably not, she says, because they emit more fossil CO_2 than they store.

Biomass burial is also cheap. As the Road to Removal analysis found, "thermal chemical" techniques, like pyrolysis, have great potential for removing and storing carbon while converting biomass into hydrogen and sustainable aviation fuel. But they require huge investment, with larger facilities potentially costing hundreds of millions of dollars. Biomass burial could even act as temporary storage until facilities are ready to convert the carbon into sustainable fuels. "Buy ourselves time and then use it later," says Baker.

Either way, biomass burial has great potential for the future of carbon storage, and therefore our environment. "The sooner we can start doing these things the greater the climate impact," Baker says.

We just need to know that the storage is durable – and if that 3775-year-old log is any indication, there's the potential to store biomass for hundreds, maybe thousands of years.

Quantum sensing for healthcare

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

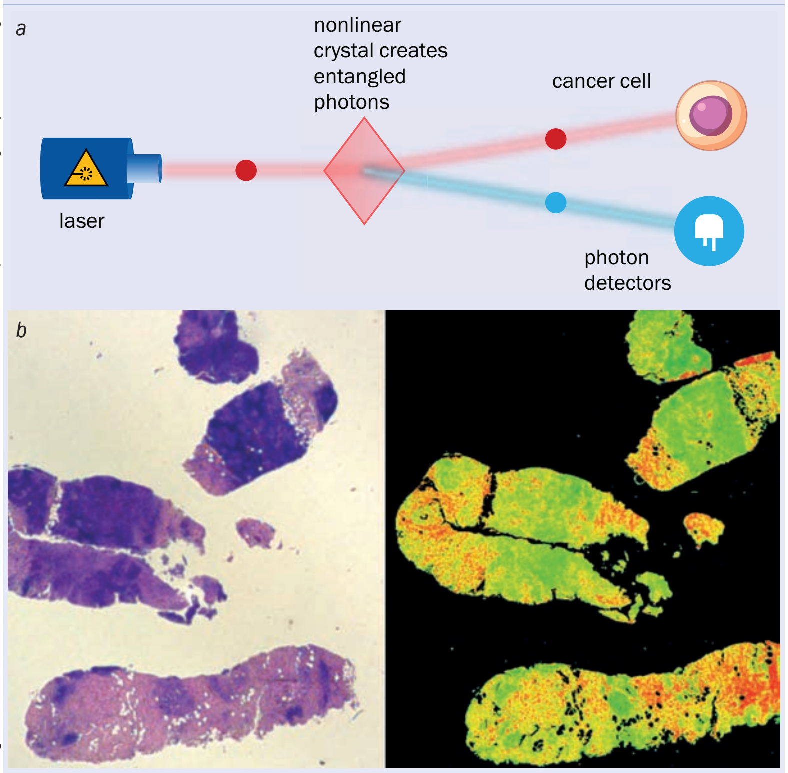
Matt Jones is doing a PhD in quantum physics within QET Labs at the University of Bristol, UK, and is part-time knowledge transfer manager at Innovate UK Business Connect. He wrote the Innovate UK report *Quantum for Life: How UK Life Sciences and Healthcare Can Benefit from Quantum Technologies*

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

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

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

1 Entangled thoughts



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

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

Sense about sensors

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

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

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

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

Quantum diagnosis

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

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

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

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

Point of care

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

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

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

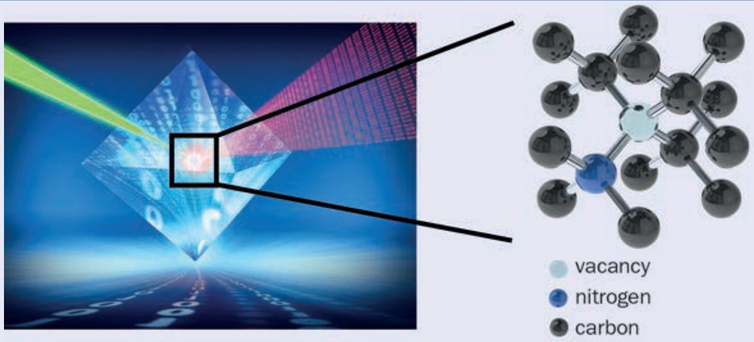
One UK company working in this area is Element Six. It has joined forces with the US-based firm QDTI to make a single-crystal diamond-based device that can quickly identify biomarkers in blood plasma, cerebrospinal fluid and other samples extracted from the body. The device detects magnetic fields produced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

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

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

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

2 Centre of attention



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

Wearable healthcare

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

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

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

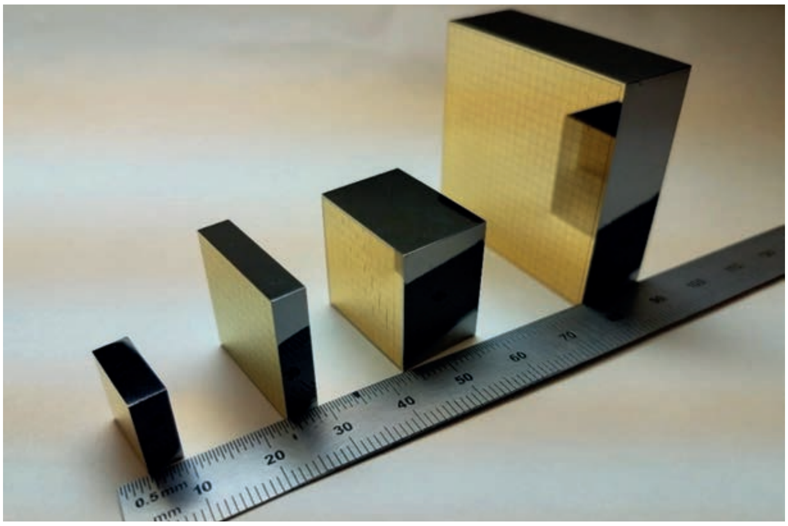
Body imaging

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

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

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

Kromek



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

Quantum technologies can help us break the technological limits of microscopy

be imaged for a long time to get enough signal.

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

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

Microscopy matters

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

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

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

Looking to the future

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

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

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

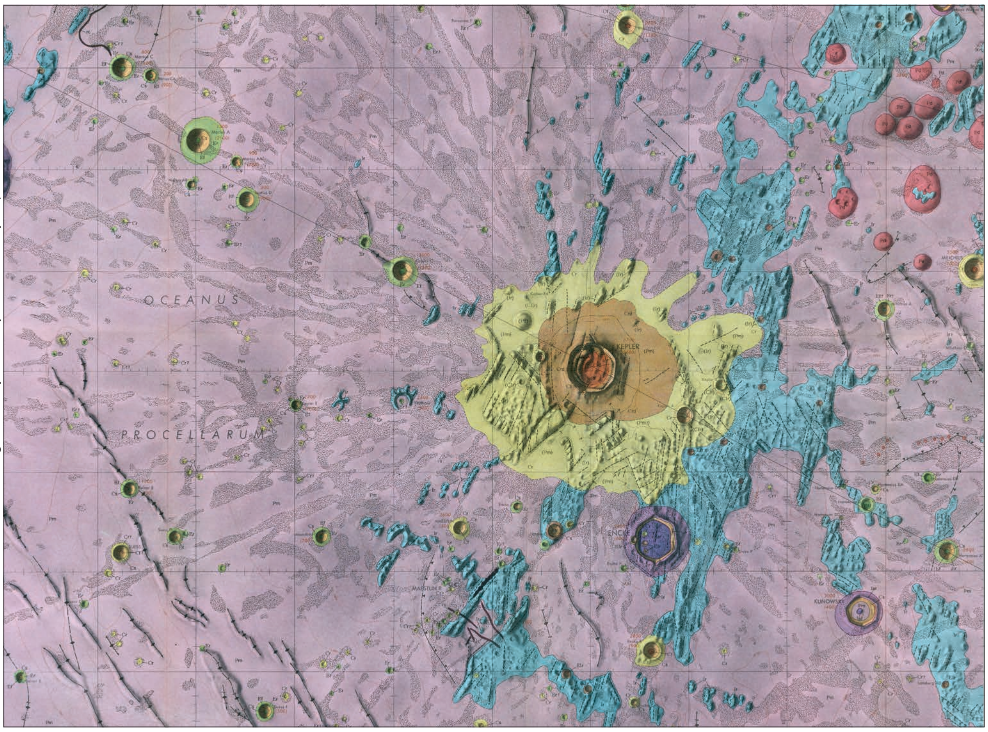
Q-BIOMED is, for example, planning to use both single-crystal diamond and nanodiamonds to develop and commercialize sensors that can diagnose and treat diseases such as cancer and Alzheimer's at much earlier stages of their development. "These healthcare ambitions are not restricted to academia, with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

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

SummerReviews

Moonstruck

Ian Randall reviews *LUNAR: a History of the Moon in Myths, Maps + Matter*



Stunning stratigraphy An excerpt from the 1962 geological map of the lunar surface, showing the Kepler crater in the centre.

LUNAR: a History of the Moon in Myths, Maps + Matter
Various authors
2024 Thames & Hudson 256pp £50.00

As I write this [and don't tell the *Physics World* editors, please] I'm half-watching out of the corner of my eye the quirky French-made, video-game spin-off series *Rabbids Invasion*. The mad and moronic bunnies (or, in a nod to the original French, *Les Lapins Crétins*) are currently making another attempt to reach the Moon – a recurring yet never-explained motif in the cartoon – by stacking up a vast pile of junk; charming chaos ensues.

As explained in *LUNAR: a History of the Moon in Myths, Maps + Matter* – the exquisite new Thames and Hudson book that presents the stunning Apollo-era Lunar Atlas alongside a collection of charming essays – madness has long been associated with the Moon. One suspects there was a good kind of mania behind the drawing up of the Lunar Atlas, a series of geological maps plotting the rock formations on the Moon's surface that are as much art as they are a visualization of data. And having drooled over *LUNAR*, truly the crème de la crème of coffee-table books, one cannot fail but to become a little mad for the Moon too.

As well as an exploration of the Moon's connections (both etymologically and philosophically) to lunacy by science writer Kate Golembiewski, the varied and captivating essays of 20 authors collected in *LUNAR* cover the gamut from the Moon's role in ancient times (did you know that the Greeks believed that the souls of the dead gather around the Moon?) through to natural philosophy, eclipses, the space race and the Artemis Programme. My favourite essays were the more off-beat ones: the Moon in silent cinema, for example, or its fascinating influence on "cartes de visite", the short-lived 19th-century miniature images whose popularity was boosted by Queen Victoria and Prince Albert. (I, for one, am now quite resolved to have my portrait taken with a giant, stylized, crescent moon prop.)

The pulse of *LUNAR*, however, are the breathtaking reproductions of all 44 of the exquisitely hand-drawn 1:1,000,000 scale maps – or "quadrangles" – that make up the US Geological Survey (USGS)/NASA Lunar Atlas.

Drawn up between 1962 and 1974 by a team of 24 cartographers, illustrators, geographers and geologists, the astonishing Lunar Atlas captures the entirety of the Moon's near side, every crater and lava-filled maria ("sea"), every terra (highland) and volcanic dome. The work began as a way to guide the robotic and human exploration of the Moon's surface and was soon augmented with images and rock samples from the missions themselves.

One could be hard-pushed to sum it up better than the American science writer Dava Sobel, who pens the book's foreword: "I've been to the Moon, of course. Everyone has, at least vicariously, visited its stark landscapes, driven over its unmarked roads. Even so, I've never seen the Moon quite the way it appears here – a black-and-white world rendered in a riot of gorgeous colours."

Many moons ago

Having been trained in geology, the sections of the book covering the history of the Lunar Atlas piqued my particular interest. The Lunar Atlas was not the first attempt to map the surface of the Moon; one of the reproductions in the book shows an earlier effort from 1961 drawn up by USGS geologists Robert Hackman and Eugene Shoemaker.

Hackman and Shoemaker's map shows the Moon's Copernicus region, named after its central crater, which in turn honours the Renaissance-era Polish polymath Nicolaus Copernicus. It served as the first demonstration that the geological principles of stratigraphy (the study of rock layers) as developed on the Earth could also be applied to other bodies. The duo started with the law of superposition; this is the principle that when one finds multiple layers of rock, unless they have been substantially deformed, the older layer will be at the bottom and the youngest at the top.

"The chronology of the Moon's geologic history is one of violent alteration," explains science historian Matthew Shindell in *LUNAR*'s second essay. "What [Hackman and Shoemaker] saw around Copernicus were multiple overlapping layers, including the lava plains of the maria […], craters displaying varying degrees of degradations, and materials and features related to the explosive impacts that had created the craters."

From these the pair developed a basic geological timeline, unpicking the recent history of the Moon one overlapping feature at the time. They identified five eras, with the Copernican, named after the crater and beginning 1.1 billion years ago, being the most recent.

Considering it was based on observations of just one small region of the Moon, their timescale was remarkably accurate, Shindell explains, although subsequent observations have redefined its stratigraphic units – for example by adding the Pre-Nectarian as the earliest era (predating the formation of Nectaris, the oldest basin), whose rocks can still be found broken up and mixed into the lunar highlands.

Accordingly, the different quadrants of the atlas very much represent an evolving work, developing as lunar exploration progressed. Later maps tended to be more detailed, reflecting a more nuanced understanding of the Moon's geological history.

New moon

Parts of the Lunar Atlas have recently found new life in the development of the first complete map of the lunar surface, the "Unified Geologic Map of the Moon". The new digital map combines the Apollo-era data with that from more recent satellite missions, including the Japan Aerospace Exploration Agency (JAXA)'s SELENE orbiter.

As former USGS director and NASA astronaut Jim Reilly said when the unified map was first published back in 2020: "People have always been fascinated by the Moon and when we might return. So, it's wonderful to see USGS create a resource that can help NASA with their planning for future missions."

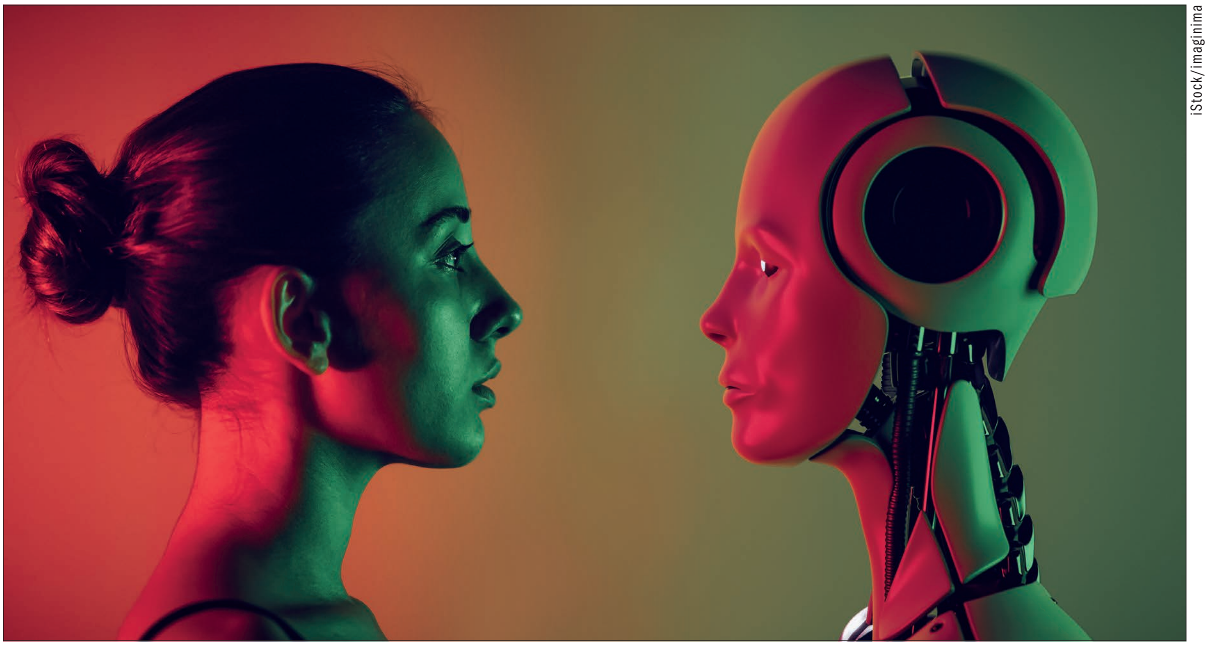
I might not be planning a Moon mission (whether by rocket or teetering tower of clutter), but I am planning to give the stunning *LUNAR* pride of place on my coffee table next time I have guests over – that's how much it's left me, ahem, "over the Moon".

Ian Randall is a science writer based in Royston, UK

Lost in the mirror?

Claire Malone reviews *The AI Mirror* by Shannon Vallor

The AI Mirror: How to Reclaim Our Humanity in an Age of Machine Thinking
Shannon Vallor
2024 Oxford University Press
272pp £22.99hb



iStock/imaginima

Long-lost twins Artificial intelligence uses vast datasets to mirror human behaviour. Will it ever match humanity's creativity, or will over-reliance on this new technology stifle innovation?

Are we at risk of losing ourselves in the midst of technological advancement? Could the tools we build to reflect our intelligence start distorting our very sense of self? Artificial intelligence (AI) is a technological advancement with huge ethical implications, and in *The AI Mirror: How to Reclaim Our Humanity in an Age of Machine Thinking*, Shannon Vallor offers a philosopher's perspective on this vital question.

Vallor, who is based at the University of Edinburgh in the UK, argues that artificial intelligence is not just reshaping society but is also subtly rewriting our relationship with knowledge and autonomy. She even goes as far as to say, "Today's AI mirrors tell us what it is to be human – what we prioritize, find good, beautiful or worth our attention."

Vallor employs the metaphor of AI as a mirror – a device that reflects human intelligence but lacks independent creativity. According to her, AI systems, which rely on curated sets of training data, cannot truly innovate or solve new challenges. Instead, they mirror our collective past, reflecting entrenched biases and limiting our ability to address unprecedented global problems like climate change. Therefore, unless we carefully consider how we build and use AI, it risks stalling human progress by locking us into patterns of the past.

View this e-magazine online to watch a video of author Shannon Vallor talking about her book

The book explores how humanity's evolving relationship with technology – from mechanical automata and steam engines to robotics and cloud computing – has shaped the development of AI. Vallor grounds readers in what AI is and, crucially, what it is not. As she explains, while AI systems appear to "think", they are fundamentally tools designed to process and mimic human-generated data.

AI effects

The book's philosophical underpinnings are enriched by Vallor's background in the humanities and her ethical expertise. She draws on myths, such as the story of Narcissus, who met a tragic end after being captivated by his reflection, to illustrate the dangers of AI. She gives as an example the effect that AI social-media filters have on the propagation and domination of Western beauty standards.

Vallor also explores the long history of literature grappling with artificial intelligence, self-awareness and what it truly means to be human. These fictional works, which include *Do Androids Dream of Electric Sheep?* by Philip K Dick, are used not just as examples but as tools to explore the complex relationship between humanity and AI. The emphasis on the ties between AI and popular culture results in writing that is both accessible and profound, deftly weaving complex ideas into a narrative that engages readers from all backgrounds.

One area where I find Vallor's conclusions contentious is her vision for AI in augmenting science communication and learning. She argues that our current strategies for science communication are inadequate and that improving public and student access to reliable information is critical. In her words: "Training new armies of science communicators is an option, but a less prudent use of scarce public funds than conducting vital research itself. This is one area where AI mirrors will be useful in the future."

In my opinion, this statement warrants significant scrutiny. Science communication and teaching are about more than simply summarising papers or presenting data; they require human connection to contextualize findings and make them accessible to broad audiences. While public distrust of experts is a legitimate issue, delegating science communication to AI risks exacerbating the problem.

AI's lack of genuine understanding, combined with its susceptibility to bias and detachment from human nuance, could further erode trust and deepen the disconnect between science and society. Vallor's optimism in this context feels misplaced. AI, as it currently stands, is ill-suited to bridge the gaps that good science communication seeks to address.

Shift of emphasis

Despite its generally critical tone, *The AI Mirror* is far from a technophobic manifesto. Vallor's insights are ultimately hopeful, offering a blueprint for reclaiming technology as a tool for human advancement. She advocates for transparency, accountability, and a profound shift in economic and social priorities. Rather than building AI systems to mimic human behaviour, she argues, we should design them to amplify our best qualities – creativity, empathy and moral reasoning – while acknowledging the risk that this technology will devalue these talents as well as amplify them.

The AI Mirror is essential reading for anyone concerned about the future of artificial intelligence and its impact on humanity. Vallor's arguments are rigorous yet accessible, drawing from philosophy, history and contemporary AI research. She challenges readers to see AI not as a technological inevitability but as a cultural force that we must actively shape.

Her emphasis on the need for a "new language of virtue" for the AI age warrants consideration, particularly in her call to resist the seductive pull of efficiency and automation at the expense of humanity. Vallor argues that as AI systems increasingly influence decision-making in society, we must cultivate a vocabulary of ethical engagement that goes beyond simplistic notions of utility and optimization. As she puts it: "We face a stark choice in building AI technologies. We can use them to strengthen our humane virtues, sustaining and extending our collective capabilities to live wisely and well. By this path, we can still salvage a shared future for human flourishing."

Vallor's final call to action is clear: we must stop passively gazing into the AI mirror and start reshaping it to serve humanity's highest virtues, rather than its worst instincts. If AI is a mirror, then we must decide what kind of reflection we want to see.

Claire Malone is a science journalist based in London and a contributing columnist for *Physics World*, www.drclairemalone.com

Beyond the Big Bang

Emma Chapman reviews *Battle of the Big Bang: The New Tales of Our Cosmic Origins* by Niayesh Afshordi and Phil Halper

View this e-magazine online to watch a trailer for the book

Battle of the Big Bang: The New Tales of Our Cosmic Origins
Niayesh Afshordi and Phil Halper
2025 University of Chicago Press
360pp
$32.50/£26.00 hb

"The universe began with a Big Bang."

I've said this neat line more times than I can count at the start of a public lecture. It summarizes one of the most incomprehensible ideas in science: that the universe began in an extreme, hot, dense and compact state, before expanding and evolving into everything we now see around us. The certainty of the simple statement is reassuring, and it is an easy way of quickly setting the background to any story in astronomy.

But what if it isn't just an over-simplified summary? What if it is misleading, perhaps even wholly inaccurate?

The Battle of the Big Bang: the New Tales of Our Cosmic Origin aims to dismantle the complacency many of us have fallen into when it comes to our knowledge of the earliest time. And it succeeds – if you push through the opening pages.

Early on, authors Niayesh Afshordi and Phil Halper say "in some sense the theory of the Big Bang cannot be trusted", which caused me to raise an eyebrow and wonder what I had let myself in for. After all, for many astronomers, myself included, the Big Bang is practically gospel. And therein lies the problem. When a theory becomes so widely accepted that it is immune to question, we've moved from science supported by evidence to belief upheld by faith.

It is easy to read the first few pages of *The Battle of the Big Bang* with deep scepticism but don't worry, your eyebrows will eventually lower. That the universe has evolved from a "hot Big Bang" is not in doubt – observations such as the measurements of the cosmic microwave background leave no room for debate. But the idea that the universe "began" as a singularity – a region of space where the curvature of space–time becomes infinite – is another matter. The authors argue that no current theory can describe such a state, and there is no evidence to support it.

An astronomical crowbar

Given the confidence with which we teach it, many might have assumed the Big Bang theory beyond any serious questioning, thereby shutting the door on their own curiosity. Well, Afshordi and Halper have written the popular science equivalent of a crowbar, gently prising that door back open without judgement, keen only to share the adventure still to be had.

A cosmologist at the University of Waterloo, Canada, Afshordi is obsessed with finding observational ways of solving problems in fundamental physics, and is known for his creative alternative theories, such as a non-constant speed of light. Meanwhile Halper, a science popularizer, has carved out a niche by interviewing leading voices in early universe cosmology on YouTube, often facilitating fierce debates between competing thinkers. The result is a book that is both authoritative and accessible – and refreshingly free from ego.

Over 12 chapters, the book introduces more than two dozen alternatives to the Big Bang singularity, with names as tongue-twisting as the theories are mind-bending. For most readers, and even this astrophysicist, the distinctions between the theories quickly blur. But that's part of the point. The focus isn't on convincing you which model is correct, it's about making clear that many alternatives exist that are all just as credible (give or take). Reading this book feels like walking through an art gallery with a knowledgeable and thoughtful friend explaining each work's nuance. They offer their own opinions in hushed tones, but never suggest that their favourite should be yours too, or even that you should have a favourite.

If you do find yourself feeling dizzy reading about the details of holographic cosmology or eternal inflation, then it won't be long before an insight into the nature of scientific debate or a crisp analogy brings you up for air. This is where the co-authorship begins to shine: Halper's presence is felt in the moments when complicated theories are reduced to an idea anyone can relate to; while Afshordi brings deep expertise and an insider's view of the cosmological community. These vivid and sometimes gossipy glimpses into the lives and rivalries of his colleagues paint a fascinating picture. It is a huge cast of characters – including Roger Penrose, Alan Guth and Hiranya Peiris – most of whom appear only for a page.

But even though you won't remember all the names, you are left with the feeling that Big Bang cosmology is a passionate, political and philosophical side of science very much still in motion.

Keep the door open

The real strength of this book is its humility and lack of defensiveness. As much as reading about the theory behind a multiverse is interesting, as a scientist, I'm always drawn to data. A theory that cannot be tested can feel unscientific, and the authors respect that instinct. Surprisingly, some of the most fantastical ideas, like pre-Big Bang cosmologies, are testable. But the tools required are almost science fiction themselves – such as a fleet of gravitational-wave detectors deployed in space. It's no small task, and one of the most delightful moments in the book is a heartfelt thank you to taxpayers, for funding the kind of fundamental research that might one day get us to an answer.

Curiosity, unashamed and persistent, is far more scientific than shutting the door for fear of the uncertain

In the concluding chapters, the authors pre-emptively respond to scepticism, giving real thought to discussing when thinking outside the box becomes going beyond science altogether. There are no final answers in this book, and it does not pretend to offer any. In fact, it actively asks the reader to recognize that certainty does not belong at the frontiers of science. Afshordi doesn't mind if his own theories are proved wrong, the only terror for him is if people refuse to ask questions or pursue answers simply because the problem is seen as intractable.

A book that leaves you feeling like you understand less about the universe than when you started it might sound like it has failed. But when that "understanding" was an illusion based on dogma, and a book manages to pry open a long-sealed door in your mind, that's a success.

The Battle of the Big Bang offers both intellectual humility and a reviving invitation to remain eternally open-minded. It reminded me of how far I'd drifted from being one of the fearless schoolchildren who, after I declare with certainty that the universe began with a Big Bang, ask, "But what came before it?". That curiosity, unashamed and persistent, is far more scientific than shutting the door for fear of the uncertain.

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

Condensed natter: bite-size reviews of recent books


Robert McCall

NASA art
This concept painting by Robert McCall shows a telescope in a hypothetical lunar observatory, sheltered from the Sun to protect its lens.

The Shape of Wonder: How Scientists Think, Work and Live
By Alan Lightman and Martin Rees

In their delightful new book, cosmologist Martin Rees and physicist and science writer Alan Lightman seek to provide "an honest picture of scientists as people and how they work and think". *The Shape of Wonder* does this by exploring the nature of science, examining the role of critical thinking, and looking at how scientific theories are created and revised as new evidence emerges. It also includes profiles of individual scientists, ranging from historical Nobel-prize winners such as physicist Werner Heisenberg and biologist Barbara McClintock, to rising stars like CERN theorist Dorota Grabowska.

Matin Durrani

● 2025 Pantheon Books

Our Accidental Universe: Stories of Discovery from Asteroids to Aliens
By Chris Lintott

TV presenter and physics professor Chris Lintott brings all his charm and wit to his new book *Our Accidental Universe*. He looks at astronomy through the lens of the human errors and accidents that lead to new knowledge. It's a loose theme that allows him to skip from the search for alien life to pulsars and the Hubble Space Telescope. Lintott has visited many of the facilities he discusses, and spoken to many people working in these areas, adding a personal touch to his stated aim of elucidating how science really gets done.

Kate Gardner

● 2024 Penguin

Science is Lit: Awesome Electricity and Mad Magnets
By Big Manny (Emanuel Wallace)

Want to feed your child's curiosity about how things work (and don't mind creating a mini lab in your house)? Take a look at *Awesome Electricity and Mad Magnets*, the second in the Science Is Lit series by Emanuel Wallace – aka TikTok star "Big Manny". Wallace introduces four key concepts of physics – force, sound, light and electricity – in an enthusiastic and fun way that's accessible for 8–12 year olds. With instructions for experiments kids can do at home, and a clear explanation of the scientific process, your child can really experience what it's like to be a scientist.

Sarah Tesh

● 2025 Puffin

Space Posters & Paintings: Art About NASA
By Bill Schwartz

Astronomy is the most visually gifted of all the sciences, with endless stunning photographs of our cosmos. But perhaps what sets NASA apart from other space agencies is its art programme, which has existed since 1962. In *Space Posters and Paintings: Art about NASA*, documentary filmmaker Bill Schwartz has curated a striking collection of nostalgic artworks that paint the history of NASA and its various missions across the solar system and beyond. Particularly captivating are pioneering artist Robert McCall's paintings of the Gemini and Apollo missions. This large-format coffee book is a perfect purchase for any astronomy buff.

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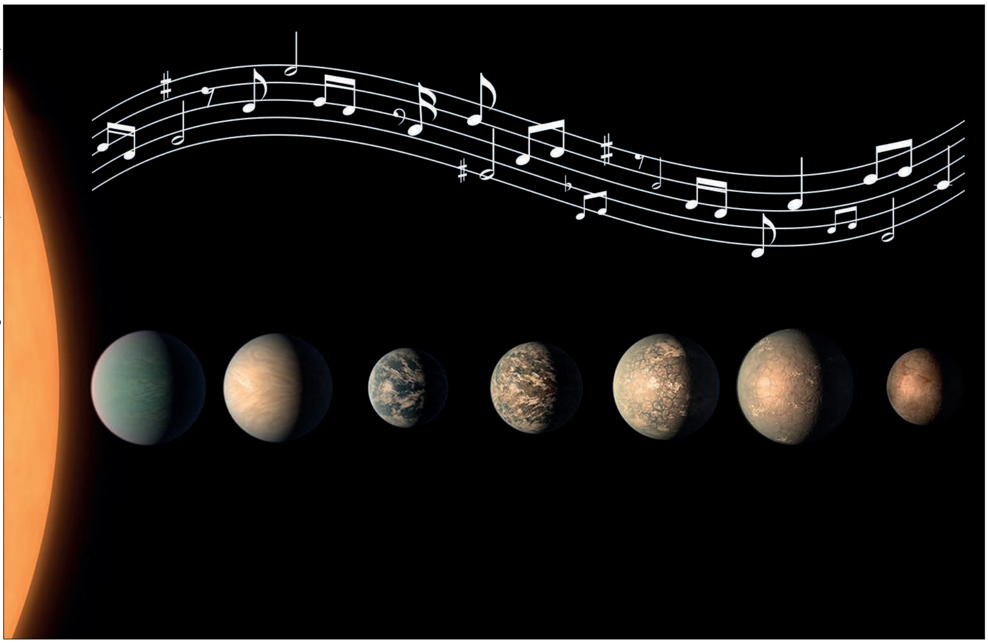
● 2024 ACC Art Books

Harmonious connections

Philip Moriarty reviews *A Perfect Harmony: Music, Mathematics and Science* by David Darling



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Otherworldly audio The planets around TRAPPIST-1 have orbital ratios that can be mapped to musical intervals.

A Perfect Harmony: Music, Mathematics and Science
David Darling
2025 Oneworld Publications 288pp £10.99pb/ £6.99ebook

CP Snow's classic *The Two Cultures* lecture, published in book form in 1959, is the usual go-to reference when exploring the divide between the sciences and humanities. It is a culture war that was raging long before the term became social-media shorthand for today's tribal battles over identity, values and truth.

While Snow eloquently lamented the lack of mutual understanding between scientific and literary elites, the 21st-century version of the two-cultures debate often plays out with a little less decorum and a lot more profanity. Hip hop duo Insane Clown Posse certainly didn't hold back in their widely memed 2010 track "Miracles", which included the lyric "And I don't wanna talk to a scientist / Y'all motherfuckers lying and getting me pissed". An extreme example to be sure, but it hammers home the point: Snow's two-culture concerns continue to resonate strongly almost 70 years after his influential lecture and writings.

A Perfect Harmony: Music, Mathematics and Science by David Darling is the latest addition to a growing genre that seeks to bridge that cultural rift. Like Peter Pesic's *Music and the Making of Modern Science*, Susan Rogers and Ogi Ogas' *This Is What It Sounds Like*, and Philip Ball's *The Music Instinct*, Darling's book adds to the canon that examines the interplay between musical creativity and the analytical frameworks of science (including neuroscience) and mathematics.

I've also contributed, in a nanoscopically small way, to this music-meets-science corpus with an analysis of the deep and fundamental links between quantum physics and heavy metal (*When The Uncertainty Principle Goes To 11*), and have a long-standing interest in music composed from maths and physics principles and constants (see my Lateral Thoughts articles from September 2023 and July 2024). Darling's book, therefore, struck a chord with me.

Darling is not only a talented science writer with an expansive back-catalogue to his name but he is also an accomplished musician (check out his album *Songs Of The Cosmos*), and his enthusiasm for all things musical spills off the page. Furthermore, he is a physicist, with a PhD in astronomy from the University of Manchester. So if there's a writer who can genuinely and credibly inhabit both sides of the arts–science cultural divide, it's Darling.

But is *A Perfect Harmony* in tune with the rest of the literary ensemble, or marching to a different beat? In other words, is this a fresh new take on the music-meets-maths (meets pop sci) genre or, like too many bands I won't mention, does it sound suspiciously like something you've heard many times before? Well, much like an old-school vinyl album, Darling's work has the feel of two distinct sides. (And I'll try to make that my final spin on groan-worthy musical metaphors. Promise.)

Not quite perfect pitch

Although the subtitle for *A Perfect Harmony* is "Music, Mathematics and Science", the first half of the book is more of a history of the development and evolution of music and musical instruments in various cultures, rather than a new exploration of the underpinning mathematical and scientific principles. Engaging and entertaining though this is – and all credit to Darling for working in a reference to Van Halen in the opening lines of chapter 1 – it's well-worn ground: Pythagorean tuning, the circle of fifths, equal temperament, *Music of the Spheres* (not the Coldplay album, mercifully), resonance, harmonics, etc. I found myself wishing, at times, for a take that felt a little more off the beaten track.

One case in point is Darling's brief discussion of the theremin. If anything earns the title of "The Physicist's Instrument", it's the theremin – a remarkable device that exploits the innate electrical capacitance of the human body to load a resonant circuit and thus produce an ethereal, haunting tone whose pitch can be varied, without, remarkably, any physical contact.

While I give kudos to Darling for highlighting the theremin, the brevity of the description is arguably a lost opportunity when put in the broader context of the book's aim to explain the deeper connections between music, maths and science. This could have been a novel and fascinating take on the links between electrical and musical resonance that went well beyond the familiar territory mapped out in standard physics-of-music texts.

As the book progresses, however, Darling moves into more distinctive territory, choosing a variety of inventive examples that are often fascinating and never short of thought-provoking. I particularly enjoyed his description of orbital resonance in the system of seven planets orbiting the red dwarf TRAPPIST-1, 41 light-years from Earth. The orbital periods have ratios, which, when mapped to musical intervals, correspond to a minor sixth, a major sixth, two perfect fifths, a perfect fourth and another perfect fifth. And it's got to be said that using the music of the eclectic Australian band King Gizzard and the Lizard Wizard to explain microtonality is nothing short of inspired.

Using the music of the eclectic Australian band King Gizzard and the Lizard Wizard to explain microtonality is nothing short of inspired

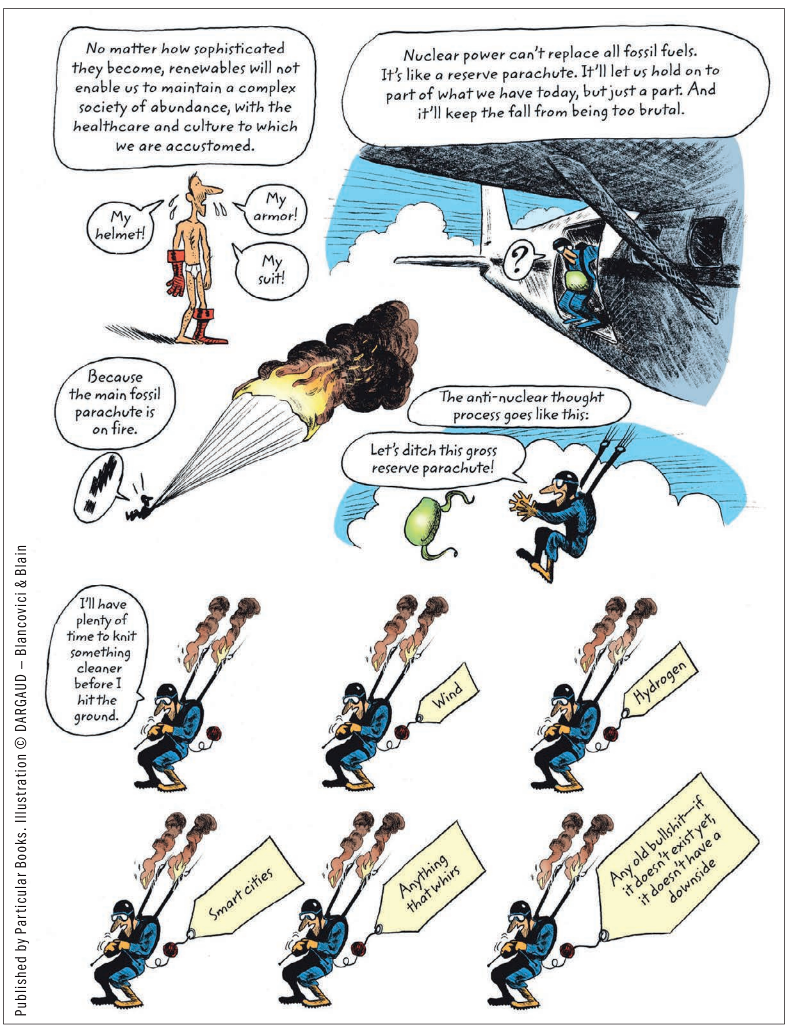
A Perfect Harmony doesn't entirely close the cultural gap highlighted by Snow all those years ago, but it does hum along pleasantly in the space between. Though the subject matter occasionally echoes well-trodden themes, Darling's perspective and enthusiasm lend it freshness. There's plenty here to enjoy, especially for physicists inclined to tune into the harmonies of the universe.

Philip Moriarty is a professor of physics at the University of Nottingham, UK. He is the author of *When the Uncertainty Principle Goes to 11: Or How to Explain Quantum Physics with Heavy Metal*, e-mail philip.moriarty@nottingham.ac.uk

No laughing matter

Mike Follows reviews *World Without End: an Illustrated Guide to the Climate Crisis* by Jean-Marc Jancovici and Christophe Blain, translated by Edward Gauvin

World Without End: an Illustrated Guide to the Climate Crisis
Jean-Marc Jancovici and Christophe Blain
2024 Particular Books £25.00hb 196pp



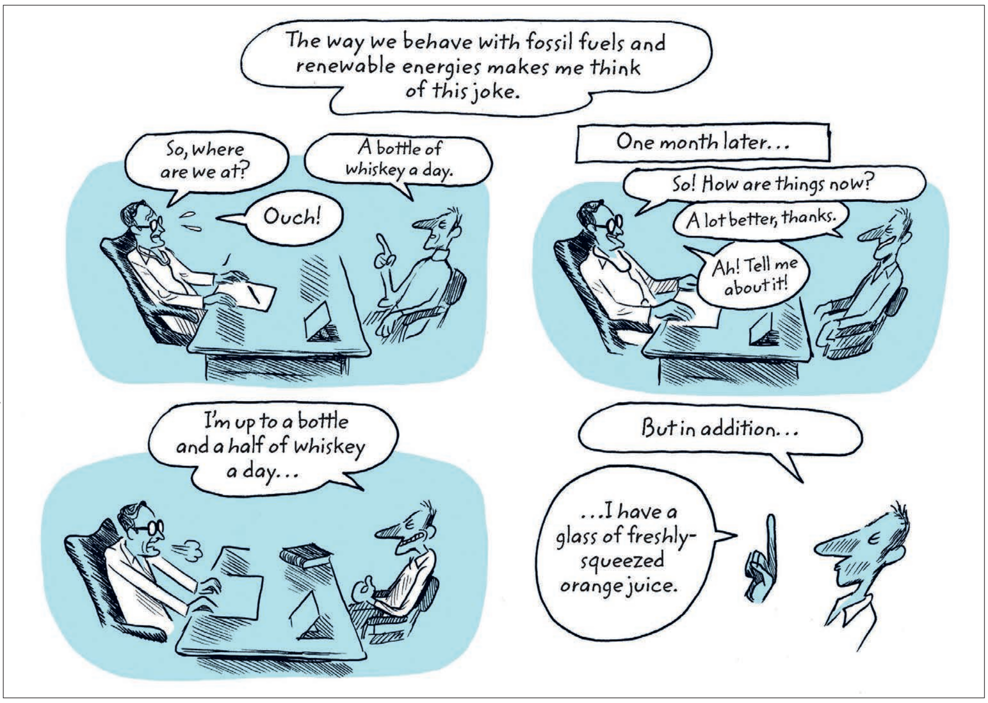
Blunt message Anti-nuclear thinking is mocked in World Without End by Jean-Marc Jancovici and Christophe Blain.

Comics are regarded as an artform in France, where they account for a quarter of all book sales. Nevertheless, the graphic novel *World Without End: an Illustrated Guide to the Climate Crisis* was a surprise French bestseller when it first came out in 2022. Taking the form of a Socratic dialogue between French climate expert Jean-Marc Jancovici and acclaimed comic artist Christophe Blain, it's serious, scientific stuff.

Now translated into English by Edward Gauvin, the book follows the conventions of French-language comic strips or *bandes dessinées*. Jancovici is drawn with a small nose – denoting seriousness – while Blain's larger nose signals humour. The first half explores energy and consumption, with the rest addressing the climate crisis and possible solutions.

Overall, this is a Trojan horse of a book: what appears to be a playful comic is packed with dense, academic content. Though marketed as a graphic novel, it reads more like illustrated notes from a series of sharp, provocative university lectures. It presents a frightening vision of the future and the humour doesn't always land.

The book spans a vast array of disciplines – not just science and economics but geography and psy-



Humorous point A joke from *World Without End* by Jean-Marc Jancovici and Christophe Blain.

chology too. In fact, there's so much to unpack that, had I Blain's skills, I might have reviewed it in the form of a comic strip myself. The old adage that "a picture is worth a thousand words" has never rung more true.

Absurd yet powerful visual metaphors feature throughout. We see a parachutist with a flaming main chute that represents our dependence on fossil fuels. The falling man jettisons his reserve chute – nuclear power – and tries to knit an alternative using clean energy, mid-fall. The message is blunt: nuclear may not be ideal, but it works.

The book is bold, arresting, provocative and at times polemical. Charts and infographics are presented to simplify complex issues, even if the details invite scrutiny. Explanations are generally clear and concise, though the author's claim that accidents like Chernobyl and Fukushima couldn't happen in France smacks of hubris.

Jancovici makes plenty of attention-grabbing statements. Some are sound, such as the notion that fossil fuels spared whales from extinction as we didn't need this animal's oil any more. Others are dubious – would a 4 °C temperature rise really leave a third of humanity unable to survive outdoors?

But Jancovici is right to say that the use of fossil fuels makes logical sense. Oil can be easily transported and one barrel delivers the equivalent of five years of human labour. A character called Armor Man (a parody of Iron Man) reminds us that fossil fuels are like having 200 mechanical slaves per person, equivalent to an additional 1.5 trillion people on the planet.

Fossil fuels brought prosperity – but now threaten our survival. For Jancovici, the answer is nuclear power, which is perhaps not surprising as it produces 72% of electricity in the author's homeland. But he cherry picks data, accepting – for example – the United Nations figure that only about 50 people died from the Chernobyl nuclear accident.

While acknowledging that many people had to move following the disaster, the author downplays the fate of those responsible for "cleaning up" the site, the long-term health effects on the wider population and the staggering economic impact – estimated at €200–500bn. He also sidesteps nuclear-waste disposal and the cost and complexity of building new plants.

While conceding that nuclear is "not the whole answer", Jancovici dismisses hydrogen and views renewables like wind and solar as too intermittent – they require batteries to ensure electricity is supplied on demand – and diffuse. Imagine blanketing the Earth in wind turbines.

Still, his views on renewables seem increasingly out of step. They now supply nearly 30% of global electricity – 13% from wind and solar, ahead of nuclear at 9%. Renewables also attract 70% of all new investment in electricity generation and (unlike nuclear) continue to fall in price. It's therefore disingenuous of the author to say that relying on renewables would be like returning to pre-industrial life; today's wind turbines are far more efficient than anything back then.

Beyond his case for nuclear, Jancovici offers few firm solutions. Weirdly, he suggests "educating women" and providing pensions in developing nations – to reduce reliance on large families – to stabilize population growth. He also cites French journalist Sébastien Bohler, who thinks our brains are poorly equipped to deal with long-term threats.

But he says nothing about the need for more investment in nuclear fusion or for "clean" nuclear fission via, say, liquid fluoride thorium reactors (LFTRs), which generate minimal waste, won't melt down and cannot be weaponized.

Perhaps our survival depends on delaying gratification, resisting the lure of immediate comfort, and adopting a less extravagant but sustainable world. We know what changes are needed – yet we do nothing. The climate crisis is unfolding before our eyes, but we're paralysed by a global-scale bystander effect, each of us hoping someone else will act first. Jancovici's call for "energy sobriety" (consuming less) seems idealistic and futile.

Still, *World Without End* is a remarkable and deeply thought-provoking book that deserves to be widely read. I fear that it will struggle to replicate its success beyond France, though Raymond Briggs' *When the Wind Blows* – a Cold War graphic novel about nuclear annihilation – was once a British bestseller. If enough people engaged with the book, it would surely spark discussion and, one day, even lead to meaningful action.

Mike Follows teaches physics at King Edward's School, Birmingham, UK, and is the foundation leader in education for physics for the 14 schools in the trust, e-mail mikefollows@physics.org

Careers

Physics beyond the classroom

Many schools and colleges encourage their students to do work experience to see what the working world is like. **Naeya Mistry**, who is doing an A-level in physics, recently got a placement at the Institute of Physics to find out more about its activities and learn how physics can be applied beyond school

IOP

Insights and innovation Student Naeya Mistry (centre left) met quantum-startup founder David Curry (centre right) as part of her work experience at the Institute of Physics, organized by Katherine Platt (left) and Anne Crean (right).

Year 12 students (aged 16 or 17) often do work experience while studying for their A-levels. It can provide valuable insights into what the working world is like and showcase what potential career routes are available. And that's exactly why I requested to do my week of work experience at the Institute of Physics (IOP).

I'm studying maths, chemistry and physics, with a particular interest in the latter. I'm hoping to study physics or chemical physics at university so was keen to find out how the subject can be applied to business, and get a better understanding of what I want to do in the future. The IOP was therefore a perfect placement for me and here are a few highlights of what I did.

Monday

My week at the IOP's headquarters in London began with a brief introduction to the Institute with the head of science and innovation, Anne Crean, and Katherine Platt, manager for the International Year of Quantum Science and Technology (IYQ). Platt, who planned and supervised my week of activities, then gave me a tour of the building and explained more about the IOP's work, including how it aims to nurture upcoming physics innovation and projects, and give businesses and physicists resources and support.

My first task was working with Jenny Lovell, project manager in the science and innovation team. While helping her organize the latest round of the IOP's medals and awards, she explained why the IOP honours the physics community in this way and described the different degrees of achievement that it recognizes.

Next I got to meet the IOP's chief executive officer Tom Grinyer, and unexpectedly the president-elect Michele Dougherty, who is a space physicist at Imperial College London. They are both inspiring people, who gave me some great advice about how I might go about my future in physics. They talked about the exciting opportunities available as a woman in physics, and how no matter where I start, I can go into many different sectors as the subject is so applicable.

To round off the day, I sat in a meeting about how the science and innovation team can increase engagement, before starting on a presentation I was due to make on Thursday about quantum physics and young people.

Tuesday

My second day began with a series of meetings. First up was the science and innovation team's weekly stand-up meeting. I then attended a larger staff meeting with most of IOP's employees, which proved informative and gave me a chance to see how different teams interact with each other. Next was the science and innovation managers' meeting, where I took the minutes as they spoke.

I then met data science lead, Robert Cocking, who went through his work on data insights. He talked about IOP membership statistics in the UK and Ireland, as well as age and gender splits, and how he can do similar breakdowns for the different areas of special interest (such as quantum physics or astronomy). I found the statistics around the representation of girls in the physics community, specifically at A-level, particularly fascinating as it applies to me. Notably, although a lower percentage of girls take A-level physics compared to boys, a higher proportion of those girls go on to study it at university.

The day ended with some time to work on my presentation and research different universities and pathways I could take once I have finished my A-levels.

Wednesday

It was a steady start to Wednesday as I continued with my presentation and research with Platt's help. Later in the morning, I attended a meeting with the public engagement team about *Mimi's Tiny Adventure*, a children's book written by Toby Shannon-Smith, public programmes manager at IOP, and illustrated by Pauline Gregory.

The book, which is the third in the *Mimi's Adventures* series, is part of the IOP's Limit Less campaign to engage young people in physics, and will be published later this year to coincide with the IYQ. It was interesting to see how the IOP advertises physics to a younger audience and makes it more engaging for them.

Platt and I then had a video call with the *Physics World* team at IOP Publishing in Bristol, joining for their daily news meeting before having an in-depth chat with the editor-in-chief, Matin Durrani, and feature editors, Tushna Commissariat and Sarah Tesh. After giving me a brief introduction to the magazine, website and team structure, we discussed physics careers. It was good hear the editors' insights as they cover a broad range of jobs in *Physics World* and all have a background in physics. It was particularly good to hear from Durrani as he studied chemical physics, which combines my three subjects and my passions.

Thursday

On Thursday I met David Curry, founder of Quantum Base Alpha – a start-up using quantum-inspired algorithms to solve issues facing humanity. We talked about physics in a business context, what he and his company do, and what he hopes for the future of quantum.

I then gave my presentation on "Why should young people care about quantum?". I detailed the importance of quantum physics, the major things happening in the field and what it can become, as well as the careers quantum will offer in the future. I also discussed diversity and representation in the physics community, and how that is translated to what I see in everyday life, such as in my school and class. As a woman of colour going into science, technology, engineering and mathematics (STEM), I think it is important for me to have conversations around diversity of both gender and race, and the combination of the two. After my presentation, Curry gave me some feedback, and we discussed what I am aiming to do at university and beyond.

Friday

For my final day, I visited the University of Sussex, where I toured the campus with Curry's daughter Kitty, an undergraduate student studying social sciences. I then met up again with Curry, who introduced me to Thomas Clarke, a PhD student in Sussex's ion quantum technologies group. We went to the physics and maths building, where he explained the simple process of quantum computing to me, and the struggles they have implementing that on a larger scale.

Clarke then gave us a tour of the lab that he shares with other PhD students, and showed us his experiments, which consisted of multiple lasers that made up their trapped ion quantum computing platform. As we read off his oscilloscope attached to the laser system, it was interesting to hear that a lot of his work involved trial and error, and the visit helped me realize that I am probably more interested in the experimental side of physics rather than pure theory.

IOP

Top people Naeya Mistry (centre) got some valuable advice from the chief executive officer of the Institute of Physics, Tom Grinyer (right), and the president-elect, Michele Dougherty (left).

My work experience week at the IOP has been vital in helping me to understand how physics can be applied in both business and academia. Thanks to the IOP's involvement in the IYQ, I now have a deeper understanding of quantum science and how it might one day be applied to almost every aspect of physics – including chemical physics – as the sector grows in interest and funding. It's been an eye-opening week, and I've returned to school excited and better informed about my potential next career steps.

Naeya Mistry is a year 12 student based in Milton Keynes, UK

Ask me anything: Tom Woodroof

Tom Woodroof did a PhD in applied nuclear physics at the University of Liverpool, UK, before leaving academia to find ways to build a more equitable and sustainable economy. He is co-founder of the company Mutual Credit Services.

Tom Woodroof

What skills do you use every day in your job?

I co-founded Mutual Credit Services in 2020 to help small businesses thrive independently of the banking sector. As a financial technology start-up, we're essentially trying to create a "commons" economy, where power lies in the hands of people, not big institutions, thereby making us more resilient to the climate crisis.

Those goals are probably as insanely ambitious as they sound, which is why my day-to-day work is a mix of complexity economics, monetary theory and economic anthropology. I spend a lot of time thinking hard about how these ideas fit together, before building new tech platforms, apps and services, which requires analytical and design thinking.

There are still many open questions about business, finance and economics that I'd like to do research on, and ultimately develop into new services. I'm constantly learning through trial projects and building a pipeline of ideas for future exploration.

Developing the business involves a lot of decision-making, project management and team building. In fact, I'm spending more and more of my time on commercialization – working out how to bring new services to market, nurturing partnerships and talking to potential early adopters. It's vital that I can explain novel financial ideas to small businesses in a way they can understand and have confidence in. So I'm always looking for simpler and more compelling ways to describe what we do.

What do you like best and least about your job?

What I like best is the variety and creativity. I'm a generalist by nature, and love using insights from a variety of disciplines. The practical application of these ideas to create a better economy feels profoundly meaningful, and something that I'd be unlikely to get in any other job. I also love the autonomy of running a business. With a small but hugely talented and enthusiastic team, we've so far managed to avoid the company becoming rigid and institutionalized. It's great to work with people on our team and beyond who are excited by what we're doing, and want to be involved.

The hardest thing is facing the omnicrisis of climate breakdown and likely societal collapse that makes this work necessary in the first place. As with all start-ups, the risk of failure is huge, no matter how good the ideas are, and it's frustrating to spend so much time on tasks that just keep things afloat, rather than move the mission forward. I work long hours and the job can be stressful.

> Curiosity, self-education and carefully-chosen guidance can get you surprisingly far

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

I spent a lot of time during my PhD at Liverpool worrying that I'd get trapped in one narrow field, or drift into one of the many default career options. I wish I'd known how many opportunities there are to do original, meaningful and self-directed work – especially if you're open to unconventional paths, such as the one I've followed, and can find the right people to do it with.

It's also easy to assume that certain skills or fields are out of reach, whereas I've found again and again that a mix of curiosity, self-education and carefully-chosen guidance can get you surprisingly far. Many things that once seemed intimidating now feel totally manageable. That said, I've also learned that everything takes at least three times longer than expected – especially when you're building something new. Progress often looks like small compounding steps, rather than a handful of breakthroughs.

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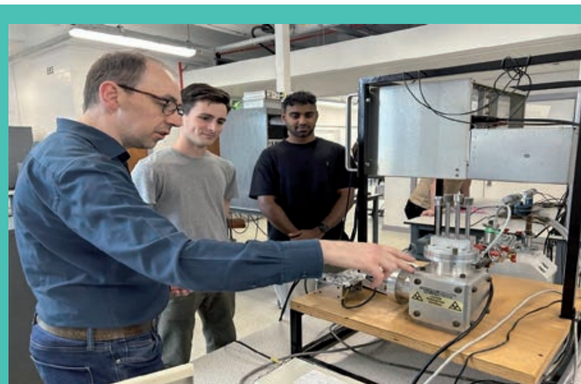

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Worming physics into your head

Physics teacher **Kate Urell** uses catchy tunes to help her students remember their lessons


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When I'm sitting in my armchair, eating chocolate and finding it hard to motivate myself to exercise, a little voice in my head starts singing "You've got to move it, move it" to the tune of will.i.am's "I like to move it". The positive reinforcement and joy of this song as it plays on a loop in my mind propels me out of my seat and onto the tennis court.

Songs like this are earworms – catchy pieces of music that play on repeat in your head long after you've heard them. Some tunes are more likely to become earworms than others, and there are a few reasons for this.

To truly hook you in, the music must be repetitive so that the brain can easily finish it. Generally, it is also simple, and has a rising and falling pitch shape. While you need to hear a song several times for it to stick, once it's wormed its way into your head, some lyrics become impossible to escape – "I just can't get you out of my head", as Kylie would say.

In his book *Musicophilia*, neurologist Oliver Sacks describes these internal music loops as "the brainworms that arrive unbidden and leave only on their own time". They can fade away, but they tend to lie in wait, dormant until an association sets them off again – like when I need to exercise. But for me as a physics teacher for 16–18 year olds, this fact is more than just of passing interest: I use it in the classroom.

There are some common mistakes students make in physics, so I play songs in class that are linked (sometimes tenuously) to the syllabus to remind them to check their work. Before I continue, I should add that I'm not advocating rote learning without understanding – the explanation of the concept must always come first. But I have found the right earworm can be a great memory aid.

I've been a physics teacher for a while, and I'll admit to a slight bias towards the music of the 1980s and 1990s. I play David Bowie's "Changes" (which the students associate with the movie *Shrek*) when I ask the class to draw a graph, to remind them to check if they need to process – or change – the data before plotting. The catchy "Ch…ch…ch…changes" is now the irritating tune they hear when I look over their shoulders to check if they have found, for example, the sine values for Snell's law, or the square root of tension if looking at the frequency of a stretched wire.

When describing how to verify the law of conservation of momentum, students frequently leave out the mechanism that makes the two trollies stick together after the collision. Naturally, this is an opportunity for me to play Roxy Music's "Let's stick together".

Meanwhile, "Ice ice baby" by Vanilla Ice is obviously the perfect earworm for calculating the specific latent heat of fusion of ice, which is when students often drop parts of the equations because they forget that the ice both melts *and* changes temperature.

In the experiment where you charge a gold leaf electroscope by induction, pupils often fail to do the four steps in the correct order. I therefore play Shirley Bassey's "Goldfinger" to remind pupils to earth the disc with their finger. Meanwhile, Spandau Ballet's bold and dramatic "Gold" is reserved for Rutherford's gold leaf experiment.

"Pump up the volume" by M|A|R|R|S or Ireland's 1990 football song "Put 'em under pressure" are obvious candidates for investigating Boyle's law. I use "Jump around" by House of Pain when causing a current-carrying conductor in a magnetic field to experience a force.

Some people may think that linking musical lyrics and physics in this way is a waste of time. However, it also introduces some light-hearted humour into the classroom – and I find teenagers learn better with laughter. The students enjoy mocking my taste in music and coming up with suitable (more modern) songs, and we laugh together about the tenuous links I've made between lyrics and physics.

More importantly, this is how my memory works. I link phrases or lyrics to the important things I need to remember. Auditory information functions as a strong mnemonic. I am not saying that this works for everyone, but I have heard my students sing the lyrics to each other while studying in pairs or groups. I smile to myself as I circulate the room when I hear them saying phrases like, "No you forgot mass × specific latent heat – remember it's 'Ice, ice baby!' ".

On their last day of school – after two years of playing these tunes in class – I hold a quiz where I play a song and the students have to link it to the physics. It turns into a bit of a sing-along, with chocolate for prizes, and there are usually a few surprises in there too. Check out the *Physics World* blog to see if you can make the connections.

Kate Urell teaches physics and maths to 16–18 year olds at Fingal Community College, Swords, Dublin, Ireland. She also works as a student teacher mentor at Dublin City University (DCU) and as a physics teaching methodologies lecturer at Hibernia College, Dublin

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- Ce, CeB6, CeF3, CeO2
- CsF, CsI
- Cr, CrO3, CrB2, Cr3C2, CrF3, Cr2N, Cr2O3, CrSi2, Cr2S3
- Co, CoFe2O4, CoO, Co3O4, CoSi2
- Cu, CuS, Cu2O, CuO, Cu3P, CuSe, Cu2S
- Dy, DyF3, Dy2O3
- Er, ErF3, Er2O3
- Eu, Eu2O3
- Gd, Gd2F3, Gd3Ga5O12
- Ga, GaSb, GaAs, GaN, Ga2O3
- Ge, Ge3N4, GeO2, GeSe2, GeS, GeTe
- Au
- Hf, HfC, HfO2
- Ho, Ho2O3
- In, In2Te3, InSb, InN, In2O3, In2O3/SnO2
- Ir, IrO2
- Fe, FeB, Fe3C, NiFe2O4, Fe2O3, Fe3O4, FeSi2, FeS2
- La, LaAlO3, LaB6, La2O3, (La0.7Sr0.3)MnO3, LaTiO3
- Pb, PbO, PbTe
- Li, Li2CO3, LiCoO2, LiF, LiMn2O4, LiNbO3, Li2O, Li3PO4
- Lu, Lu2O3
- Mg, MgAl2O4, MgB2, MgF2, MgO, Mg2Si, MgS
- Mn, MnO, MnO2, Mn2O3, MnTe
- HgTe
- Mo, MoB, MO2C, MoS2, MoO3, MoO2, MoSe2, MoSi2, MoTe2
- Nd, Nd2O3
- Ni, Ni2B, NiSi2, NiO, NiTe
- Nb, NbC, Nb2O5, NbO2, NbSe2
- Os
- Pd, PdO
- P, P2O5
- Pt
- KNbO3
- Pr, Pr2O3
- Re
- Rh, Rh2O3
- Ru, RuO2
- Sm, SmF3, Sm2O3
- Sc, Sc2O3
- Se, SeO2
- Si, SiC, SiO2, SiO, Si3N4, SiS2
- Ag, AgCl, Ag2O
- Na, Na5Al3F14, Na2CO3, NaCl, NaF, Na2O2
- Sr, SrCO3, SrF2, SrMoO4, SrO, SrRuO3, SrS, SrTiO3, SrZrO3
- S
- Ta, TaC, TaN, Ta2O5, TaSe2, TaSi2
- Te, TeO2
- Tb, TbF3, TbOF, Tb4O7
- Sn, SnF2, SnO2, SnS2, SnTe
- Ti, Ti3Al, TiB2, TiC, TiO2, TiF3, TiO, TiN, Ti2O3, TiSe2, TiSi2
- W, WC, WO3, WSe2, WSi2, WS2, WTe2
- V, VC, VO2, VN, V2O3, V2O5, VSe2, V2S3
- Yb, YbF3, Yb2O3
- Y, Y3Al5O12, Y3Fe5O12, YF3, Y2O3
- Zn, ZnF2, Zn3N2, ZnO, Zn3P2, ZnSe, ZnS, ZnTe
- Zr, ZrB2, ZrC, ZrCl4, ZrF4, ZrN, ZrO2, ZrSi2, ZrO2/Y2O3

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