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February 2026

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physicsworld
Volume 39 No 2

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

Opinion and reviews

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Physics World is published monthly as 12 issues per annual volume by IOP Publishing Ltd, No.2 The Distillery, Glassfields, Avon Street, Bristol, BS2 0GR, UK

Printed in the UK by Warners (Midlands) plc, The Maltings, West Street, Bourne, Lincolnshire PE10 9PH

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Cover image
Could icy moons harbour life? 20
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News & Analysis

CERN accepts $1bn in private cash

British physicist Mark Thomson is now in charge of the CERN particle-physics lab, which recently received $1bn in private donations for its next collider project, as **Michael Banks** reports

The CERN particle-physics lab near Geneva, which last month saw Mark Thomson installed as its new director-general, has received $1bn from private donors towards the construction of the Future Circular Collider (FCC). The cash marks the first time in the lab's 72-year history that individuals and philanthropic foundations have agreed to support a major CERN project. If built, the FCC would be the successor to the Large Hadron Collider (LHC), where the Higgs boson was discovered.

CERN originally released a four-volume conceptual design report for the FCC in early 2019, with more detail included in a three-volume feasibility study that came out last year. It calls for a giant tunnel some 90.7 km in circumference – roughly three times as long as the LHC – that would be built about 200 m underground on average.

The FCC has been recommended as the preferred option for the next flagship collider at CERN in the ongoing process to update the European Strategy for Particle Physics, which will be passed over to the CERN Council in May 2026. If the plans are given the green light by CERN Council in 2028, construction on the FCC electron–positron machine, dubbed FCC-ee, would begin in 2030. It would start operations in 2047, a few years after the High Luminosity LHC (HL-LHC) closes down, and run for about 15 years until the early 2060s.

The FCC-ee would focus on creating a million Higgs particles in total to allow physicists to study its properties with an accuracy an order of magnitude better than is possible with the LHC. The FCC feasibility study then calls for a hadron machine, dubbed FCC-hh, to replace the FCC-ee in the existing 91 km tunnel. It would be a "discovery machine", smashing together protons at high energy – about 85 TeV – with the aim of creating new particles. If built, the FCC-hh will begin operation in 2073 and run to the end of the century.

CERN

Bigger and better The Large Hadron Collider at CERN will shut down later this year to make way for a major upgrade – the High-Luminosity LHC.

The funding model for the FCC-ee, which is expected to have a price tag of about $18bn, is still a work in progress. But it is estimated that at least two-thirds of the construction costs will come from CERN's 24 member states, with the rest needing to be found elsewhere. One option to plug that gap is private donations and in late December CERN received a significant boost from several organizations including the Breakthrough Prize Foundation, the Eric and Wendy Schmidt Fund for Strategic Innovation, and the entrepreneurs John Elkann and Xavier Niel. Together, they pledged a total of $1bn towards the FCC-ee.

Costas Fountas, president of the CERN Council, says CERN is "extremely grateful" for the interest. "This once again demonstrates CERN's relevance and positive impact on society, and the strong interest in CERN's future that exists well beyond our own particle physics community," he notes.

Eric Schmidt, who co-founded Google, claims that he and Wendy Schmidt were "inspired by the ambition of this project". The FCC, he believes, is an instrument that "could push the boundaries of human knowledge and deepen our understanding of the fundamental laws of the universe" and could lead to technologies that benefit society "in profound ways" from medicine to computing to sustainable energy.

The cash promised has been welcomed by outgoing CERN director-general Fabiola Gianotti. "It's the first time in history that private donors wish to partner with CERN to build an extraordinary research instrument that will allow humanity to take major steps forward in our understanding of fundamental physics and the universe," she said. "I am profoundly grateful to them for their generosity, vision, and unwavering commitment to knowledge and exploration."

Further boost

The cash comes a few months after the Circular Electron–Positron Collider (CEPC) – a rival collider to the FCC-ee that would involve building a 100 km underground tunnel to study the Higgs – was not considered for inclusion in China's next five-year plan, which runs from 2026 to 2030. There has been much discussion in China about whether the CEPC is the right project for the country, with the collider facing criticism from particle physicist and Nobel laureate Chen-

Ning Yang, before he died last year.

Wang Yifang of the Institute of High Energy Physics in Beijing says the organization will submit the CEPC for consideration again in 2030 unless the FCC is officially approved before then. But for particle theorist John Ellis from Kings College London, China's decision to effectively put the CEPC on the back burner "certainly simplifies the FCC discussion". "However, an opportunity for growing the world particle-physics community has been lost, or at least deferred [by the decision]," Ellis told *Physics World*.

Ellis adds that he would welcome China's participation in the FCC. "Their accelerator and detector [technical design reviews] show that they could bring a lot to the table, if the political obstacles can be overcome," he says.

If the FCC-ee goes ahead, China could perhaps make significant "in-kind" contributions like those that occur with the ITER experimental fusion reactor, which is currently being built in France. In this kind of agreement, instead of cash payments, the countries provide components, equipment and other materials.

Those considerations and more will now fall to Thomson, who took over from Gianotti as CERN director-general on 1 January for a five-year term. As well as working on funding requirements for the FCC-ee, top of his in-tray will be shutting down the LHC in June to make way for further work on the HL-LHC, which involves installing powerful new superconducting magnets and improving the detection.

About 90% of the 27 km LHC accelerator will be affected by the upgrade with a major part being to replace the magnets in the final focus systems of the two large experiments, ATLAS and CMS. These magnets will take the incoming beams and then focus them down to less than 10 μm in cross section. The upgrade includes the installation of new state-of-the-art niobium-tin (Nb_3Sn) superconducting focusing magnets.

The HL-LHC will probably not turn on until 2030, which is when Thomson's term will nearly be over but that doesn't deter him from leading the world's foremost particle-physics lab. "It's an incredibly exciting project," Thomson told the *Guardian*. "It's more interesting than just sitting here with the machine hammering away."

Michael Banks is news editor of *Physics World*

People

Norbert Holtkamp starts life as boss of Fermilab

Particle physicist Norbert Holtkamp has taken over as the new director of Fermi National Accelerator Laboratory. He took up the position on 12 January, replacing Young-Kee Kim from the University of Chicago, who held the job on an interim basis following the resignation of Lia Merminga last year.

With a PhD in physics from the Technical University in Darmstadt, Germany, Holtkamp has managed large scientific projects throughout his career. Holtkamp is the former deputy director of the SLAC National Accelerator Laboratory at Stanford University where he managed the construction of the Linac Coherent Light Source upgrade, the world's most powerful X-ray laser, along with more than $2bn of on-site construction projects. He has also worked at the ITER fusion experiment, which is currently under construction in Cadarache, France.

Holtkamp is not new to Fermilab, having been there between 1998 and 2001. As lab boss, one of his main aims will be to oversee the completion of the $5bn Long-Baseline Neutrino Facility-Deep Underground Neutrino Experiment (LBNF-DUNE) at Fermilab, which is expected to come online towards the end of the decade.

JJ Starr, Fermilab

Lab figurehead As new director of Fermilab, one of Norbert Holtkamp's main aims will be to oversee the completion of the $1.5bn Long-Baseline Neutrino Facility-Deep Underground Neutrino Experiment.

LBNF-DUNE will study the properties of neutrinos in unprecedented detail, as well as the differences in behaviour between neutrinos and antineutrinos. The DUNE detector, which lies about 1300 km from Fermilab, will measure the neutrinos that are generated by Fermilab's accelerator complex, which is just outside Chicago.

In a statement, Holtkamp said he is "deeply honoured" to lead the lab. "Fermilab has done so much to advance our collective understanding of the fundamentals of our universe," he says. "I am committed to ensuring the laboratory remains the neutrino capital of the world, and the safe and successful completion of LBNF-DUNE is key to that goal. I'm excited to rejoin Fermilab at this pivotal moment to guide this project and our other important modernization efforts to prepare the lab for a bright future."

Fermilab has experienced a difficult few years, with questions raised about its internal management and external oversight. In August 2024 a group of anonymous self-styled whistleblowers published a 113-page "white paper" on the arXiv preprint server, asserting that the lab was "doomed without a management overhaul" (arXiv:2407.13924). Then in October that year, a new organization – Fermi Forward Discovery Group – was announced to manage the lab for the US Department of Energy.

That move came under scrutiny given it is dominated by the University of Chicago and Universities Research Association (URA), a consortium of research universities, which had already been part of the management since 2007. Then a month later, almost 2.5% of Fermilab's employees were laid off.

"We're excited to welcome Norbert, who brings of a wealth of scientific and managerial experience to Fermilab," noted University of Chicago president Paul Alivisatos, who is also chair of the board of directors of Fermi Forward Discovery Group.

Michael Banks

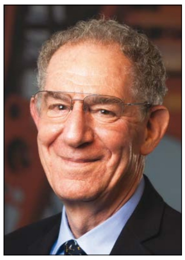
People

Daniel Jaffe to lead Giant Magellan Telescope project

Astronomer Daniel Jaffe has been appointed the next president of the Giant Magellan Telescope Corporation – the international consortium building the $2.5bn Giant Magellan Telescope (GMT). He succeeds Robert Shelton, who announced his retirement last year after eight years in the role.

A former head of astronomy at the University of Texas at Austin from 2011 to 2015, Jaffe became vice-president for research at the university from 2016 to 2025 and also served as interim provost from 2020 to 2021. Jaffe has sat on the board of directors of the Association of Universities for Research in Astronomy and the Gemini Observatory, and played a role in establishing the University of Texas at Austin's partnership in the GMT.

Under construction in Chile and expected to be complete in the 2030s, the GMT consists of seven mirrors to create a 25.4 m telescope. From the ground it will produce images 4–16 times sharper than the James Webb Space Telescope and will investigate the origins of the chemical elements, and search for signs of life on distant planets.



Giant Magellan Telescope – GMTO Corporation

Taking the helm Jaffe joins the Giant Magellan Telescope Corporation as it aims to secure the funding necessary to complete the $2.5bn telescope.

"I am honoured to lead the GMT at this exciting stage," says Jaffe. "[It] represents a profound leap in our ability to explore the universe and employ a host of new technologies to make fundamental discoveries."

"[Jaffe] brings decades of leadership in research, astronomy instrumentation, public–private partnerships and academia," notes Taft Armandroff, chair of the board of directors of the GMTO Corporation. "His deep understanding of the GMT, combined with his experience leading large research enterprises and cultivating a collaborative environment, make him exceptionally well suited to lead the observatory."

Jaffe joins the GMT at a pivotal time, as it aims to secure the funding necessary to complete the telescope, with just over $1bn from private funds having been pledged so far. The collaboration recently added Northwestern University and the Massachusetts Institute of Technology to its international consortium taking the number of members to 16.

In June 2025 the GMT, which is already 40% completed, received approval from the National Science Foundation to advance into its "major facilities final design phase", one of the final steps before becoming eligible for federal construction funding. But it faces competition from another next-generation telescope – the Thirty Meter Telescope (TMT) – that will use a 30 m-diameter primary mirror.

The TMT team chose Hawaii's Mauna Kea peak as its location. However, construction has been delayed following protests by Indigenous Hawaiians.

Michael Banks

Particle physics

Russia to revive abandoned Soviet-era particle accelerator

Russia wants to restart a Soviet-era particle accelerator that has been abandoned since the 1990s. The Kurchatov Institute for High Energy Physics has allocated 176 million rubles ($25m) to assess the current condition of the unfinished 600 GeV Proton Accelerator and Storage Complex (UNK) in Protvino near Moscow. The move is part of plans to strengthen Russia's technological sovereignty and its activity in high-energy physics.

Although work on the UNK was officially halted in the 1990s, construction only ceased in 2013. At that time, a 21 km tunnel had been built at a depth of 60 m along with underground experimental hall lighting and ventilation systems.

According to physicist Mikhail Kovalchuk, president of the Kurchatov Institute National Research Center, Western sanctions provided an additional impetus to restore the project, as scientists who had previously worked in CERN projects could no longer do so. "By participating in [CERN] projects, we not only preserved our scientific potential and survived a difficult period, but also enriched ourselves intellectually and technologically," added Kovalchuk. "Today we are self-sufficient."

INR RAS

Ambitious plans The revived Proton Accelerator and Storage Complex could be used to generate an intense beam of neutrinos to be sent to the Baikal Deep Underwater Neutrino Telescope.

Anatoli Romaniouk, a Russian particle physicist who has worked at CERN since 1990, told *Physics World* that a revival of the UNK will at least maintain fundamental physics research in Russia. "If this project is realized, then there is hope that it will be possible to at least somewhat slow down the scientific lag of Russian physics with global science," says Romaniouk.

While official plans for the accelerator have not been disclosed, it is thought that the proton beam energy could be upgraded to reach 3 TeV. Romaniouk says it is also unclear what kind of science will be done with the accelerator, which will depend on what ideas come forward.

Some Russian scientists say that it could be used to produce neutrinos. This would involve putting a neutrino detector nearby to characterize the beam before it is sent some 4000 km towards Lake Baikal where a neutrino detector – the Baikal Deep Underwater Neutrino Telescope – is already installed 1 km underground. "I think it's possible to find an area of high-energy physics where the research with the help of this collider could be beneficial," adds Romaniouk.

Eugene Gerden

India turns to small modular reactors

As in the UK, India's nuclear industry is looking to small modular nuclear reactors to help meet climate targets, but as **T V Padma** reports, there are concerns over their commercial viability

India has been involved in nuclear energy and power for decades, but now the country is turning to small modular nuclear reactors (SMRs) as part of a new, long-term push towards nuclear and renewable energy. In December 2025 the country's parliament passed a bill that for the first time allows private companies to participate in India's nuclear programme, which could see them involved in generating power, operating plants and making equipment.

Some commentators are unconvinced that the move will be enough to help meet India's climate pledge to achieve 500 GW of non-fossil-fuel based energy generation by 2030. Interestingly, however, India has now joined other nations, such as Russia, the UK and China, in taking an interest in SMRs. These could help stem the overall decline in nuclear power, which now accounts for just 9% of electricity generated around the world – down from 17.5% in 1996.

Last year India's finance minister Nirmala Sitharaman announced a nuclear-energy mission funded with 200 billion Indian rupees ($2.2bn) to develop at least five indigenously designed and operational SMRs by 2033. Unlike huge, conventional nuclear plants, such as pressurized heavy-water reactors (PHWRs), most or all components of an SMR are manufactured in factories before being assembled at the reactor site. SMRs typically generate less than 300 MW of electrical power but – being modular – additional capacity can be brought online quickly and easily given their lower capital costs, shorter construction times, ability to work with lower-capacity grids and lower carbon emissions.

Despite their promise, there are only two fully operating SMRs in the world – both in Russia – with two further high-temperature gas-cooled SMRs currently being built in China. In June 2025 Rolls-Royce SMR was selected as the preferred bidder by Great British Nuclear to build the UK's first fleet of SMRs, with plans to provide 470 MW of low-carbon electricity.

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Better by design? Unlike huge, conventional nuclear plants, most or all components of a small modular nuclear reactor are manufactured in factories before being assembled at the reactor site.

Cost benefit analysis

An official at India's Department of Atomic Energy told *Physics World* that part of that mix of five new SMRs in India could be a 200 MW Bharat small modular reactor, which are based on pressurized water reactor technology and use slightly enriched uranium as a fuel. Other options include 55 MW small modular reactors, and the Indian government also plans to partner with the private sector to deploy 220 MW Bharat small reactors.

Despite such moves, some are unconvinced that small nuclear reactors could help India scale its nuclear ambitions. "SMRs are still to demonstrate that they can supply electricity at scale," says Karthik Ganesan, a fellow and director of partnerships at the Council on Energy, Environment and Water, a non-profit policy research think-tank based in New Delhi. "SMRs are a great option for captive consumption, where large investment that will take time to start generating is at a premium."

Ganesan, however, says it is too early to comment on the commercial viability of SMRs because cost reductions from SMRs depend on how much of the technology is produced in a factory and in what quantities. "We are yet to get to that point and any test reactors deployed would certainly not be the ones to benchmark their long-term competitiveness," he says. "[But] even at a higher tariff, SMRs will still have a use case for industrial consumers who want certainty in long-term tariffs and reliable continuous supply in a world where carbon-dioxide emissions will be much smaller than what we see from the power sector today."

M V Ramana from the University of British Columbia, Vancouver, who works in international security and energy supply, is concerned about the cost efficiency of SMRs compared with their traditional counterparts. "Larger reactors are cheaper on a per-megawatt basis because their material and work requirements do not scale linearly with power capacity," says Ramana. This, according to Ramana, means that the electricity SMRs produce will be more expensive than nuclear energy from large reactors, which are already far more expensive than renewables such as solar and wind energy.

Clean or unclean?

Even if SMRs take over from PHWRs, there is still the question of what do with their nuclear waste. In Ramana's view,, all activities linked to the nuclear fuel chain have significant health and environmental impacts. Ramana adds that those pollutants remain hazardous for hundreds of thousands of years. "There is no demonstrated solution to managing these radioactive wastes – nor can there be, given the challenge of trying to ensure that these materials do not come into contact with living beings," says Ramana.

Ganesan, however, thinks that nuclear energy is still clean as it produces electricity with a much lower environmental footprint, especially when it comes to so-called "criteria pollutants": ozone; particulate matter; carbon monoxide; lead; sulphur dioxide; and nitrogen dioxide. While nuclear waste still needs to be managed, Ganesan says the associated costs are already included in the price of setting up a reactor. "In due course, with technological development, the burn-up will be significantly higher and waste generated a lot lesser."

T V Padma is a freelance science writer based in India

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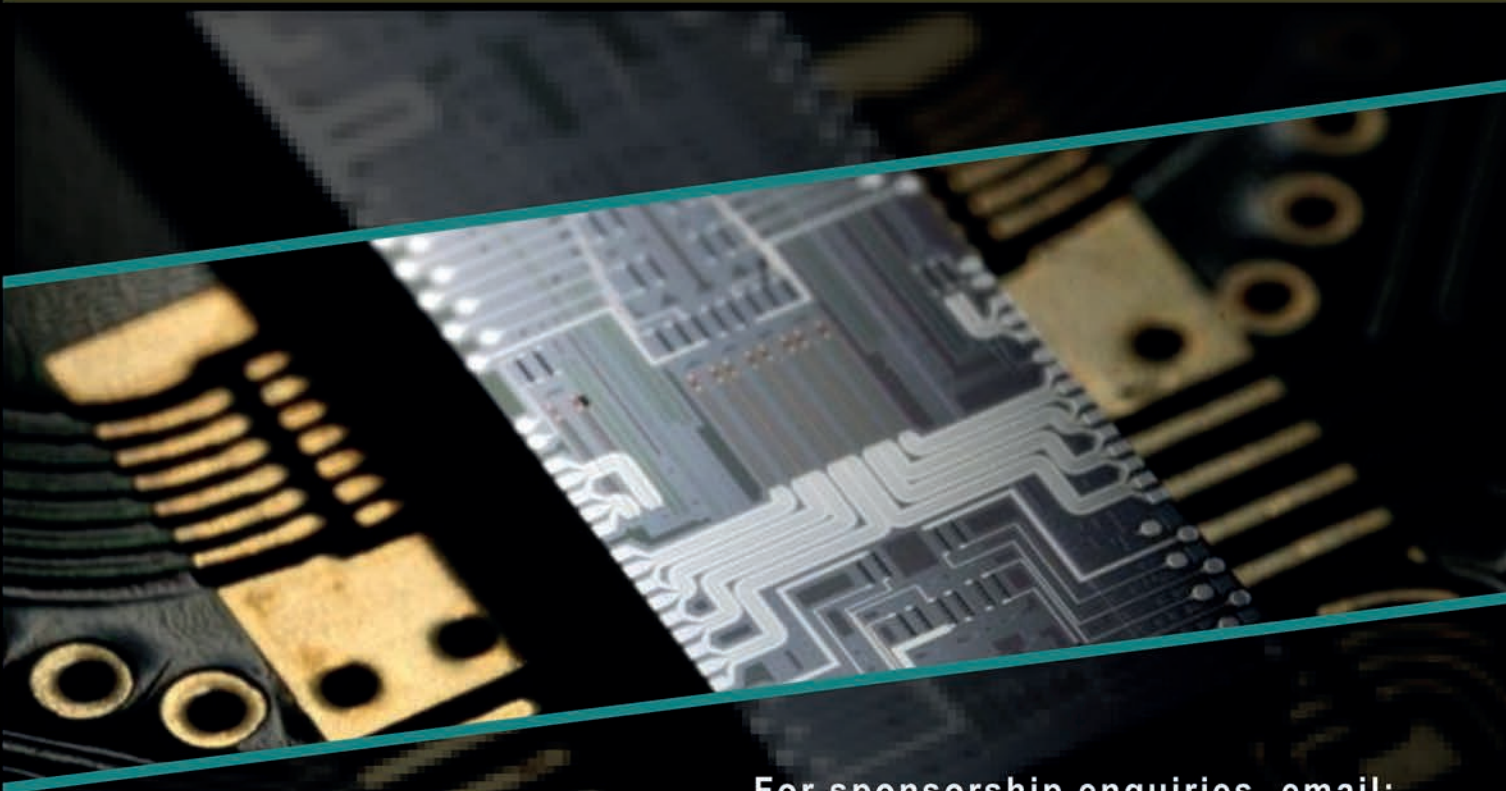

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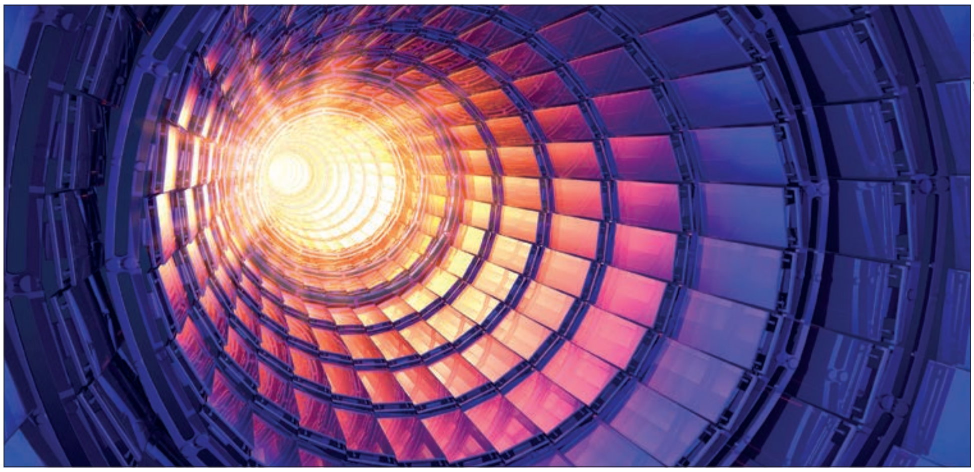
Research updates

CERN delves into the strong force

Measurements at the Compact Muon Solenoid suggests that tetraquarks are tightly bound, but more work is needed, as **Isabelle Dumé** explains



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Charming measurement Physicists have studied all-charm tetraquarks that were produced by colliding protons at CERN's Large Hadron Collider.

Researchers at CERN have made the first measurements of the quantum properties of a family of three "all-charm" tetraquarks that was recently discovered at the lab's Large Hadron Collider (LHC). The findings could help shed more light on the properties of the strong nuclear force as well as improve our understanding of how ordinary matter forms (*Nature* **648** 58).

The LHC has in recent years discovered tens of massive particles called hadrons, which are made of quarks bound together by the strong force. Quarks come in six types: up, down, charm, strange, top and bottom and most observed hadrons comprise two or three quarks (called mesons and baryons, respectively). Physicists have also observed exotic hadrons that comprise four or five quarks – tetraquarks and pentaquarks respectively. Those seen so far usually contain a charm quark and its antimatter counterpart (a charm antiquark), with the remaining two or three quarks being up, down or strange quarks, or their antiquarks.

Identifying and studying tetraquarks and pentaquarks helps physicists better understand how the strong force, which also binds protons and neutrons in atomic nuclei, binds quarks together. Physicists are still divided, however, as to the nature of these exotic hadrons. Some models suggest that their quarks are tightly bound via the strong force, so making these hadrons compact objects. Others say that the quarks are only loosely bound. To confuse things further, there is evidence that in some exotic hadrons, the quarks might be both tightly and loosely bound at the same time.

The latest results from the Compact Muon Solenoid (CMS) Collaboration suggests that tetraquarks are indeed tightly bound. In their work, CMS physicists studied all-charm tetraquarks, which comprise two charm quarks and two charm antiquarks, that were produced by colliding protons at high energies at the LHC. Three states of this tetraquark have been identified at the LHC: X(6900); X(6600); and X(7100), where the numbers denote their approximate mass in millions of electron volts.

The team measured the fundamental properties of these tetraquarks, including their quantum numbers: parity (P); charge conjugation (C); angular momentum, and spin (J). P determines whether a particle has the same properties as its spatial mirror image; C whether it has the same properties as its antiparticle; and J, the total angular momentum of the hadron. These numbers provide information on the internal structure of a tetraquark.

The researchers used a version of a well-known technique called angular analysis, which is similar to the technique used to characterize the Higgs boson. This approach focuses on the angles at which the decay products of the all-charm tetraquarks are scattered. "We call this technique quantum state tomography," CMS team member Chiara Mariotti of the INFN Torino in Italy told *Physics World*. "Here, we deduce the quantum state of an exotic state X from the analysis of its decay products. In particular, the angular distributions in the decay $X \to J/\psi J/\psi$, followed by J/ψ decays into two muons, serve as analysers of polarization of two J/ψ particles."

The researchers analysed all-charm tetraquarks produced at the CMS experiment between 2016 and 2018. They calculated that J is likely to be 2 and that P and C are both +1, with this combination of properties being expressed as 2++. "This result favours models in which all four quarks are tightly bound," says particle physicist Timothy Gershon of the UK's University of Warwick, who was not involved in this study. "However, the question is not completely put to bed. The sample size in the CMS analysis is not sufficient to exclude fully other possibilities, and additionally certain assumptions are made that will require further testing in future."

Indeed, the findings do not completely rule out other models and further studies with larger data samples will be needed. The CMS Collaboration is now gathering more data and exploring additional decay modes of these exotic tetraquarks. "This will ultimately improve our understanding how this matter forms, which, in turn, could help refine our theories of how ordinary matter comes into being," says Mariotti.

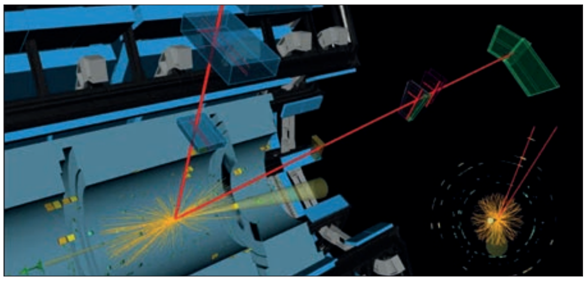
Particle physics

Higgs decay to muon–antimuon pairs sheds light on the origin of mass

A new measurement by CERN's ATLAS Collaboration has strengthened evidence that the masses of fundamental particles originate through their interaction with the Higgs field. Building on earlier results from CERN's CMS Collaboration, the observations suggest that muon–antimuon pairs (dimuons) can be created by the decay of Higgs bosons (*Phys. Rev. Lett.* **135** 231802).

In the Standard Model of particle physics, fermions are organized into three different generations. The first generation comprises the two lightest quarks (up and down), the lightest lepton (the electron) and the electron neutrino. The second includes the strange and charm quarks, the muon and its neutrino; and the third generation the bottom and top quarks, the tau and its neutrino.

All of the quarks and leptons have both right- and left-handed components, which relate to the direction of a particle's spin relative to its direction of motion (right-handed if both directions are aligned; left-handed if they are anti-aligned).



CERN

Smashing result Work on the ATLAS detector at CERN has found that muon–antimuon pairs can be created by the decay of Higgs bosons – agreeing with previous results.

In the 1960s it was proposed that the Higgs field acts as a bridge between each particle's left- and right-handed components in a way that respects the Standard Model's underlying symmetry. This interaction causes the particle to constantly flip between its two components, creating a resistance to motion that can be perceived as mass. However, higher-mass particles must interact more strongly with this Higgs field – but the strong and electromagnetic forces can only differentiate between these particles according to their charges (colour and electrical).

So how does the Higgs field distinguish between particles in different generations if their charges are identical? Key to solving this mystery is observing the decay products of Higgs bosons with different interaction strengths. In 2022, proton–proton collision experiments at CERN's Large Hadron Collider independently observed Higgs bosons decaying to tau–antitau pairs at the same rate as predicted by theory.

A year earlier, similar experiments by the CMS Collaboration probed the second generation by observing muon–antimuon pairs from the decays of Higgs bosons. This rarer event occurs in just 1 in 5000 Higgs decays. In their latest study, the ATLAS Collaboration have now reproduced this CMS result independently. They collided protons at about 13 TeV and observed muon–antimuon pairs in the same range of energies predicted by theory. These new results bring dimuon observations to a statistical significance of 3.4σ – up from 3.0σ in 2021.

Sam Jarman

KATRIN and MicroBooNE fail to spot sterile neutrinos

Two major experiments have found no evidence for sterile neutrinos – hypothetical particles that could help explain some puzzling observations in particle physics. The KATRIN experiment searched for sterile neutrinos that could be produced during the radioactive decay of tritium; whereas the MicroBooNE experiment looked for the effect of sterile neutrinos on the transformation of muon neutrinos into electron neutrinos (*Nature* 648 64 and 648 70).

There is some experimental evidence that the current Standard-Model description of neutrino oscillation is not quite right. This includes lower-than-expected neutrino fluxes from some beta-decaying nuclei and some anomalous oscillations in neutrino beams. One possible explanation for these oscillation anomalies is the existence of a fourth type of neutrino. Because we have yet to detect this particle, the assumption is that it does not interact via the weak interaction – which is why these hypothetical particles are called sterile neutrinos.

Markus Breig/KIT

Back to the drawing board Work on the KATRIN experiment in Germany has found no evidence for sterile neutrinos.

Now, two neutrino experiments have both reported no evidence of sterile neutrinos. One is KATRIN, which is located at the Karlsruhe Institute of Technology in Germany. Its aim is to make a very precise measurement of the mass of the electron antineutrino. If sterile neutrinos exist, then they could sometimes be emitted in place of electron antineutrinos during beta decay. This would change the electron energy spectrum – but this was not observed at KATRIN.

Meanwhile, physicists on the MicroBooNE experiment at Fermilab in the US looked for evidence for sterile neutrinos in how muon neutrinos oscillate into electron neutrinos. If sterile neutrinos exist, they would be involved in the oscillation process and would therefore affect the number of electron neutrinos detected by MicroBooNE. Neutrino beams from two different sources were used in the experiments, but no evidence for sterile neutrinos was found.

"Any time you rule out one place where physics beyond the Standard Model could be, that makes you look in other places," says Justin Evans at the UK's University of Manchester, who is co-spokesperson for MicroBooNE.

Hamish Johnston

Materials

New insulating aerogel could make windows more energy efficient

An aerogel material that is more than 99% transparent to light and is an excellent thermal insulator has been developed by Ivan Smalyukh and colleagues at the University of Colorado Boulder in the US. The material can be manufactured in large slabs and could herald a major advance in energy-efficient windows (*Science* **390** 1171).

While the insulating properties of building materials have steadily improved over the past decades, windows have consistently lagged behind. The problem is that current materials used in windows – mostly glass – have an inherent trade-off between being insulating and optically transparent. This is addressed to some extent by using two or three layers of glass but windows still are the largest source of heat loss from most buildings.

A solution to the window problem could lie with aerogels in which the liquid component of a regular gel is replaced with air. This creates solid materials with networks of pores that make aerogels the lightest solid materials ever produced. If the solid component is a poor conductor of heat, then the aerogel will be an extremely good thermal insulator. While this problem can be overcome fairly easily in thin aerogel films, creating appropriately-sized pores on the scale of practical windows has so far proven much more difficult, leading to a hazy, translucent appearance.

Glenn Asakawa/CU Boulder

Clear improvement The mesoporous, optically clear heat insulator maintains its transparency even when fabricated in slabs over 3 cm thick and a square metre in area.

Now, Smalyukh's team has developed a new fabrication technique involving a removable template. Their approach hinges on the tendency of surfactant molecules called CPCL to self-assemble in water. Under carefully controlled conditions, the molecules spontaneously form networks of cylindrical tubes, called micelles. Once assembled, the aerogel precursor – a silicone material called polysiloxane – condenses around the micelles, freezing their structure in place.

As a result, the mesoporous, optically clear heat insulator (MOCHI) stays transparent even when fabricated in slabs over 3 cm thick and a square metre in area. This suggests that it could be used to create practical windows and if rolled out on commercial scales, could lead to entirely new ways to manage interior heating and cooling.

According to the team's calculations, a building retrofitted with MOCHI windows could boost its energy efficiency from around 6% (a typical value in current buildings) to over 30%, while reducing the heat energy passing through by around 50%. "MOCHI glass units can provide a similar rate of heat transfer to high-performing building roofs and walls, with thicknesses comparable to double pane windows," notes Smalyukh.

Sam Jarman

Quantum

Qubit 'recycling' gives neutral-atom quantum computing a boost

A team at the US-based firm Atom Computing has reported an improvement in quantum-error reduction in quantum processors based on neutral atoms. By keeping large numbers of qubits operational for the computations, the work represents major progress in neutral atom quantum computing (*Phys. Rev. X* 15 041040).

While neutral atoms offer several advantages over other qubit types, they traditionally have significant drawbacks for one of the most common approaches to error correction. In this approach, some of the entangled qubits are set aside as so-called "ancillaries", used for mid-circuit measurements that can indicate how a computation is going and what error correction interventions may be necessary.

In neutral-atom quantum computing, however, such interventions are generally destructive. Atoms that are not in their designated state are simply binned off – a profligate approach that makes it challenging to scale up atom-based computers. The tendency to discard atoms is particularly awkward because the traps that confine atoms are already prone to losing atoms, which introduces additional errors while reducing the number of atoms available for computations.

iStock/Ratsanai

Let's go round again A new recycling approach could help retain more atoms for calculations in quantum computers.

As well as demonstrating protocols for performing measurements to detect errors in quantum circuits with little atom loss, the researchers at Atom Computing also showed they could re-use ancillary atoms – a double-pronged way of retaining more atoms for calculations. In addition, they demonstrated that they could replenish the register of atoms for the computation from a spatially separated stash in a magneto-optic trap without compromising the quantum state of the atoms already in the register.

Matt Norcia, one of the Atom Computing researchers behind the work, says that these achievements are key to running computations without running out of atoms. "Any useful quantum computations will require the execution of many layers of gates, which will not be possible unless the atom number can be maintained at a steady-state level throughout the computation," says Norcia.

Norcia and his collaborators worked with ytterbium atoms, which he describes as "natural qubits" since they have two ground states. A further advantage is that the transitions between these qubit states and other states used for imaging and cooling are weak, meaning the researchers could couple just one qubit state to these other states at a time.

Anna Demming

Biophysics

Wearable sensor continuously monitors foetal movement

Engineers and obstetricians at Monash University in Australia have created a lightweight, easily wearable, adhesive patch-based sensor that can continuously monitor and interpret foetal movement patterns in the third trimester of pregnancy. The patches could be used to help detect any potential complications and improve foetal wellbeing (*Sci. Adv.* 11 eady2661).

Reduced foetal movement can be associated with potential impairment in the central nervous system and musculoskeletal system, and is a common feature observed in pregnancies that end in foetal death and stillbirth. A foetus compromised *in utero* may reduce movements as a compensatory strategy to lower oxygen consumption and conserve energy. Currently such assessment of foetal movement is performed only periodically, with an ultrasound exam at a hospital or clinic.

Yap *et al.*, *Sci. Adv.* **11** eady2661

Baby steps
The researchers tested their new device by examining foetal movement and comparing it with ultrasound examinations.

To help identify foetuses at risk of complications, the Monash team developed an artificial intelligence-powered wearable pressure–strain combo sensor system that continuously and accurately detects foetal movement-induced motion in the mother's abdominal skin. The system comprises two soft, thin and flexible patches designed to conform to the abdomen of a pregnant woman. One patch incorporates an octagonal gold nanowire-based strain sensor (the "Octa" sensor), while the other is an interdigitated electrode-based pressure sensor. The patches feature a soft polyimide-based flexible printed circuit that integrates a thin lithium polymer battery and various integrated circuit chips, including a Bluetooth radiofrequency system.

The researchers validated their foetal movement monitoring system by comparing it with simultaneous ultrasound exams, examining 59 healthy pregnant women at Monash Health. Each participant had the pressure sensor attached to the area of their abdomen where they felt the most vigorous foetal movements while the strain sensor was attached to the region closest to foetal limbs. An accelerometer placed on the participant's chest captured non-foetal movement data for signal denoising and training the machine-learning model.

The "band-aid"-like sensors could detect foetal movements such as kicking, waving, hiccups, breathing, twitching, and head and trunk motion and could discriminate between foetal and non-foetal movement with over 90% accuracy. The researchers note that the pressure sensor demonstrated higher sensitivity to movements directly beneath it compared with motion farther away, while the Octa sensor performed consistently across a wider sensing area. "By integrating sensor data with AI, the system automatically captures a wider range of foetal movements than existing wearable concepts while staying compact and comfortable," says co-author Fae Marzbanrad.

The next steps towards commercialization include carrying out large-scale clinical studies in out-of-hospital settings, to evaluate foetal movements and investigate the relationship between movement patterns and pregnancy complications.

Cynthia Keen

Optics

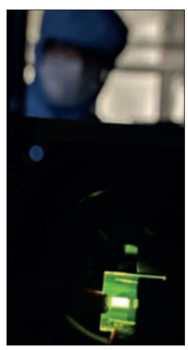
Organic LEDs can electrically switch the handedness of emitted light

Researchers have developed organic light emitting diodes (OLEDs) that can electrically switch between emitting left- or right-handed circularly polarized (CP) light – without needing different molecules for each handedness. The findings could have applications in low-power displays and quantum technologies (*Nature Photonics* **19** 1361).

OLEDs usually only emit either left- or right-handed CP light depending on the chirality of the light-emitting molecules used to create the device. A chiral molecule is one that has two mirror-image structural isomers that can't be superimposed on top of each other. Each of these non-superimposable "enantiomer" molecules will absorb, emit and refract circularly polarized light with a defined spin angular momentum. Each enantiomer produces CP light with a different handedness, through an optical mechanism called normal circularly polarized electroluminescence.

OLED designs typically require access to both enantiomers, but most chemical synthesis processes produce racemic mixtures – equal amounts of the two enantiomers – that are difficult to separate. Extracting each enantiomer so that they can be used individually is complex and expensive, but researchers at the University of Oxford have now simplified this process by using a molecule – *(P)*-aza[6]helicene – that can switch between emitting left- and right-handed CP light.

(P)-aza[6]helicene is a right-handed enantiomer and even though it is just a one-handed form, the researchers found a way to control the handedness of the OLED, enabling it to switch between both forms. "Our work shows that either handedness can be accessed from a single-handed chiral material without changing the composition or thickness of the emissive layer," says lead author Matthew Fuchter.



Matt Fuchter, University of Oxford

Chiral control
Researchers have created an organic LED that can generate left- or right-handed circularly polarized light from the same form of light-emitting molecule.

Instead of making a structural change, the researchers altered the way that the electric charges are recombined in the device, using interlayers to alter the recombination position and charge carrier mobility inside the device. Depending on where the recombination zone is located, this leads to situations where there is balanced or unbalanced charge transport, which then leads to different handedness of CP light in the device. "This work contributes to the growing body of evidence suggesting further rich physics at the intersection of chirality, charge and spin," says Fuchter. "We have many ongoing projects to try and understand and exploit such interplay."

Liam Critchley

Opinion

physicsworld

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Bibliographic codes ISSN 0953-8585 (print)
ISSN 2058-7058 (online) CODEN PHWOEW

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A degree of success

The 10th annual *Physics World Careers* guide showcases job options for physicists

I hear it all the time: physics students have only the haziest idea of what they can do with a physics degree. Staying in academia is the obvious option but they're often not sure what else is out there. With hefty student debts to pay off, getting a well-paid job in finance seems to top many physicists' wish lists these days. But there are lots of other options, from healthcare, green energy and computing to education, aviation and construction.

Some of the many things you can do with a physics degree are covered in the latest edition of *Physics World Careers*, which is published on 4 February. This bumper, 96-page digital guide contains profiles of physicists working across a variety of fields, along with career-development advice and a directory of employers looking to hire physicists. Now in its 10th year, the guide has become an indispensable source of careers information for physicists setting out in the world of work.

The 2026 edition of *Physics World Careers* includes, for example, an article featuring two leaders from the UK's intelligence agency GCHQ, a spotlight on the many jobs in nuclear energy, as well as careers tips from a recent Physics World Live panel. Remember that if you're ready to start your job search, you can find all the latest opportunities on the Physics World Jobs portal, which has vacancies in physics and engineering for people at all career stages.

Although the International Year of Quantum Science and Technology is drawing to a close this month, quantum remains one of the most attractive areas for physicists right now. As well as plenty of opportunities in pure research, there are countless companies – small and large – seeking to exploit phenomena such as superposition and entanglement for practical purposes. Quantum skills are in high demand – if anything, there are concerns that there aren't enough people with the right skills in the jobs pipeline (see pp25–29).

Meanwhile, in this issue of *Physics World* we've got a profile of Rob Farr, a theoretical physicist who's spent more than 25 years in the food industry (see pp31–32). He's a great example of a physicist doing something you might not expect, in his case going from the chilly depths of ice cream science to the dark arts of coffee production and brewing. But that's the beauty of a physics degree – it provides skills, knowledge and insight that can be applied to very different areas.

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

Transactions Learning to take risks

Honor Powrie is an engineer who doesn't mind taking risks – but only if it's done in a controlled manner. So what skills would she need to be a fully-fledged entrepreneur?

I am intrigued by entrepreneurship. Is it something we all innately possess – or can entrepreneurship be taught to anyone (myself included) for whom it doesn't come naturally? Could we all – with enough time, training and support – become the next Jeff Bezos, Richard Branson or Martha Lane Fox?

In my professional life as an engineer in industry, we often talk about the importance of invention and innovation. Without them, products will become dated and firms will lose their competitive edge. However, inventions don't necessarily sell themselves, which is where entrepreneurs have a key influence.

So what's the difference between inventors, innovators and entrepreneurs? An inventor, to me, is someone who creates a new process, application or machine. An innovator is a person who introduces something new or does something for the first time. An entrepreneur, however, is someone who sets up a business or takes on a venture, embracing financial risks with the aim of profit.

Scientists and engineers are naturally good inventors and innovators. We like to solve problems, improve how we do things, and make the world more ordered and efficient. In fact, many of the greatest inventors and innovators of all time were scientists and engineers – think James Watt, George Stephenson and Frank Whittle.

But entrepreneurship requires different, additional qualities. Many entrepreneurs come from a variety of different backgrounds – not just science and engineering – and tend to have finance in their blood. They embrace risk and have unlimited amounts of courage and business acumen – skills I'd need to pick up if I wanted to be an entrepreneur myself.

Risk and reward

Engineers are encouraged to take risks, exploring new technologies and designs; in fact, it's critical for companies seeking to stay competitive. But we take risks in a calculated and professional manner that prioritizes safety, quality, regulations and ethics, and project success. We balance risk taking with risk management, spotting and assessing potential risks – and mitigating or removing them if they're big.

Shutterstock/Lightspring

Taking flight What skills do entrepreneurs need to get their ideas off the ground – and how would you teach them to scientists and engineers?

Courage is not something I've always had professionally. Over time, I have learned to speak up if I feel I have something to say that's important to the situation or contributes to our overall understanding. Still, there's always a fear of saying something silly in front of other people or being unable to articulate a view adequately. But entrepreneurs have courage in their DNA.

So can entrepreneurship be taught? Specifically, can it be taught to people like me with a technical background – and, if so, how? Some of the most famous innovators, like Henry Ford, Thomas Edison, Steve Jobs, James Dyson and Benjamin Franklin, had scientific or engineering backgrounds, so is there a formula for making more people like them?

Skill sets and gaps

Let's start by listing the skills that most engineers have that could be beneficial for entrepreneurship. In no particular order, these include:

- problem-solving ability: essential for designing effective solutions or to identify market gaps;
- innovative mindset: critical for building a successful business venture;
- analytical thinking: engineers make decisions based on data and logic, which is vital for business planning and decision making;
- persistence: a pre-requisite for delivering engineering projects and needed to overcome the challenges of starting a business;
- technical expertise: a significant competitive advantage and providing credibility, especially relevant for tech start-ups.

However, there are mindset differences between engineers and entrepreneurs that any training would need to overcome. These include:

- risk tolerance: engineers typically focus on improving reliability and reducing risk, whilst entrepreneurs are more comfortable with embracing greater uncertainty;
- focus: engineers concentrate on delivering to requirements, whilst entrepreneurs focus on consumer needs and speed to market;
- business acumen: a typical engineering education doesn't cover essential business skills such as marketing, sales and finance, all of which are vital for running a company.

Such skills may not always come naturally to engineers and scientists, but they can be incorporated into our teaching and learning. Some great examples of how to do this were covered in *Physics World* last year. In addition, there is a growing number of UK universities offering science and engineering degrees combined with entrepreneurship.

The message is that whilst some scientists and engineers become entrepreneurs, not all do. Simply having a science or engineering background is no guarantee of becoming an entrepreneur, nor is it a requirement. Nevertheless, the problem-solving and technical skills developed by scientists and engineers are powerful assets that, when combined with business acumen and entrepreneurial drive, can lead to business success.

Of course, entrepreneurship may not suit everybody – and that's perfectly fine. No-one should be forced to become an entrepreneur if they don't want to. We all need to play to our core strengths and interests and build well-rounded teams with complementary skill sets – something that every successful business needs. But surely there's a way of teaching entrepreneurship 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

Enhancing a sense of belonging

Ensuring that students have a sense of belonging in physics can bring numerous benefits to the subject, as **Jenna Padgett** explains

iStock/SeventyFour

Building a more welcoming subject Students from under-represented groups typically face many microaggressions in their day-to-day university experience. Creating a sense of belonging for these students helps physics as a whole, not just the individuals.

Physics students from under-represented groups consistently report a lower sense of belonging at university than their over-represented peers. These students experience specific challenges that make them feel undervalued and excluded. Yet a strong sense of belonging has been shown to lead to improved academic performance, greater engagement in courses and better mental wellbeing. It is vital, then, that universities make changes to help eliminate these challenges.

Students are uniquely placed to describe the issues when it comes to belonging in physics. With this mind, as an undergraduate physics student with a passion for making the discipline more diverse and inclusive, I conducted focus groups with current and former physics students, interviewed experts and performed an analysis of current literature. This was part of a summer project funded by the Royal Institution and is currently being finalized for publication.

From this work it became clear that under-represented groups face many challenges to developing a strong sense of belonging in physics, but, at the same time, there are ways to improve the everyday experiences of students. When it comes to barriers, one is the widely held belief – reflected in the way physicists are depicted in the media and textbooks – that you need to be a "natural genius" to succeed in university physics. This notion hampers students from under-represented groups, who see peers from the over-represented majority appearing to grasp concepts more quickly and lecturers suggesting certain topics are "easy".

The feeling that physics demands natural ability also arises from the so-called "weed out" culture, which is defined as courses that are intentionally designed to filter students out, reduce class sizes and diminish sense of belonging. Students who we surveyed believe that the high fail rate is caused by a disconnect between the teaching and workshops on the course and the final exam.

A third cause of this perception that you need some innate ability to succeed in physics is the attitudes and behaviour of some professors, lecturers and demonstrators. This includes casual sexist and racist behaviour; belittling students who ask for help; and acting as if they're uninterested in teaching. Students from under-represented groups report significantly lower levels of respect and recognition from instructors, which damages their resilience and weakens sense of belonging.

Students from under-represented groups are also more likely to be isolated from their class mates and feel socially excluded from them. This means they lack a support network, leaving them with no-one to turn to when they encounter challenges. Outside the lecture theatre, students from under-represented groups typically face many microaggressions in their day-to-day university experience. These are subtle indignities or insults, unconsciously or consciously, towards minorities such as people of colour being told they "speak English very well", male students refusing to accept women's ideas, and the assumption that gender minorities will take on administrative roles in group projects.

> Students from under-represented groups are more likely to feel socially excluded, which means they lack a support network when they encounter challenges

Focus on the future

So what can be done? The good news is that there are many solutions to mitigate these issues and improve a sense of belonging. First, institutions should place more emphasis on small group "active learning" – which includes discussions, problem solving and peer-based learning. These pedagogical strategies have been shown to boost belonging, particularly for female students. After these active-learning sessions, non-academic, culturally sensitive social lunches can help turn "course friends" to "real friends" who choose to meet socially and can become a support network. This can help build connections within and between degree cohorts.

Another solution is for universities to invite former students to speak about their sense of belonging and how it evolved or improved throughout their degree. Hearing about struggles and learning tried-and-tested strategies to improve resilience can help students better prepare for stressful situations. Alumni are more relatable than generic messaging from the university wellbeing team.

Building closer links between students and staff also enhances a sense of belonging. It helps humanise lecturers and demonstrate that staff care about student wellbeing and success. This should be implemented by recognizing staff efforts formally so that the service roles of faculty members are formally recognized and professionalized.

Universities should also focus on hiring more diverse teaching staff, who can serve as role models, using their experiences to relate to and engage with under-represented students. Students will end up feeling more embedded within the physics community, improving both their sense of belonging and performance.

Universities should focus on hiring more diverse teaching staff, who can serve as role models, using their experiences to relate to and engage with under-represented students

One practical way to increase diversity in hiring is for institutions to re-evaluate what they value. While securing large grants is valuable, so is advocating for equality, diversity and inclusion; public engagement; and the ability to inspire the next generation of physicists.

Another approach is to establish "departmental action teams" to find tailored solutions to unite undergraduates, postgraduates, teaching and research staff. Such teams identify issues specific to their particular university, and they can gather data through surveying the department to identify trends and recommend practical changes to boost belonging.

Implementing these measures will not only improve the sense of belonging for students from under-represented groups but also cultivate a more inclusive, diverse physics workforce. That in turn will boost the overall research culture, opening up research directions that may have previously been overlooked, and yielding stronger scientific outputs. It is crucial that we do more to support physics students from under-represented groups to create a more diverse physics community. Ultimately, it will benefit physics and society as a whole.

Jenna Padgett is a physics student at the University of Edinburgh who is interested in physics education research and building a more inclusive physics community

Reviews

Managing our Martian limits

Emma Chapman reviews *Becoming Martian: How Living in Space Will Change Our Bodies and Minds* by Scott Solomon

Becoming Martian: How Living in Space Will Change Our Bodies and Minds
Scott Solomon
February 2026 MIT Press 264pp £27hb

iStock/Denis Art

Biological limits
A sustainable Mars colony will need to include raising children there, but childbirth would be very risky on Mars.

"It's hard to say when exactly sending people to Mars became a goal for humanity," ponders author Scott Solomon in his new book *Becoming Martian: How Living in Space Will Change Our Bodies and Minds* – and I think we'd all agree. Ten years ago, I'm not sure any of us thought even returning to the Moon was seriously on the cards. Yet here we are, suddenly living in a second space age, where the first people to purchase one-way tickets to the Red Planet have likely already been born.

The technology required to ship humans to Mars, and the infrastructure required to keep them alive, is well constrained, at least in theory. One could write thousands of words discussing the technical details of reusable rocket boosters and underground architectures. However, *Becoming Martian* is not that book. Instead, it deals with the effect Martian life will have on the human body – both in the short term across a single lifetime; and in the long term, on evolutionary timescales.

This book's strength lies in its authorship: it is not written by a physicist enthralled by the engineering challenge of Mars, nor by an astronomer predisposed to romanticizing space exploration. Instead, Solomon is a research biologist who teaches ecology, evolutionary biology and scientific communication at Rice University in Houston, Texas.

Becoming Martian starts with a whirlwind, stripped-down tour of Mars across mythology, astronomy, culture and modern exploration. This effectively sets out the core issue: Mars is fundamentally different from Earth, and life there is going to be very difficult. Solomon goes on to describe the effects of space travel and microgravity on humans that we know of so far: anaemia, muscle wastage, bone density loss and increased radiation exposure, to name just a few.

> Mars is fundamentally different from Earth, and life there is going to be very difficult

Where the book really excels, though, is when Solomon uses his understanding of evolutionary processes to extend these findings and conclude how Martian life would be different. For example, childbirth becomes a very risky business on a planet with about one-third of Earth's gravity. The loss of bone density translates into increased pelvic fractures, and the muscle wastage into an inability for the uterus to contract strongly enough. The result? All Martian births will likely need to be C-sections.

Solomon applies his expertise to the whole human body, including our "entourage" of micro-organisms. The indoor life of a Martian is likely to affect the immune system to the degree that contact with an Earthling would be immensely risky. "More than any other factor, the risk of disease transmission may be the wedge that drives the separation between people on the two planets," he writes. "It will, perhaps inevitably, cause the people on Mars to truly become Martians." Since many diseases are harboured or spread by animals, there is a compelling argument that Martians would be vegan and – a deal-breaker for some I imagine – unable to have any pets. So no dogs, no cats, no steak and chips on Mars.

Let's get physical

The most fascinating part of the book for me is how Solomon repeatedly links the biological and psychological research with the more technical aspects of designing a mission to Mars. For example, the first exploratory teams should have odd numbers, to make decisions easier and us-versus-them rifts less likely. The first colonies will also need to number between 10 000 and 11 000 individuals to ensure enough genetic diversity to protect against evolutionary concepts such as genetic drift and population crashes.

Amusingly, the one part of human activity most important for a sustainable colony – procreation – is the most understudied. When a NASA scientist made the suggestion a colony would need private spaces with soundproof walls, the backlash was so severe that NASA had to reassure Congress that taxpayer dollars were not being "wasted" encouraging sexual activity among astronauts.

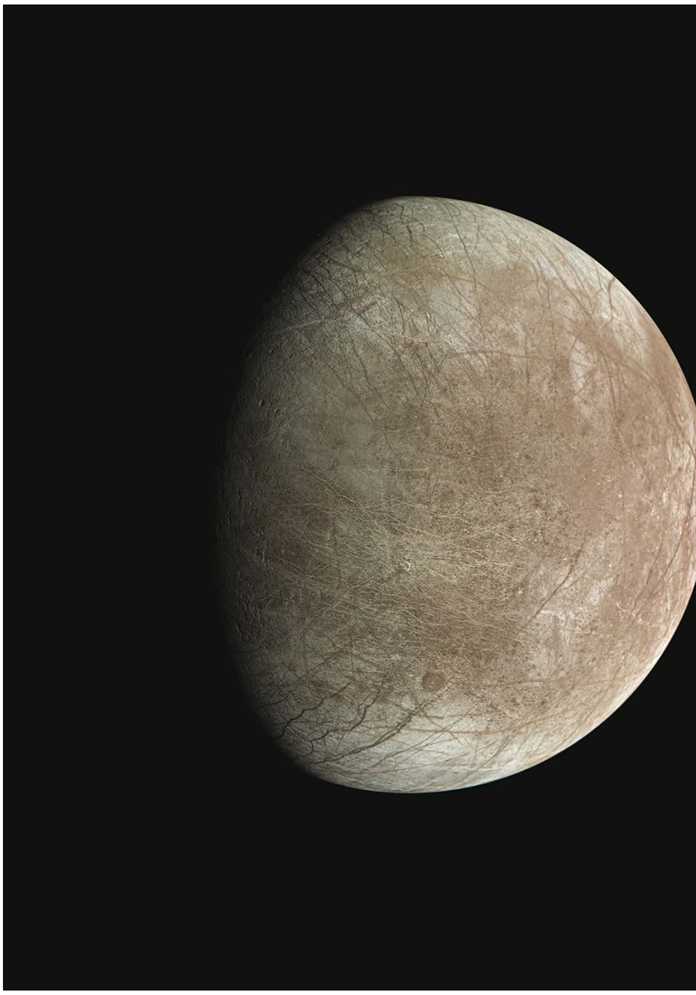
Solomon's writing is concise yet extraordinarily thorough – there is always just enough for you to feel you can understand the importance and nuance of topics ranging from Apollo-era health studies to evolution, and from AI to genetic engineering. The book is impeccably researched, and he presents conflicting ethical viewpoints so deftly, and without apparent judgement, that you are left plenty of space to imprint your own opinions. So much so that when Solomon shares his own stance on the colonization of Mars in the epilogue, it comes as a bit of a surprise.

In essence, this book lays out a convincing argument that it might be our biology, not our technology, that limits humanity's expansion to Mars. And if we are able to overcome those limitations, either with purposeful genetic engineering or passive evolutionary change, this could mean we have shed our humanity.

Becoming Martian is one of the best popular-science books I have read within the field, and it is an uplifting read, despite dealing with some of the heaviest ethical questions in space sciences. Whether you're planning your future as a Martian or just wondering if humans can have sex in space, this book should be on your wish list.

Emma Chapman is an astrophysicist at the University of Nottingham, UK, and author of *Radio Universe: How to Explore Space Without Leaving Earth* and *First Light: Switching on Stars at the Dawn of Time*

Exploring the icy moons of the solar system



Far from the Sun's heat, orbiting the outer planets of the solar system, are moons with oceans of liquid water beneath their frozen surfaces. **Keith Cooper** finds out how planetary scientists are unravelling the mysteries of these frigid systems to see if they hold life beyond our planet

Keith Cooper is a science writer based in the UK

Our blue planet is a Goldilocks world. We're at just the right distance from the Sun that Earth – like Baby Bear's porridge – is not too hot or too cold, allowing our planet to be bathed in oceans of liquid water. But further out in our solar system are icy moons that eschew the Goldilocks principle, maintaining oceans and possibly even life far from the Sun.

We call them icy moons because their surface, and part of their interior, is made of solid water-ice. There are over 400 icy moons in the solar system – most are teeny moonlets just a few kilometres across, but a handful are quite sizeable, from hundreds to thousands of kilometres in diameter. Of the big ones, the best known are Jupiter's moons, Europa, Ganymede and Callisto, and Saturn's Titan and Enceladus.

Yet these moons are more than just ice. Deep beneath their frozen shells – some –160 to –200 °C cold and bathed in radiation – lie oceans of water, kept liquid thanks to tidal heating as their interiors flex in the strong gravitational grip of their parent planets. With water being a prerequisite for life as we know it, these frigid systems are our best chance for finding life beyond Earth.

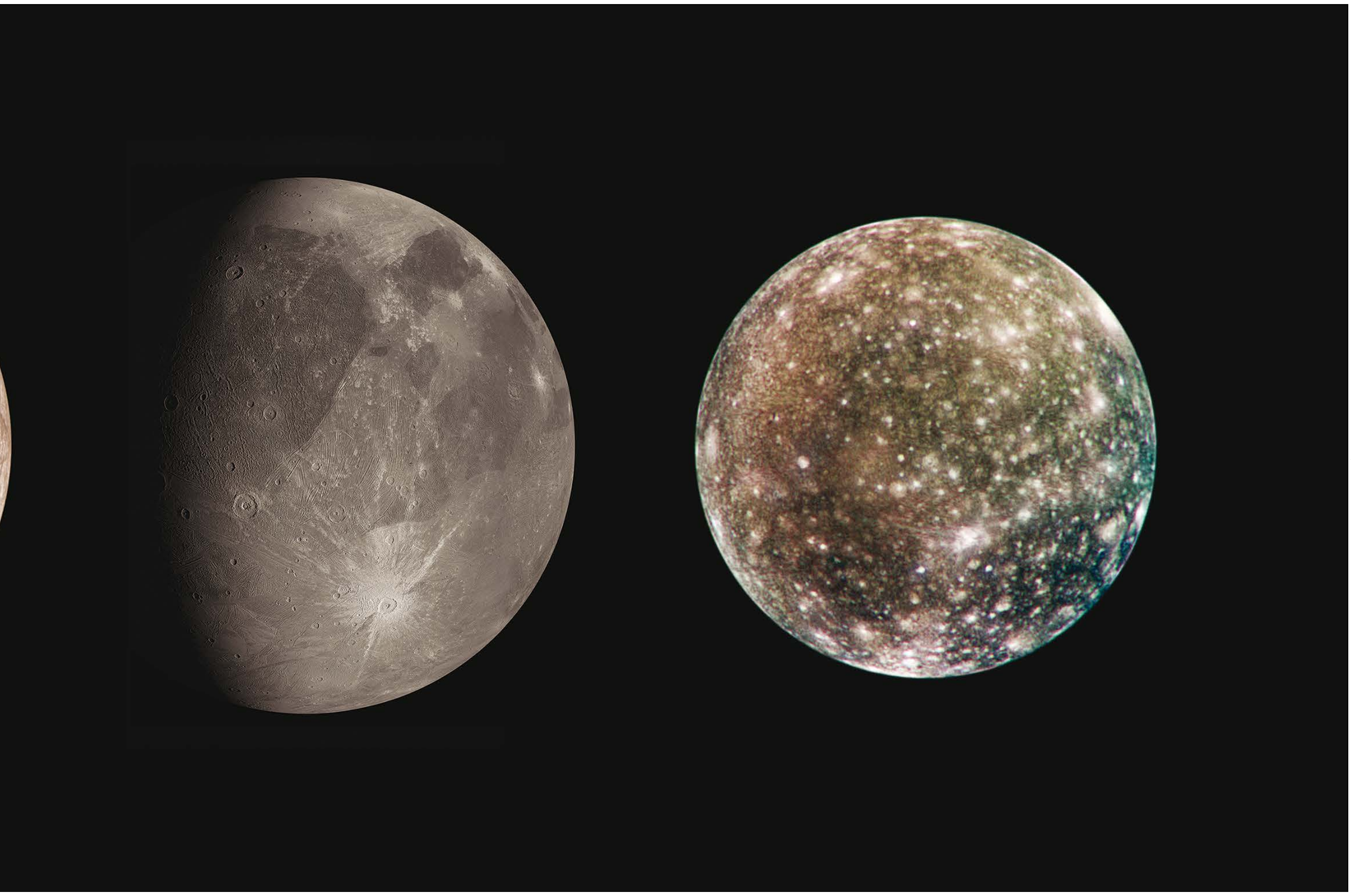
The first hints that these icy moons could harbour oceans of liquid water came when NASA's Voyager 1 and 2 missions flew past Jupiter in 1979. On Europa they saw a broken and geologically youthful-looking surface, just millions of years old, featuring dark cracks that seemed to have slushy material welling up from below. Those hints turned into certainty when NASA's Galileo mission visited Jupiter between 1995 and 2003. Gravity and magnetometer experiments proved that not only does Europa contain a liquid layer, but so do Ganymede and Callisto.

Meanwhile at Saturn, NASA's Cassini spacecraft (which arrived in 2004) encountered disturbances in the ringed planet's magnetic field. They turned out to be caused by plumes of water vapour erupting out of giant fractures splitting the surface of Enceladus, and it is believed that this vapour originates from an ocean beneath the moon's ice shell. Evidence for an ocean on Titan is a little less certain, but gravity and radio measurements performed by Cassini and its European-built lander Huygens point towards the possibility of some liquid or slushy water beneath the surface.

Water, ice and JUICE

"All of these ocean worlds are going to be different, and we have to go to all of them to understand the whole spectrum of icy moons," says Amanda Hendrix, director of the Planetary Science Institute in Arizona, US. "Understanding what their oceans are like can tell us about habitability in the solar system and where life can take hold and evolve."

To that end, an armada of spacecraft will soon be on their way to the icy moons of the outer planets, building on the successes of their predecessors Voyager, Galileo and Cassini–Huygens. Leading the charge is NASA's Europa Clipper, which is already heading to Jupiter. Clipper will reach its destination in 2030, with the Jupiter Icy moons Explorer (JUICE) from the European Space Agency (ESA) just a year behind it. Europa is the primary target of scientists because it is possibly Jupiter's most interesting moon as a result of its "astrobiological poten-



By Jove
Three of Jupiter's largest moons have solid water-ice. (Left) Europa, imaged by the JunoCam on NASA's Juno mission to Jupiter. The surface sports myriad fractures and dark markings. (Middle) Ganymede, also imaged by the Juno mission, is the largest moon in our solar system. (Right) Our best image of ancient Callisto was taken by NASA's Galileo spacecraft in 2001. The arrival of JUICE in the Jovian system in 2031 will place Callisto under much-needed scrutiny.

tial". That's the view of Olivier Witasse, who is JUICE project scientist at ESA, and it's why Europa Clipper will perform nearly 50 fly-bys of the icy moon, some as low as 25 km above the surface. JUICE will also visit Europa twice on its tour of the Jovian system.

The challenge at Europa is that it's close enough to Jupiter to be deep inside the giant planet's magnetosphere, which is loaded with high-energy charged particles that bathe the moon's surface in radiation. That's why Clipper and JUICE are limited to fly-bys; the radiation dose in orbit around Europa would be too great to linger. Clipper's looping orbit will take it back out to safety each time. Meanwhile, JUICE will focus more on Callisto and Ganymede – which are both farther out from Jupiter than Europa is – and will eventually go into orbit around Ganymede.

"Ganymede is a super-interesting moon," says Witasse. For one thing, at 5262 km across it is larger than Mercury, a planet. It also has its own intrinsic magnetic field – one of only three solid bodies in the solar system to do so (the others being Mercury and Earth).

Beneath the icy exterior

It's the interiors of these moons that are of the most interest to JUICE and Clipper. That's where the oceans are, hidden beneath many kilometres of ice. While the missions won't be landing on the Jovian moons, these internal structures aren't as inaccessible as we might at first think. In fact, there are three independent methods for probing them.

If a moon's ocean contains salts or other electrically conductive contaminants, interesting things happen when passing through the parent planet's variable magnetic field. "The liquid is a conductive layer within a varying magnetic field and that induces a magnetic field in the ocean that we can measure with a magnetometer using Faraday's law," says Witasse. The amount of salty contaminants, plus the depth of the ocean, influence the magnetometer readings.

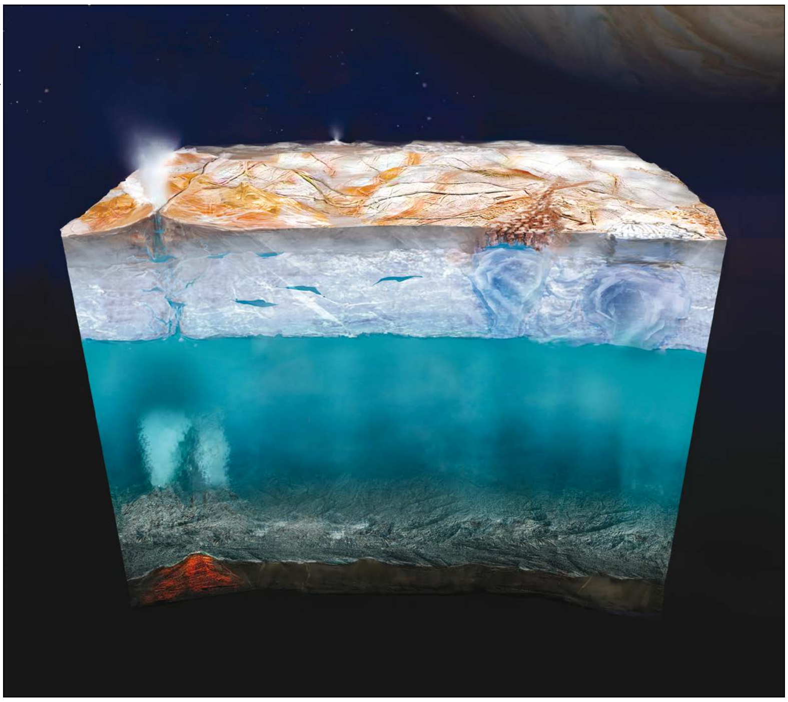
Then there's radio science – the way that an icy moon's mass bends a radio signal from a spacecraft to Earth. By making multiple fly-bys with different trajectories during different points in a moon's orbit around its planet, the moon's gravity field can be measured. Once that is known to exacting detail, it can be applied to models of that moon's internal structure.

Perhaps the most remarkable method, however, is using a laser altimeter to search for a tidal bulge in the surface of a moon. This is exactly what JUICE will be doing when in orbit around Ganymede. Its laser altimeter will map the shape of the surface – such as hills and crevasses – but gravitational tidal forces from Jupiter are expected to cause a bulge on the surface, deforming it by 1–10 m. How large the bulge is depends upon how deep the ocean is.

"If the surface ice is sitting above a liquid layer then the tide will be much bigger because if you sit on liquid, you are not attached to the rest of the moon," says Witasse. "Whereas if Ganymede were solid the tide would be quite small because it is difficult to move one big, solid body."

As for what's below the oceans, those same gravity and

NASA/JPL-Caltech



Many layers A cross section of Jupiter's moon Europa, showing its internal layering: a rocky core and ocean floor (possibly with hydrothermal vents), the ocean itself and the ice shell above.

NASA/JPL/Space Science Institute

Ocean spray Geysers of water vapour loaded with salts and organic molecules spray out from the tiger stripes on Enceladus.

radio-science experiments during previous missions have given us a general idea about the inner structures of Jupiter's Europa, Ganymede and Callisto. All three have a rocky core. Inside Europa, the ocean surrounds the core, with a ceiling of ice above it. The rock–ocean interface potentially provides a source of chemical energy and nutrients for the ocean and any life there.

Ganymede's interior structure is more complex. Separating the 3400 km-wide rocky core and the ocean is a layer, or perhaps several layers, of high-pressure ice, and there is another ice layer above the ocean. Without that rock–ocean interface, Ganymede is less interesting from an astrobiological perspective.

Meanwhile, Callisto, being the farthest from Jupiter, receives the least tidal heating of the three. This is reflected in Callisto's lack of evolution, with its interior having not differentiated into layers as distinct as Europa and Ganymede. "Callisto looks very old," says Witasse. "We're seeing it more or less as it was at the beginning of the solar system."

Crazy cryovolcanism

Tidal forces don't just keep the interiors of the icy moons warm. They can also drive dramatic activity, such as cryovolcanoes – icy eruptions that spew out gases and volatile materials like liquid water (which quickly freezes in space), ammonia and hydrocarbons. The most obvious example of this is found on Saturn's Enceladus, where giant water plumes squirt out through "tiger stripe" cracks at the moon's south pole.

But there's also growing evidence of cryovolcanism on Europa. In 2012 the Hubble Space Telescope caught sight of what looked like a water plume jetting out 200 km from the moon. But the discovery is controversial despite more data from Hubble and even supporting evidence found in archive data from the Galileo mission. What's missing is cast-iron proof for Europa's plumes. That's where Clipper comes in.

"We need to find out if the plumes are real," says Hendrix. "What we do know is if there is plume activity happening on Europa then it's not as consistent or ongoing as is clearly happening at Enceladus."

At Enceladus, the plumes are driven by tidal forces from Saturn, which squeeze and flex the 500 km-wide moon's innards, forcing out water from an underground ocean through the tiger stripes. If there are plumes at Europa then they would be produced the same way, and would provide access to material from an ocean that's dozens of kilometres below the icy crust. "I think we have a lot of evidence that something is happening at Europa," says Hendrix.

These plumes could therefore be the key to characterizing the hidden oceans. One instrument on Clipper that will play an important role in investigating the plumes at Europa is an ultraviolet spectrometer, a technique that was very useful on the Cassini mission.

Because Enceladus' plumes were not known until Cassini discovered them, the spacecraft's instruments had not been designed to study them. However, scientists were able to use the mission's ultraviolet imaging spectrometer to analyse the vapour when it was between Cassini and the Sun. The resulting absorption lines in the spectrum showed the plumes to be mostly pure water, ejected into space at a rate of 200 kg per second.

The erupted vapour freezes as it reaches space and some of it snows back down onto the surface. Cassini's ultraviolet spectrometer was again used, this time to detect solar ultraviolet light reflected and scattered off these icy particles in the uppermost layers of Enceladus' surface. Scientists found that any freshly deposited snow from the plumes has a different chemistry from older surface material that has been weathered and chemically altered by micrometeoroids and radiation, and therefore a different ultraviolet spectrum.

Icy moon landing

Another two instruments that Cassini's scientists adapted to study the plumes were the cosmic dust analyser, and the ion and neutral mass spectrometer. When Cassini flew through the fresh plumes and Saturn's

E-ring, which is formed from older plume ejections, it could "taste" the material by sampling it directly. Recent findings from this data indicate that the plumes are rich in salt as well as organic molecules, including aliphatic and cyclic esters and ethers (carbon-bonded acid-based compounds such as fatty acids) (*Nature Astron*. **9** 1662). Scientists also found nitrogen- and oxygen-bearing compounds that play a role in basic biochemistry and which could therefore potentially be building blocks of prebiotic molecules or even life in Enceladus' ocean.

While Cassini could only observe Enceladus' plumes and fresh snow from orbit, astronomers are planning a lander that could let them directly inspect the surface snow. Currently in the technology development phase, it would be launched by ESA sometime in the 2040s to arrive at the moon in 2054, when winter at Enceladus' southern, tiger stripe-adorned pole turns to spring and daylight returns.

"What makes the mission so exciting to me is that although it looks like every large icy moon has an ocean, Enceladus is one where there is a very high chance of actually sampling ocean water," says Jörn Helbert, head of the solar system section at ESA, and the science lead on the prospective mission.

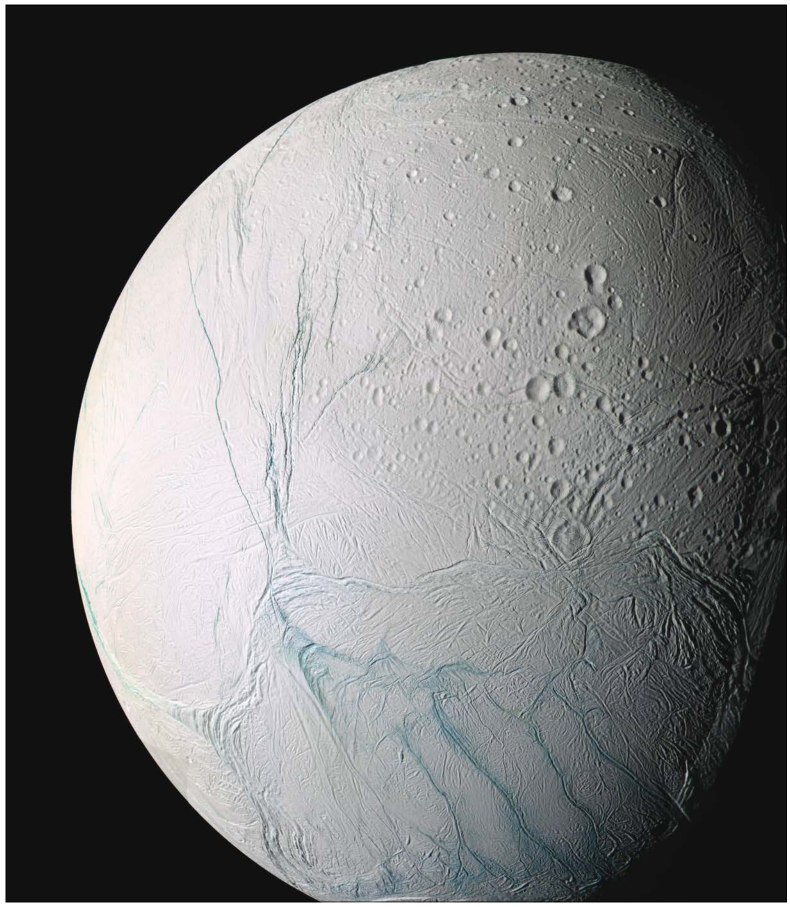
The planned spacecraft will fly through the plumes with more sophisticated instruments than Cassini's, designed specifically to sample the vapour (like Clipper will do at Europa). Yet adding a lander could get us even closer to the plume material. By landing close to the edge of a tiger stripe, a lander would dramatically increase the mission's ability to analyse the material from the ocean in the form of fresh snow. In particular, it would look for biosignatures – evidence of the ocean being habitable, or perhaps even inhabited by microbes.

However, new research urges caution in drawing hasty conclusions about organic molecules present in the plumes and snow. While not as powerful as Jupiter's, Saturn also has a magnetosphere filled with high-energy ions that bombard Enceladus. A recent laboratory study, led by Grace Richards of the Istituto Nazionale di Astrofisica e Planetologia Spaziale (IAPS-INAF) in Rome, found that when these ions hit surface-ice they trigger chemical reactions that produce organic molecules, including some that are precursors to amino acids, similar to what Cassini tasted in the plumes.

So how can we be sure that the organics in Enceladus' plumes originate from the ocean, and not from radiation-driven chemistry on the surface? It is the same quandary for dark patches around cracks on the surface of Europa, which seem to be rich with organic molecules that could either originate via upwelling from the ocean below, or just from radiation triggering organic chemistry. A lander on Enceladus might solve not just the mystery of that particular moon, but provide important pointers to explain what we're seeing on Europa too.

More icy companions

Enceladus is not Saturn's only icy moon; there's Titan too. As the ringed planet's largest moon at 5150 km across, Titan (like Ganymede) is larger than Mercury. However, unlike the other moons in the solar system, Titan has a thick atmosphere rich in nitrogen and methane. The atmosphere is opaque, hiding the surface from spacecraft in orbit except at infrared wavelengths and radar, which means that getting below the smoggy atmosphere is a must.



NASA/JPL/Space Science Institute

Blue moon
Enceladus, as seen by Cassini in 2006. The tiger stripes are the blue fractures towards the south.

ESA did this in 2005 with the Huygens lander, which, as it parachuted down to Titan's frozen surface, revealed it to be a land of hills and dune plains with river channels, lakes and seas of flowing liquid hydrocarbons. These organic molecules originate from the methane in its atmosphere reacting with solar ultraviolet.

Until recently, it was thought that Titan has a core of rock, surrounded by a shell of high-pressure ice, above which sits a layer of salty liquid water and then an outer crust of water ice. However, new evidence from re-analysing Cassini's data suggests that rather than oceans of liquid water, Titan has "slush" below the frozen exterior, with pockets of liquid water (*Nature* **648** 556). The team, led by Flavio Petricca from NASA's Jet Propulsion Laboratory, looked at how Titan's shape morphs as it orbits Saturn. There is a several-hour lag between the moon passing the peak of Saturn's gravitational pull and its shape shifting, implying that while there must be some form of non-solid substance below Titan's surface to allow for deformation, more energy is lost or dissipated than would be if it was liquid water. Instead, the researchers found that a layer of high-pressure ice close to its melting point – or slush – better fits the data.

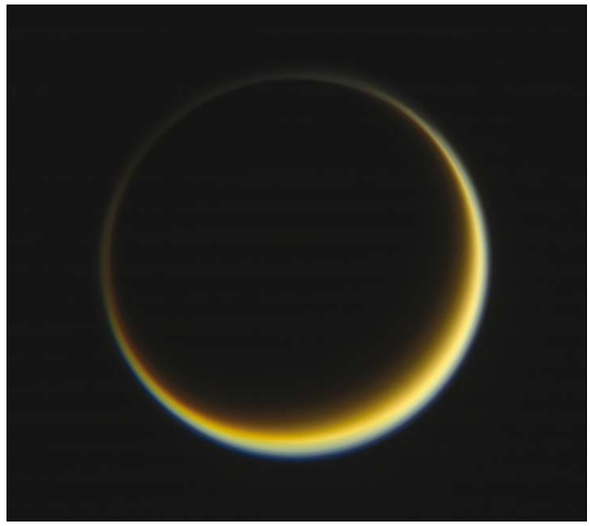
To find out more about Titan, NASA is planning to follow in Huygens' footsteps with the Dragonfly mission but in an excitingly different way. Set to launch in 2028, Dragonfly should arrive at Titan in 2034 where it will deploy a rotorcraft that will fly over the moon's surface, beneath the smog, occasionally touching down to take readings. Scientists are intending to use Dragonfly to sample surface material with a mass spectrometer to

It's becoming clear that icy ocean moons could far outnumber more traditional habitable planets like Earth, not just in our solar system

identify organic compounds and therefore better assess Titan's biological potential. It will also perform atmospheric and geological measurements, even listening for seismic tremors while landed, which could provide further clues about Titan's interior.

Jupiter and Saturn are also not the only planets to possess icy moons. We find them around Uranus and Neptune too. Even the dwarf planet Pluto and its largest moon Charon have strong similarities to icy moons. Whether any of these bodies, so far out from the Sun, can maintain an ocean is unclear, however.

Recent findings point to an ocean deep inside Uranus' moon Ariel that may once have been 170 km deep, kept warm by tidal heating (*Icarus* **444** 116822). But over time Ariel's orbit around Uranus has become increasingly circular, weakening the tidal forces acting on it, and the ocean has partly frozen. Another of Uranus' moons, Miranda, has a chaotic surface that appears to have melted and refrozen, and the pattern of cracks on its surface strongly suggests that the moon also contains an


NASA/JPL/Space Science Institute

Hello halo Titan is different to other icy moons in that it has a thick atmosphere, seen here with the moon in silhouette.

ocean, or at least did 150 million years ago. A new mission to Uranus is a top priority in the US's most recent Decadal Review.

It's becoming clear that icy ocean moons could far outnumber more traditional habitable planets like Earth, not just in our solar system, but across the galaxy (although none have been confirmed yet). Understanding the internal structures of the icy moons in our solar system, and characterizing their oceans, is vital if we are to expand the search for life beyond Earth.

Where next for quantum tech?

Quantum technology is developing at an incredible pace, but what are the biggest challenges and opportunities for the field? At a recent conference organized by the Institute of Physics, **Matin Durrani** talked to four future leaders from academia and industry about how quantum can grow and develop

The International Year of Quantum Science and Technology, which ends this month, has celebrated all the great developments in the sector – but what challenges and opportunities lie in store? That was the question deliberated by four future leaders in the field at the Royal Institution in central London in November. The discussion took place during the two-day conference "Quantum science and technology: the first 100 years; our quantum future", which was part of a week of quantum-related events in the UK organized by the Institute of Physics.

As well as outlining the technical challenges in their fields, the speakers all stressed the importance of developing a "skills pipeline" so that the quantum sector has enough talented people to meet its needs. Also vital will be the need to communicate the mysteries and potential of quantum technology – not just to the public but to industrialists, government officials and venture capitalists.

Two of the speakers – Nicole Gillett (Riverlane) and Muhammad Hamza Waseem (Quantinuum) – are from the quantum tech industry, with Mehul Malik (Heriot-Watt University) and Sarah Alam Malik (University College London) based in academia. The following is an edited version of the discussion.

What will be the biggest or most important application of quantum technology in your field over the next 10 years?

Nicole Gillett: If you look at roadmaps of quantum-computing companies, you'll find that IBM, for example, intends to build the world's first utility scale and fault-tolerant quantum computer by the end of the decade. Beyond 2033, they're committing to have a system that could support 2000 "logical qubits", which are essentially error-corrected qubits, in which the data of one qubit has been encoded into many qubits.

What can be achieved with that number of qubits is a difficult question to answer but some theorists, such as Juan Maldacena, have proposed some very exotic ideas, such as using a system of 7000 qubits to simulate black-hole dynamics. Now that might not be a particularly

INTERNATIONAL YEAR OF Quantum Science and Technology

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

Quantum's future leaders

Tushna Commissariat

Deep thinkers The challenges and opportunities for quantum science and technology were discussed during a conference organized by the Institute of Physics at the Royal Institution on 5 November 2025 by (left to right, seated) Muhammad Hamza Waseem; Sarah Alam Malik; Mehul Malik; and Nicole Gillett. The discussion was chaired by *Physics World* editor-in-chief Matin Durrani (standing, far right).

Now at IBM Quantum, **Nicole Gillett** was, at the time of the discussion, senior software engineer at Riverlane, in Cambridge, UK. The company is a leader in quantum error correction, which is a critical part of a fully functioning, fault-tolerant quantum computer. Errors arise because quantum bits, or qubits, are so fragile and correcting them is far trickier than with classical devices. Riverlane is seeking to correct for errors without disturbing a device's quantum states. Gillett was part of a team trying to implement error-correcting algorithms on real quantum-computing chips.

Mehul Malik, who studied physics at a liberal arts college in New York, was attracted to quantum physics because of what he calls a "weird middle ground between artistic creative thought and the rigour of physics". After doing a PhD at the University of Rochester, he spent five years as a postdoc with Anton Zeilinger at the University of Vienna in Austria before moving to Heriot-Watt University in the UK. As head of its Beyond Binary Quantum Information research group, Malik works on quantum information processing and communication and fundamental studies of entanglement.

Sarah Alam Malik is a particle physicist at University College London, using particle colliders to detect and study potential candidates for dark matter. She is also trying to use quantum computers to speed up the discovery of new physics given that what she calls "our most cherished and compelling theories" for physics beyond the Standard Model, such as supersymmetry, have not yet been seen. In particular, Malik is trying to find new physics in a way that's "model agnostic" – in other words, using quantum computers to search particle-collision data for anomalous events that have not been seen before.

Muhammad Hamza Waseem studied electrical engineering in Pakistan, but got hooked on quantum physics after getting involved in recreating experiments to test Bell's inequalities in what he claims was the first quantum optics lab in the country. Waseem then moved to the University of Oxford in the UK, to do a PhD studying spin waves to make classical and quantum logic circuits. Unable to work when his lab shut during the COVID-19 pandemic, Waseem approached Quantinuum to see if he could help them in their quest to build quantum computers using ion traps. Now based at the company, he studies how quantum computers can do natural-language processing. "Think ChatGPT, but powered with quantum computers," he says.

useful industry application, but it tells you about the potential power of a machine like this.

Mehul Malik: In my field, quantum networks that can distribute individual quantum particles or entangled states over large and short distances will have a significant impact within the next 10 years. Quantum networks will connect smaller, powerful quantum processors to make a larger quantum device, whether for computing or communication. The technology is quite mature – in fact, we've already got a quantum network connecting banks in London.

I will also add something slightly controversial. We often try to distinguish between quantum and non-quantum technologies, but what we're heading towards is combining classical state-of-the-art devices with technology based on inherently quantum effects – what you might call "quantum adjacent technology". Single-photon detectors, for example, are going to revolutionize healthcare, medical imaging and even long-distance communication.

Quantum technology is letting us ask fundamental questions about nature

Sarah Alam Malik, University College London

Sarah Alam Malik: For me, the biggest impact of quantum technology will be applying quantum computing algorithms in physics. Can we quantum simulate the dynamics of, say, proton–proton collisions in a more efficient and accurate manner? Can we combine quantum computing with machine learning to sift through data and identify anomalous collisions that are beyond those expected from the Standard Model?

Quantum technology, in other words, is letting us ask very fundamental questions about nature. Emerging in theoretical physics, for example, is the idea that the fundamental layer of reality may not be particles and fields, but units of quantum information. We're looking at the world through this new quantum-theoretic lens and asking questions like, whether it's possible to measure entanglement in top quarks and even explore Bell-type inequalities at particle colliders.

One interesting quantity is "magic", which is a measure of how far you are from having something that can be classically simulable (*Phys. Rev. D* **110** 116016).

The more magic there is in a system the less easy it is to simulate classically – and therefore the greater the computational resource it possesses for quantum computing. We're asking how much "magic" there is in, for instance, top quarks produced at the Large Hadron Collider. So one of the most important developments for me may well be asking questions in a very different way to before.

For quantum theory to have a big impact, we have to make quantum physics more accessible to everyone

Muhammad Hamza Waseem, Quantinuum

Muhammad Hamza Waseem: Technologically speaking, the biggest impact will be simulating quantum systems using a quantum computer. In fact, researchers from Google already claim to have simulated a wormhole in a quantum computer, albeit a very simple version that could have been tackled with a classical device (*Nature* **612** 55).

But the most significant impact has to do with education. I believe quantum theory teaches us that reality is not about particles and individuals – but relations. I'm not saying that particles don't exist but they emerge from the relations. In fact, with colleagues at the University of Oxford, we've used this idea to develop a new way of teaching quantum theory, called Quantum in Pictures.

We've already tried our diagrammatic approach with a group of 16–18-year-olds, teaching them the entire quantum-information course that's normally given to postgraduates at Oxford. At the end of our two-month course, which had one lecture and tutorial per week, students took an exam with questions from past Oxford papers. An amazing 80% of students passed and half got distinctions.

I've also tried the same approach on pupils in Pakistan: the youngest, who was just 13, can now explain quantum teleportation and quantum entanglement. My point is that for quantum theory to have a big impact, we have to make quantum physics more accessible to everyone.

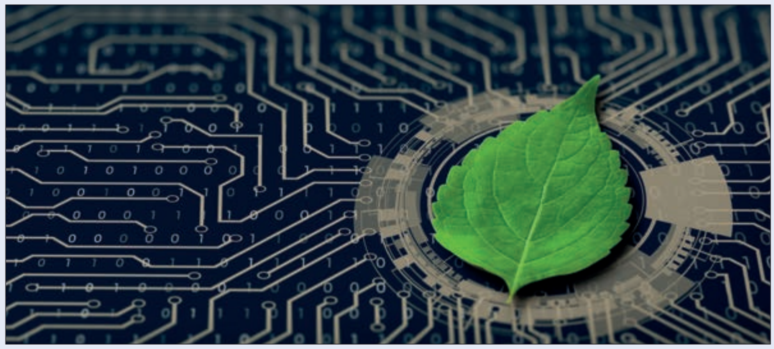
What will be the biggest challenges and difficulties over the next 10 years for people in quantum science and technology?

Nicole Gillett: The challenge will be building up a big enough quantum workforce. Sometimes people hear the words "quantum computer" and get scared, worrying they're going to have to solve Hamiltonians all the time. But is it possible to teach students at high-school level about these concepts? Can we get the ideas across in a way that is easy to understand so people are interested and excited about quantum computing?

At Riverlane, we've run week-long summer workshops for the last two years, where we try to teach undergraduate students enough about quantum error correction so they can do "decoding". That's when you take the results of error correction and try to figure out what errors occurred on your qubits. By combining lectures and hands-on tutorials we found we could teach students about error corrections – and get them really excited too.

We had students from physics, philosophy, maths and computer science take the course – the only pre-requisite, apart from being curious about quantum computers, is some kind of coding ability. My point is that these kinds of boot camps are going to be so important to inspire future generations. We need to make the information accessible to people because otherwise our biggest challenge will be not having a workforce ready for quantum computing.

Towards "green" quantum technology



(iStock/Peach)

Today's AI systems use vast amounts of energy, but should we also be concerned about the environmental impact of quantum computers? Google, for example, has already carried out quantum error-correction experiments in which data from the company's quantum computers had to be processed once every microsecond per round of error correction (*Nature* **638** 920). "Finding ways to process it to keep up with the rate at which it's being generated is a very interesting area of research," says Nicole Gillett.

However, quantum computers could cut our energy consumption by allowing calculations to be performed far more quickly and efficiently than is possible with classical machines. For Mehul Malik, another important step towards "green" quantum technology will be to lower the energy that quantum devices require and to build detectors that work at room temperature and are robust against noise. Quantum computers themselves can also help, he thinks, by discovering energy-efficient technologies, materials and batteries.

Our biggest challenge will be not having a workforce ready for quantum computing

Nicole Gillett, Riverlane

Mehul Malik: One of the big challenges is international cooperation and collaboration. Imagine if, in the early days of the Internet, the US military had decided they'd keep it to themselves for national-security reasons or if CERN hadn't made the World Wide Web open source. We face the same challenge today because we live in a world that's becoming polarized and protectionist – and we don't want that to hamper international collaboration.

Over the last few decades, quantum science has developed in a very international way and we have come so far because of that. I have lived in four different continents, but when I try to recruit internationally, I face significant hurdles from the UK government, from visa fees and so on. To really progress in quantum tech, we need to collaborate and develop science in a way that's best for humanity not just for each nation.

Sarah Alam Malik: One of the most important challenges will be managing the hype that inevitably surrounds the field right now. We've already seen this with artificial intelligence (AI), which has gone though the whole hype

A quantum laptop?

(iStock/inkoly)

Will we ever see portable quantum computers or will they always be like today's cloud-computing devices in distant data centres? Muhammad Hamza Waseem certainly does not envisage a word processor that uses a quantum computer. But he points to companies like SPINQ, which has built a two quantum bit computer for educational purposes. "In a sense, we already have a portable quantum computer," he says. For Mehul Malik, though, it's all about the market. "If there's a need for it," he joked, "then somebody will make it."

If I were science minister...

(Shutterstock/jenny on the moon)

When asked by Peter Knight – one of the driving forces behind the UK's quantum-technology programme – what the panel would do if they were science minister, Nicole Gillett said she would seek to make the UK the leader in quantum computing by investing heavily in education. Mehul Malik would cut the costs of scientists moving across borders, pointing out that many big firms have been founded by immigrants. Sarah Alam Malik called for long-term funding – and not to give up if short-term gains don't transpire. Muhammad Hamza Waseem, meanwhile, said we should invest more in education, research and the international mobility of scientists.

cycle. Lots of people were initially interested, then the funding dried up when reality didn't match expectations. But now AI has come back with such resounding force that we're almost unprepared for all the implications of it.

Quantum can learn from the AI hype cycle, finding ways to manage expectations of what could be a very transformative technology. In the near- and mid-term, we need to not overplay things and be cautious of this potentially transformative technology – yet be braced for the impact it could have. It's a case of balancing hype with reality.

Muhammad Hamza Waseem: Another important challenge is how to distribute funding between research on applications and research on foundations. A lot of the good technology we use today emerged from foundational ideas in ways that were not foreseen by the people originally working on them. So we must ensure that foundational research gets the funding it deserves or we'll hit a dead end at some point.

Will quantum tech alter how we do research, just as AI could do?

Mehul Malik: AI is already changing how I do research, speeding up the way I discover knowledge. Using Google Gemini, for example, I now ask my browser questions instead of searching for specific things. But you still have to verify all the information you gather, for example, by checking the links it cites. I recently asked AI a complex physics question to which I knew the answer and the solution it gave was terrible. As for how quantum is changing research, I'm less sure, but better detectors through quantum-enabled research will certainly be good.

Muhammad Hamza Waseem: AI is already being deployed in foundational research, for example, to discover materials for more efficient batteries. A lot of these applications could be integrated with quantum computing in some way to speed work up. In other words, a better understanding of quantum tech will let us develop AI that is safer, more reliable, more interpretable – and if something goes wrong, you know how to fix it. It's an exciting time to be a researcher, especially in physics.

Sarah Alam Malik: I've often wondered if AI, with the breadth of knowledge that it has across all different fields, already has answers to questions that we couldn't answer – or haven't been able to answer – just because of the boundaries between disciplines. I'm a physicist and so can't easily solve problems in biology. But could AI help us to do breakthrough research at the interface between disciplines?

What lessons can we learn from the boom in AI when it comes to the long-term future of quantum tech?

Nicole Gillett: As a software engineer, I once worked at an Internet security company called CloudFlare, which taught me that it's never too early to be thinking about how any new technology – both AI and quantum – might be abused. What's also really interesting is whether AI and machine learning can be used to build quantum computers by developing the coding algorithms they need. Companies like Google are active in this area and so are Riverlane too.

Mehul Malik: I recently discussed this question with a friend who works in AI, who said that the huge AI boom

> **We need to diversify early on so that the power [of quantum tech] is not in the hands of a few privileged monopolies**
>
> Mehul Malik, Heriot-Watt University

in industry, with all the money flowing in to it, has effectively killed academic research in the field. A lot of AI research is now industry-led and goal-orientated – and there's a risk that the economic advantages of AI will kill curiosity-driven research. The remedy, according to my friend, is to pay academics in AI more as they are currently being offered much larger salaries to work in the private sector.

Another issue is that a lot of power is in the hands a just a few companies, such as Nvidia and ASML. The lesson for the quantum sector is that we need to diversify early on so that the power to control or chart the course of quantum technologies is not in the hands of a few privileged monopolies.

Sarah Alam Malik: Quantum technology has a lot to learn from AI, which has shown that we need to break down the barriers between disciplines. After all, some of the most interesting and impactful research in AI has happened because companies can hire whoever they need to work on a particular problem, whether it's a computer scientist, a biologist, a chemist, a physicist or a mathematician.

Nature doesn't differentiate between biology and physics. In academia we not only need people who are hyper specialized but also a crop of generalists who are knee-deep in one field but have experience in other areas too.

The lesson from the AI boom is to blur the artificial boundaries between disciplines and make them more porous. In fact, quantum is a fantastic playground for that because it is inherently interdisciplinary. You have to bring together people from different disciplines to deliver this kind of technology.

Muhammad Hamza Waseem: AI research is in a weird situation where there are lots of excellent applications but so little is understood about how AI machines work. We have no good scientific theory of intelligence or of consciousness. We need to make sure that quantum computing research does not become like that and that academic research scientists are well-funded and not distracted by all the hype that industry always creates.

At the start of the previous century, the mathematician David Hilbert said something like "physics is becoming too difficult for the physicists". I think quantum computing is also somewhat becoming too challenging for the quantum physicists. We need everyone to get involved for the field to reach its true potential. ■

Careers

A theorist's journey in food

From ice cream to instant coffee, theoretical physicist Rob Farr has spent his career studying the fundamental properties of food materials to help manufacturers optimize production processes, as **Joe McEntee** finds out

iStock/fabiomax

Caffeine boost Rob Farr's career at JDE Peet's, the multinational coffee and tea company, spanned diverse aspects of coffee production, brewing and packaging.

Rob Farr is a theorist and computer modeller whose career has taken him down an unconventional path. He studied physics at the University of Cambridge, UK, from 1991 to 1994, staying on to do a PhD in statistical physics. But while many of his contemporaries then went into traditional research fields – such as quantum science, high-energy physics and photonic technologies – Farr got a taste for the food and drink manufacturing industry. It's a multidisciplinary field in which Farr has worked for more than 25 years.

After leaving academia in 1998, first stop was Unilever's €13bn foods division. For two decades, latterly as a senior scientist, Farr guided R&D teams working across diverse lines of enquiry – "doing the science, doing the modelling", as he puts it. Along the way, Farr worked on all manner of consumer products including ice-cream, margarine and non-dairy spreads, as well as "dry" goods such as bouillon cubes. There was also the occasional foray into cosmetics, skin creams and other non-food products.

As a theoretical physicist working in industrial-scale food production, Farr's focus has always been on the materials science of the end-product and how it gets processed. "Put simply," says Farr, "that means making production as efficient as possible – regarding both energy and materials use – while developing 'new customer experiences' in terms of food taste, texture and appearance."

Ice-cream physics

One tasty multiphysics problem that preoccupied Farr for a good chunk of his time at Unilever is ice cream. It is a hugely complex material that Farr likens to a high-temperature ceramic, in the sense that the crystalline part of it is stored very near to the melting point of ice. "Equally, the non-ice phase contains fats," he says, "so there's all sorts of emulsion physics and surface science to take into consideration."

Ice cream also has polymers in the mix, so theoretical modelling needs to incorporate the complex physics of polymer–polymer phase separation as well as polymer flow, or "rheology", which contributes to the product's texture and material properties. "Air is another significant component of ice cream," adds Farr, "which means it's a foam as well as an emulsion."

> If you want to study a parameter space that's not been explored before, the only way to do that is to simulate the core processes using fundamental physics

As well as trying to understand how all these subcomponents interact, there's also the thorny issue of storage. After it's produced, ice cream is typically kept at low temperatures of about −25 °C – first in the factory, then in transit and finally in a supermarket freezer. But once that tub of salted-caramel or mint choc chip reaches a consumer's home, it's likely to be popped in the ice compartment of a fridge freezer at a much milder −6 or −7 °C.

Manufacturers therefore need to control how those temperature transitions affect the recrystallization of ice. This unwanted outcome can lead to phenomena like "sintering" (which makes a harder product) and "ripening" (which can lead to big ice crystals that can be detected in the mouth and detract from the creamy texture).

"Basically, the whole panoply of soft-matter physics comes into play across the production, transport and storage of ice cream," says Farr. "Figuring out what sort of materials systems will lead to better storage stability or a more consistent product texture are non-trivial questions given that the global market for ice cream is worth in excess of €100bn annually."

A shot of coffee?

After almost 20 years working at Unilever, in 2017 Farr took up a role as coffee science expert at JDE Peet's, the Dutch multinational coffee and tea company. Switching from the chilly depths of ice cream science to the dark arts of coffee production and brewing might seem like a steep career phase change, but the physics of the former provides a solid bridge to the latter.

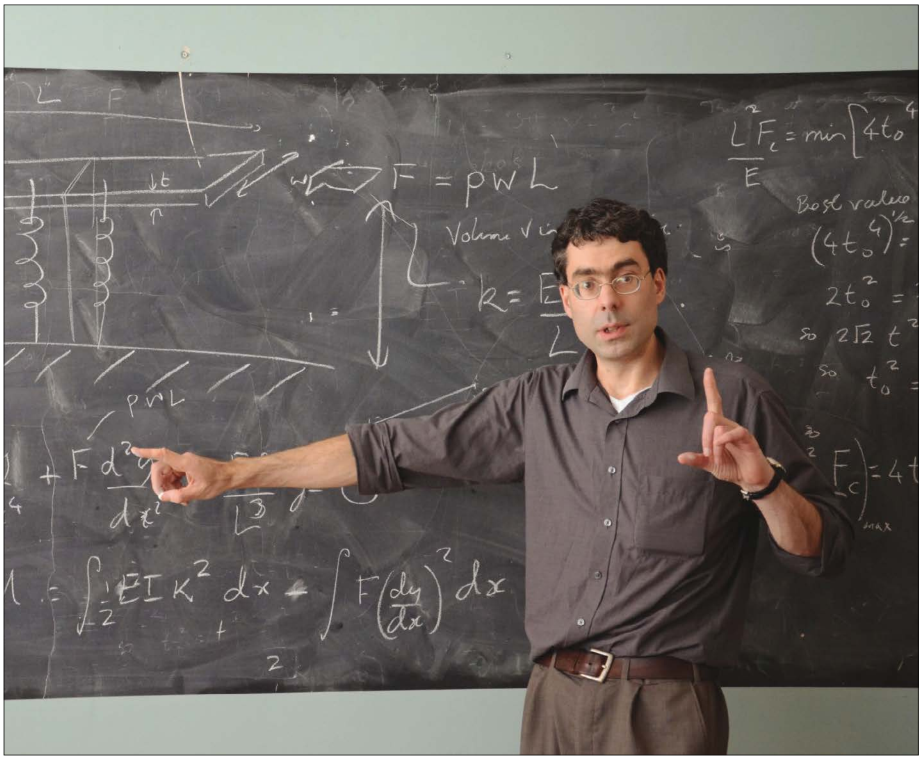
The overlap is evident, for example, in how instant coffee gets freeze-dried – a low-temperature dehydration process that manufacturers use to extend the shelf-life of perishable materials and make them easier to transport. In the case of coffee, freeze drying (or lyophilization, as it's commonly known) also helps to retain flavour and aromas.

After roasting and grinding the raw coffee beans, manufacturers extract a coffee concentrate using high pressure and water. This extract is then frozen, ground up and placed in a vacuum well below 0 °C. A small amount of heat is applied to sublime the ice away and remove the remaining water from the non-ice phase.

The quality of the resulting freeze-dried instant coffee is better than ordinary instant coffee. However, freeze-drying is also a complex and expensive process, which manufacturers seek to fine-tune by implementing statistical methods to optimize, for example, the amount of energy consumed during production.

Such approaches involve interpolating the gaps between existing experimental data sets, which is where a physics mind-set comes in. "If you want to study a parameter space that's not been explored before," says Farr, "the only way to do that is to simulate the core processes using fundamental physics."

A senior scientist needs to be someone who colleagues come to informally to discuss their technical challenges



London Institute for Mathematical Sciences

Cool science "The whole panoply of soft-matter physics comes into play across the production, transport and storage of ice-cream," says industrial physicist Rob Farr.

Beyond the production line, Farr has also sought to make coffee more stable when it's stored at home. Sustainability is the big driver here: JDE Peet's has committed to make all its packaging compostable, recyclable or reusable by 2030. "Shelf-life prediction has been a big part of this R&D initiative," he explains. "The work entails using materials science and the physics of mass transfer to develop next-generation packaging and container systems."

Line of sight

After eight years unpacking the secrets of coffee physics at JDE Peet's, Farr was given the option to relocate to the Netherlands in mid-2025 as part of a wider reorganization of the manufacturer's corporate R&D function. However, he decided to stay put in Oxford and is now deciding between another role in the food manufacturing sector, or moving into a new area of research, such as nuclear energy, or even education.

Farr believes he gained a lot from his time at JDE Peet's. As well as studying a wide range of physics problems, he also benefited from the company's rigorous approach to R&D, whereby projects are regularly assessed for profitability and quickly killed off if they don't make the cut. Such prioritization avoids wasted effort and investment, but it also demands agility from staff scientists, who have to build long-term research strategies against a project landscape in constant flux.

To thrive in that setting, Farr says collaboration and an open mind are essential. "A senior scientist needs to be someone who colleagues come to informally to discuss their technical challenges," he says. "You can then find the scientific question which underpins seemingly disparate problems and work with colleagues to deliver commercially useful solutions." For Farr, it's a self-reinforcing dynamic. "As more people come to you, the more helpful you become – and I love that way of working."

What Farr calls "line-of-sight" is another unique feature of industrial R&D in food materials. "Maybe you're only building one span of a really long bridge," he notes, "but when you can see the process end-to-end, as well as your part in it, that is a fantastic motivator." Indeed, Farr believes that for physicists who want a job doing something useful, the physics of food materials makes a great career. "There are," he concludes, "no end of intriguing and challenging research questions."

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

Ask me anything: Andrew Lamb


Delta.g

Andrew Lamb is the chief technology officer (CTO) and co-founder of Delta.g – a Birmingham-based quantum gravity sensor company. Lamb has been key to the development of quantum gravity gradiometers, from world-first demonstrations out of the lab, to delivering the first industry-developed device under contract to the UK Department for Transport. Delta.g was awarded the Institute of Physics' 2025 qBIG prize, which celebrates and promotes the innovation and commercialization of quantum technologies in the UK and Ireland. Lamb, along with Delta.g colleagues Jonathan Winch and Benjamin Adams, was also awarded the 2025 Institute of Physics' Clifford Paterson Medal and Prize, for "the realization of the first commercialized quantum sensor of gravity gradients under commercial contract and demonstrating its relevance to transport applications".

What skills do you use every day in your job?

A quantum sensor is a combination of lots of different parts working together in harmony: a sensor head containing the atoms and isolating them from the environment; a laser system to probe the quantum structure and manipulate atomic states; electronics to drive the power and timing of a device; and software to control everything and interpret the data. As the person building, developing and maintaining these devices you need to have expertise across all these areas. In addition to these skills, as the CTO my role also requires me to set the company's technical priorities, determine the focus of R&D activities and act as the top technical authority in the firm.

In a developing field like quantum metrology, evidence-based decision making is crucial as you critically assess information, disregarding what is irrelevant and making an informed choice – especially when the "right answer" may not be obvious for months or even years. Challenges arise that may never have been solved before, and the best way to do so is to dive deep into the "why and how" something happens. Once the root cause is identified a creative solution then needs to be found; whether it is something brand new, or implementing an approach from an entirely different discipline.

What do you like best and least about your job?

The best thing about my job is the way in which it enables me to grow my knowledge and understanding of a wide variety of fields, while also providing me opportunities for creative problem solving. When you surround yourself with people who are experts in their field, there is no end to the opportunities to learn. Before co-founding Delta.g I was a researcher at the University of Birmingham where I learnt my technical skills. Moving into a start-up, we built a multidisciplinary team to address the operational, regulatory and technical barriers to establish a disruptive product in the marketplace. The diversity created within our company has afforded a greater pool of experts to learn from.

As the CTO, my role sits at the intersection of the technical and the commercial within the business. That means it is my responsibility to translate commercial milestones into a scientific plan, while also explaining our progress to non-experts. This can be challenging and quite stressful at times – particularly when I need to describe our scientific achievements in a way that truly reflects our advances, while still being accessible.

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

For a long time, I didn't know what direction I wanted to take, and I used to worry that the lack of a clear purpose would hold me back. Today I know that it doesn't. Instead of fixating on finding a perfect path early on, it's far more valuable to focus on developing skills that open doors. Whether those skills are technical, managerial or commercial, no knowledge is ever wasted. I'm still surprised by how often something I learned as far back as GCSE ends up being useful in my work now.

I also wish I had understood just how important it is to stay open to new opportunities. Looking back, every pivotal point in my career – switching from civil engineering to a physics degree, choosing certain undergraduate modules, applying for unexpected roles, even co-founding Delta.g – came from being willing to make a shift when an opportunity appeared. Being flexible and curious matters far more than having everything mapped out from the beginning.

Being flexible and curious matters far more than having everything mapped out from the beginning

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Chess960 and gliding grasshoppers

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

Chess is a seemingly simple game, but one that hides incredible complexity. In the standard game, the starting positions of the pieces are fixed, so top players rely on memorizing a plethora of opening moves, which can sometimes result in boring, predictable games. It's also the case that playing as white, and therefore going first, offers an advantage.

In the 1990s former chess world champion Bobby Fischer proposed another way to play chess to encourage more creative play. This form of the game – dubbed Chess960 – keeps the pawns in the same positions but randomizes where the pieces at the back of the board – the knights, bishops, rooks, king and queen – are placed at the start while keeping the rest of the rules the same. It is named after the 960 starting positions that result from mixing it up at the back and it was thought that Chess960 could allow for more permutations that would make the game fairer for both players.

Yet research by physicist Marc Barthelemy at Paris-Saclay University suggests it's not as simple as this (arXiv:2512.14319). He used an open-source chess program called Stockfish to analyse each of the 960 starting positions and developed a statistical method to measure decision-making complexity by calculating how much "information" a player needs to identify the best moves.

Barthelemy found that the standard game can be unfair, as players with black pieces who go second have to keep up with the moves from the player with white pieces. Yet regardless of mixing it up at the back, he discovered that white still has an advantage in almost all – 99.6% – of the 960 positions. He also found that the standard set-up – rook, knight, bishop, queen, king, bishop, knight, rook – is nothing special and is presumably a historical accident, possibly because the starting positions are easy to remember, being visually symmetrical. For a more fair and balanced match, Barthelemy suggests playing position #198, which has the starting positions as queen, knight, bishop, rook, king, bishop, knight, rook.


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Game on New research finds that white still has an advantage in chess even if the back pieces are placed in unconventional positions at the start.

Yes, there's too much hype

Quantum physicist **Alain Aspect** from the Université Paris-Saclay, who shared the 2022 Nobel Prize for Physics, thinks quantum computing is suffering from exaggerated press releases from companies and universities. (Source: *El País*)

Highly trained scientific leaders are spending their time typing out letters

President of the Royal Society **Paul Nurse** says that UK scientists are hampered by a lack of administrative support, adding that UK universities are "third-worldish" compared to their Chinese counterparts. (Source: *Times*)

Grasshopper robots

While much insight has been gleaned from how grasshoppers hop, their gliding prowess has mostly been overlooked. Now researchers at Princeton University have studied how these gangly insects deploy and retract their wings to inspire a new approach to flying robots (*J. R. Soc. Interface* **23** 20250117).

Typical insect-inspired robot designs are often based on bees and flies. They feature constant flapping motion, yet that requires a lot of power so the robots either carry heavy batteries or are tethered to a power supply. Grasshoppers, however, are able to jump and glide as well as flap their wings and while they are not the best gliding insect, they have another trick as they are able to retract and unfurl their wings.

Grasshoppers have two sets of wings: the forewings are mainly used for protection and camouflage, while the hindwings are used for flight and are corrugated, which allows them to fold in neatly like an accordion. In the new work, a team of engineers, biologists and entomologists analysed the wings of the American grasshopper, also known as the bird grasshopper, due to its superior flying skills. They took CT scans of the insects and then used the findings to 3D-print model wings. They attached these wings to small frames to create grasshopper-inspired gliders, finding that their performance was on par with that of actual grasshoppers.

The researchers also tweaked certain wing features such as the shape, camber and corrugation, finding that a smooth wing produced gliding that was more efficient and repeatable than one with corrugations. "This showed us that these corrugations might have evolved for other reasons," notes Princeton engineer Aimy Wissa, who adds that "very little" is known about how grasshoppers deploy their wings. Further work could result in new ways to extend the flight time for insect-sized robots without the need for heavy batteries or tethering. "By combining biology with engineering, we're able to build and ideate on something completely new," adds Lee.

Michael Banks is news editor of *Physics World*

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